CRANFIELD UNIVERSITY

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An investigation of the mirroring of supply chain configuration modularity, and product modularity in contemporary supply chains

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ABSTRACT

The introduction of new to market products is a challenge, in high technology markets, where speed and product variation are key considerations. High technology companies require the ability to simultaneously combine operational excellence, customer intimacy and product leadership. A lack of coordination between new product development (NPD), product planning and supply chain configuration (SCC) is a recognised cause of many early-life product failures. This research has one objective: to increase our understanding of the role of modularity in linking SCC and NPD decisions. The research incorporates general systems theory (GST) and knowledge-based theory (KBT), in mirroring product modularity (PM) and SCC modularity (SCCM) within contemporary supply networks.

A systematic literature review (SLR) advocates the use of modular design, in linking these concepts and boosting the rate of innovation. The literature indicates that product architecture (PA) and SCC tend to be mirrored in modularity levels, post product launch, and this mirroring is desirable. The literature identified a gap in how SCCM is conceptualised, and how this mirroring manifests itself. These gaps are addressed in the empirical research conducted in project two, where the SCCM construct was developed and used to assess the manifestation and benefits of PM and SCCM mirroring across ten products (UoA) in five case companies across four industry sectors. Mirroring is evident, in six of the UoA, the remaining four UoA exhibit a medium level of mirroring, post product launch. The contribution to theory is a conceptualisation of SCCM where supply chain tiering is a main indicator. Propensity for modules to decouple; early supplier involvement, and a mirrored product and SCC life cycle perspective are the three causal linkages which enable mirroring of PM and SCCM post product launch.

The SLR identified the use of co-development (CD), feedback (FC) and feedforward anticipatory control (FAC) at concept design to increase the mirroring of PM and SCCM, post product launch. In project three hypotheses were tested which advocate the use of these mechanisms, and the associated underlying mechanisms were investigated. The findings indicate use of CD and FAC, but a lack of FC, and mirroring support for platform design. The contribution to practice is an intervention framework applied at the concept stage that improves the coordination between NPD, SCC and product planning for new to market products.

Keywords: Supply chain configuration, new product development, product planning

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The good life is one inspired by love,

and guided by knowledge

– Betrand Russell (1872-1970)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

CAS	Complex adaptive system
CD	Co-development
CE	Concurrent engineering
CUV	Cross over utility vehicle
DA	Data access
ESI	Early supplier involvement
FC	Feedback control
FAC	Feedforward anticipatory control
KBV	Knowledge based view
LL	Limited life
MSC	Multi-tier supply chain
NPD	New product development
OEM	Original equipment manufacturer
OM	Organisational modularity
PA	Product architecture
PM	Product modularity
PSA	Primary sub-assembler
PV	Product use variety
QCA	Qualitative comparative analysis
RPM	Revolutions per minute
RQ	Research question
SC	Supply chain
SCA	Supply chain architecture
SCC	Supply chain configuration
SCCM	Supply chain configuration modularity
SCT	Supply chain tiering
SKU	Stockable known units
SLR	Systematic literature review
SUV	Standard utility vehicle
TLA	Top level assembly
UOA	Units of analysis
UMC	Unit manufacturing cost

KEY DEFINITIONS

Abductive methods

Abduction is a way of relating an observation or case to a theory (or vice versa) that results in a plausible explanation

Source: Charmaz, K. "Grounded Theory Methods in Social Justice Research" in N.K. Denzin and Y.S. Lincoln, eds., *Handbook of Qualitative Research,* 4th ed. Thousand Oaks, CA: Sage, 2011.

Case

A case is a device often used for organizing and analysing qualitative data that helps explain how individuals progress through social settings or experiences.

Source: Becker, H. *Outsiders: Studies in the Sociology of Deviance,* New York: Free Press, 1963.
Cases are particularly useful when there is uncertainty in the definition of constructs.

Source: Mukherjee, A., Mitchell, W. and Talbot, F.B. (2000), "*The impact of new manufacturing technologies and strategically flexible production*", *Journal of Operations Management*, Vol. 18, pp. 139-68.

Case study

A case study is preferred when the inquirer seeks answers to how or why questions, when the enquirer has little control over events being studied, when the object of study is a contemporary phenomenon in a real-life context, when boundaries between the phenomenon and the context are not clear, and when it is desirable to use multiple sources of evidence.

Source: Yin, R. Case Study Research: Design and Methods, 5th ed. Thousand Oaks, CA: Sage 2014.

Coding

Central to effective case research is the coding of the observations and data collected in the field. It is important to try to reduce data into categories

Source: Miles, H. and Huberman, M. (1994), *Qualitative Data Analysis: A Sourcebook*, Sage Publications, Beverly Hills, CA.

Comparative Concepts

The comparative concept method (QCA) is a research strategy that focuses on patterns of similarities and differences across a limited range of cases. QCA employs methodologies that are set-theoretic as opposed to correlational. Comparative case method is one type of cross-case or between-case analysis.

Source: George, A.L. and Bennett, A. *Case Studies and Theory Development in the Social Sciences*, Cambridge, MA: MIT Press, 2005.

Conceptual framework

A conceptual framework explains, either graphically or in narrative form, the main things that are to be studied, the key factors, constructs or variables and the presumed relationships amongst them.

Source: Miles, H. and Huberman, M. (1994), *Qualitative Data Analysis: A Sourcebook*, Sage Publications, Beverly Hills, CA.

Constructivism

All knowledge is claims, and their evaluation take place within a conceptual framework through which the world is described and explained. A constructivist seeks to explain how human beings interpret or construct some *X* in specific contexts. Many constructivists hold that *X* is something that should be severely criticised, changed, or overthrown.

Source: Hacking, I. *The Social Construction of What?* Cambridge, MA: Harvard University Press, 1999.

Data

Data are facts or information in the form of recorded observations, either textual (qualitative) or numeric (quantitative) form. Data become the evidence a researcher uses in support of hypotheses, assertions, claims, and findings.

Source: Bernard, H.R., and Ryan, G.W. *Analyzing Qualitative Data.* Thousand Oaks, CA: Sage, 2010.

Deductive methods	Deductive reasoning is defined as a theory testing process, which commences with an established theory or generalization, and seeks to test whether the theory applies to specific instances (Hyde, 2000). General conclusions are presented based on the corroboration or falsification of the hypotheses through empirical tests. The deductive research process starts with a strong theoretical footing. Its aim is to test theoretical knowledge that has been developed prior to empirical research. **Source:** Hyde, K.F. (2000), "*Recognising deductive processes in qualitative research*", Qualitative Market Research: An International Journal, Vol. 3 No. 2, pp. 82-90.
Inductive methods	Empirical observations (facts) are the starting point of inductive research. Argumentation in this process moves from a specific empirical case or a collection of observations to general law, i.e. from facts to theory. The inductive research process be described as the mirror image of the deductive process (Johnson, 1996). Following this research process, hypotheses are developed based on the empirical study instead of prior to observations. **Source:** Johnson, C. (1996), "Deductive versus inductive reasoning: a closer look at economics", Social Science Journal, Vol. 33 No. 3, pp. 287-99.
Mirroring	The mirroring hypothesis posits that, in the design of a complex system, the technical architecture, division of labor and division of knowledge will "mirror" one another in the sense that the network structure of one corresponds to the structure of the others. Mirroring systems record and reflect input data and identify specific situations which call for intervention. The literature that pertains to the mirroring hypothesis commonly draws on two distinct sources for its motivation: 1) the literature on organisation design and organisations as complex systems and 2) the literature on product development and products as complex systems **Source:** Colfer, L. and Baldwin, C.Y. (2010), "The mirroring hypothesis: Theory, evidence and exceptions". *Harvard Business School Finance Working Paper,* (10-058).

Modularity	Scholars in the organisation-design tradition usually attribute the concept of modularity to Simon (1981), who used the parable of Hora and Tempus to illustrate the advantage of partitioning a complex problem into parsimoniously linked sub-problems: Hora ... put together subassemblies of about ten elements each. ... Hence, when Hora had to put down a partly assembled watch…he lost only a small part of his work, and he assembled his watches in only a fraction of the man-hours it took Tempus. (Simon, 1981, p. 188). By partitioning the watch into subassemblies, Hora made it easier to cope with the complexity of creating a watch. At the system level, Simon called the property of being divisible into loosely linked subsystems "near-decomposability." **Source:** Simon, Herbert A. 1981. The Sciences of the Artificial, 2nd Ed. Cambridge, MA: MIT Press.
NAAMS	NAAMS is a Global Standard for Components for Automotive Assembly and Stamping. These components are produced and maintained through collaboration efforts between Chrysler LLC., Ford Motor Company, General Motors Company, and their respective suppliers. **Source:** http://www.uscar.org
Parallelism	The fact of being similar in development or form. Parnas (1978) stressed the benefits of parallelism, arguing that it is easier to split development work across a group if people can work independently and in parallel. To support parallelism, Parnas encouraged developers to avoid sharing assumptions and data. Specifically, he contended that every developer's task assignment, or product module, should be *"characterized by its knowledge of a design decision that it hides from all others*" (1972: p. 1056). **Source:** Parnas, David L. 1978. Some software engineering principles. Hoffman, D. and D. Weiss, eds. Software Fundamentals: Collected Papers by David L. Parnas. Addison-Wesley, Boston, MA.
Physical Internet	The physical internet (PI, π) is an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols. **Source:** Montreuil, Meller and Ballot, 2012.

Radical constructivism	Focuses on the individual knower and acts of cognition. The central idea in radical constructivism is that human knowledge cannot consist in accurate representation or faithful copying of an external reality, existing apart from the knower's experiences. **Source:** von Glasersfield, E. "*Radical Constructivism: A Way of Knowing and Learning",* London: Falmer Press, 1995.
Theory	A theory may be viewed as a system of constructs and variables in which constructs are related to each other by hypothesis and the variables are related to each other by hypotheses **Source:** Baccarach, S.B. (1989), "Organisational theories: some criteria for evaluation", *Academy of Management Review*, Vol. 14 No. 4, pp. 496-515. The process of theory testing involves measuring constructs and verifying relationships. **Source:** Eisenhardt, K.M. (1989), "Building theory from case study research", *Academy of Management Review*, Vol. 14 No. 4, pp. 532-50.

1. LINKING DOCUMENT

1.1. INTRODUCTION

This introduction discusses the business problem driving this research, it provides an explanation of the concepts that are core to the overall study, and presents the research questions deduced from the academic literature. The three research projects completed as partial fulfilment of the Doctor of Business Administration (DBA) build on each other as will be demonstrated over the course of this linking document. This document discusses the background and rationale for this study; synthesises the research methodology, findings and contribution; presents limitations of the study, and identifies opportunities for further research.

1.1.1. Background and rationale

This research has one overarching objective: to increase our understanding of the process of mirroring PA and SCC, at the product concept stage. The mirroring hypothesis embeds causal relationships between product and organisation architectures (Henderson and Clark, 1990), and implies a positive bi-directional relationship between these concepts. This research extends organisation management, incorporating SCC for new to market products, outside the domain of a single company. Whilst eighty percent of total SCC cost (Dowlatshahi, 1996); seventy percent of product cost (Appelqvist *et al.*, 2004) and eighty percent of product quality (Dowlatshahi, 1998; Gunasekaran *et al.*, 2004) are determined during NPD, SCC research predominantly treats financial performance as the sole determinant of NPD performance, when in fact NPD performance measures are multi-dimensional (Montoya-Weiss and Calantone, 1994; Cooper, 1986).

Whilst SCC design is recognised as a source of competitive advantage, and more sustainable than product differentiation (Flint, 2007), there is a lack of a framework for incorporating SCC decisions at the product concept design stage. In this research a process approach was selected, where the NPD process involves SCC decisions from idea generation to market launch, shown below in Figure 1-1. Innovation is a process of interrelated sub processes, ‘not just the conception of a new idea, the invention of a new device, or the development of a new market, but the process of these acting in an integrated fashion' (Myers and Marquis, 1969). The general depiction of the innovation process as unidirectional does not reflect its inherently iterative and concurrent nature (Fortuin, 2006). PA and SCC design have much to learn from each other as products progress through the NPD process, from concept to market launch.

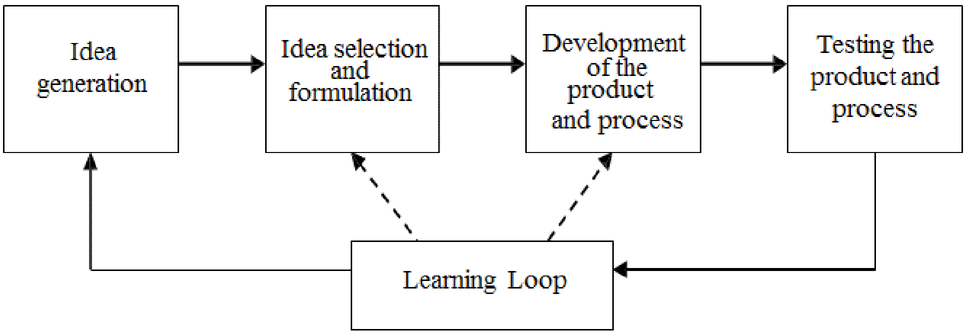


Figure 1-1. General representation of the R&D process
Source: Tidd, Bessant and Pavitt (2001)

Configurable systems are based upon whole-part relationships and embody dynamic properties. SCC innovation includes product, process, resource, organisation, and competitive strategy-related configuration, together with changes in lead-time, pricing, location, supplier selection, product or process costs and contracts (Chandra and Grabis, 2016). SCC has a key role to play in providing fast response, addressing early product design conformance, the lack of which often results in early product failure. "Supply chain innovation combines developments in information and related technologies with new logistic and marketing procedures to improve operational efficiency and enhance service effectiveness" (Bello *et al.*, 2004, p.57). SCC and service innovation should not be treated as an unconstrained think-outside-the-box brainstorming activity with few principles to guide the innovation process. Ostrom *et al.* (2010) identify continuous innovation as a perennial challenge and opportunity for services.

NPD innovation must extend to improved systems, organisation design, and development processes. Baldwin (2008) defines SCC systems as networks in which the nodes are the tasks-cum-agents while the linkages are transfers of material, energy and information.

Transactions are defined as ‘mutually agreed-upon transfers with compensation and are located within the task network’. (Baldwin, 2008 p. 155). ‘Since placing a transaction in a location generates costs companies tend to locate transactions at the thin crossing points of the task network, that is, the module boundaries, where these costs are low’ (Sorkun and Furlan, 2016).

Modular PA offers defined module interfaces, supporting independent design and manufacturing (Baldwin and Clark, 2000). PM can facilitate a proprietary architecture where the focal company knows the interface specifications that make components plug-and-play compatible, and can deploy fast upgradability to create product advantage, based on pre-defined module interface design rules. With modular architecture many product variation and upgrade capabilities are transferred by the OEM or focal company to and from suppliers and customers. Modular SCC offers defined module interfaces, supporting knowledge sharing throughout the product life cycle (Ülkü and Schmidt, 2011; Chandra and Grabis, 2016; Cabigiosu and Camuffo, 2017).

Disruptive product and SCC technology and innovation have permeated contemporary supply chains, which for this research is defined as the period 2012 to 2017. NPD life cycles have decreased to three years and less for complex new-to-market products such as automobiles, and to less than twelve months for many consumer electronic products. As a result, companies are under increasing pressure to leverage core internal and partner NPD and SCC capabilities (Hugos, 2006). Many technologies including, but not limited to block chain, cloud computing, additive manufacturing, robotics, artificial intelligence and digitisation are altering product delivery systems and require SCC integration at the product concept stage. Earlier adoption of these process technologies is supported by IoT (Intelligence of Things™)[1], cloud computing, Omni-Channel, and the physical internet platforms which is applying the principles of the Internet to logistics, shown in Appendix 1-6, Page 429. These technologies and platforms are redefining competitiveness, with companies required to increase SCC innovation in market differentiation, outsourcing, re-use and risk mitigation areas, shown below in Figure 1-2.

[1] Intelligence of things is a Trademark of Flex.

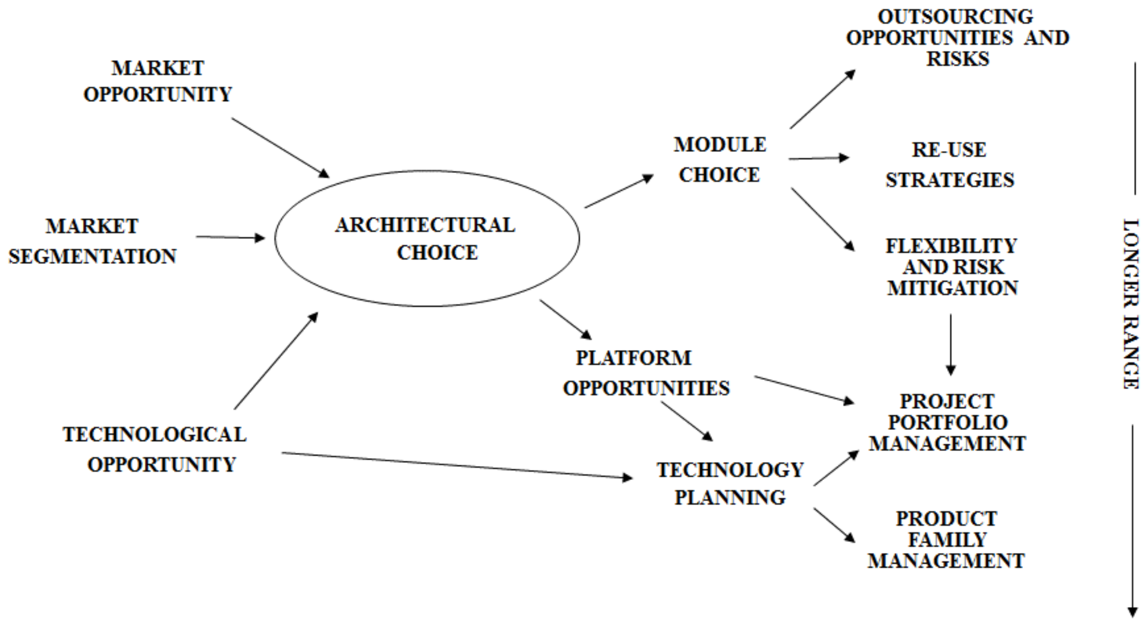


Figure 1-2. Role of architecture in product development
Source: Whitney et al. (2003)

This research is designed to contribute to existing literature incorporating SCC at the product concept design stage, in contemporary supply chains. Further aims include increasing the new product introduction rate (NPIR); minimising early product life failure (Trkman and McCormack 2009), and supporting a circular economy. As much as $4.5 trillion USD of economic value gain is achievable by 2030, by ‘going circular’ at scale (Lacy and Rutqvist, 2015). This is encouraging corporate leaders to look at sustainable SCC, and models that design out waste. This research builds on the concept of modularity in delivering reusability, reconfigurability and extensibility of products through the mirroring of PM and SCCM. The relative cost of product development is shifting from production, to increased investment in product development. If a company can create a component design that can be used in several product variations or across product generations, or preferably both, this results in significant development time and cost savings, combined with economies of learning and quality improvements at the component level.

1.1.2. Framing the business problem

Whilst academic research has identified the strategic significance of NPD in the achievement of global economic success (Fiol, 1996), many authors claim that our knowledge of NPD processes is incomplete. Despite compelling argument for coordinated NPD and SCC (Lee and Sasser, 1995; Novak and Eppinger, 2001), there is a lack of research in this area. Fisher (1997) was the first to research the alignment between supply chain (SC) strategy and products. Nascent research stresses the need to link SCC with NPD; ensuring product availability at the launch date (van Hoek and Chapman, 2006); focusing on product attribute or variable and SC attribute or variable matching (Abdelkafi *et al*., 2010; Pero *et al.*, 2010; Stavrulaki and Davis, 2010), and the effect of this matching on SC performance (Khan *et al.*, 2012).

The ’financial livelihood of a company is directly impacted by SCC decisions and new product diffusion’ (Amini and Li, 2011). The company I work for provides Sketch-to-Scale™ [2] solutions from product concept design to product re-use across a range of product technology sectors. Our focus is on the cultivation and acceleration of collective innovation across the supply base together with sustained innovation throughout the product life cycle. My interest is grounded in my experience in developing SC solutions with Flex, and my background in product design and SC practice. As a team member in many new product design teams, my design assurance role piqued my interest in this field and informed this research. I made use of the contact network I had developed during my career, as the basis for the case study research that were conducted in projects two and three. My motivation for conducting this research was to contribute to bridging the gap between academic research and business practice in contemporary supply chains. Academic research must remain relevant, dynamic, and rigorous in supporting the challenges of flexible supply chains. This empirical research contributes to the debate linking structural SCC decisions and decisions characterising links among supply chain partners with early product concept design. Companies in high technology sectors are searching beyond their industries for product and SC technologies and innovation,

[2] Sketch-to-Scale is Trademark of Flex.

participating in innovative networks, and connecting knowledge across product and SC communities (Podolny, 2001). With the convergence of technologies, there are benefits to be leveraged through comparative product design, across industries. Comparative research is often used in the early stages of the development of a branch of science. Whilst academics and practitioners have devoted increasing attention to the study of the relationships between supply and product features (Fisher, 1997; Randall and Ulrich, 2001), there remains a 'lack of inclusion of SCC decisions in NPD' (Ellram, 2008). The inter-relationship of product concept design and contemporary SCC chain design is a source of value differentiation, yet there is a dearth of case research in this area. Lau *et al.* (2007) argue that the benefits of PM should be translated into company capabilities leading to improved company performance.

The focus of this research is on new-to-market products (Ansoff, 1980), shown below in Figure 1-3. In assessing how products are related to SCC, one must consider the operational links between product creation and product delivery, and consider NPD and SCC as service activities. Relative to markets, companies have superior capacity for central planning (Alchian and Demsetz, 1972) and rich contextual communication (Monteverde, 1995). Blackhorse *et al.* (2004) recognise there are considerable benefits discussing SCC concurrently with NPD at the product concept stage. Previous research has sought to extend traditional manufacturing management techniques to SCC, however these techniques often function poorly when applied to services. Manufacturing techniques are "operationally distinctive and managerially different", from services (Sampson, 2015, p.9). There have been various streams of thought that have limited the science and study of services. A survey of service researchers conducted by Edvardsson *et al.* (2005) concludes, "On lower abstraction levels a general service definition does not exist. It has to be determined at a specific level, in a specific company, for a specific service, from a specific perspective" (Edvardsson, Gustafsoon and Roos, 2005, p.119).

Nickerson and Zenger (2004) argue that, when problems are fully decomposable, several independent companies can work efficiently in parallel, coordinated by markets. As the sub-problems become interdependent and non-decomposable, it is more efficient to bring the search process within the purview of a single company.

		Industry			Contextual variables	
		Type	Region	Unit of analysis	Clockspeed	Stage in Product lifecycle
Product	New to World					
	New to Market					
	New to Company					

Figure 1-3. Area of research focus
Source: Ansoff (1980) business growth matrix

1.2. RESEARCH CONCEPTS

Three research concepts NPD, SCC and product planning describe the phenomenon of theoretical interest and are precursors to constructs that will be developed during project one. ‘For organisation research to fulfil its potential for description, explanation, and prescription, it is first necessary to discover relevant concepts for theory building that guide the creation and validation of constructs’ (Corley and Gioia, 2011). Constructs are abstract theoretical formulations about phenomena of interest (Pedhazur and Schmelkin, 1991; Morgeson and Hofmann, 1999), and their primary purpose is to delineate a domain of attributes that can be operationalised, and preferably quantified. Our concern with construct development and measurement sometimes often blinds us to arguably the more important work of concept development in organisational management research.

1.2.1. New product development

New products and services continue to be the lifeblood of business. Schumpeter (1934) emphasises the importance of new products in stimulating economic growth. Hauser, Tellis and Griffin (2006) highlight that thirty-two percent of sales revenue and thirty-one percent of profit are generated by new-to-market products, with approximately one-third of revenue generated by products launched within the previous five years.

Krishnan and Ulrich (2001) define NPD as ‘the transformation of a market opportunity and a set of assumptions about product technology into a product available for sale’. Other definitions emphasise the phases of NPD, from concept generation to product planning, product and process engineering, pilot production and ramp-up (Wheelwright and Clark, 1992). This research focuses on NPD as a multi-disciplinary management process, incorporating a physical product and the delivery of a differentiated SCC. New products can be classified as new-to-world, new-to-market or new-to-company. Krishnan and Ulrich (2001) propose five product developments during concept development: 1) product attributes; 2) product concept; 3) variants of the product to be offered and which components will be shared across which variants; 4) product architecture, and 5) physical form and industrial design, where concept development decisions define the extended product offerings including life cycle services and after-sale supplies. Only ten percent of new products introduced are new-to-company and new-to-market (Booz, Allen and Hamilton, 1982), whilst seventy percent of new products are improvements, cost reductions or additions to existing lines (Griffin, 1997). Johne and Snelson (1988) indicate that the NPD options for new and existing product lines focus on altering the variables around design and engineering, research and development, production management, marketing or economics. This research focuses on new-to-market products at the concept development phase, and expands on Johne and Snelson’s NPD options for new products, by incorporating SCC requirements.

Brown and Eisenhardt (1995) categorise NPD literature into three work-streams: 1) product development as a rational plan; 2) a communication web, and 3) disciplined problem-solving. NPD in innovative companies such as Apple, Google or Tesla appears to follow the disciplined problem-solving process, promoting early supplier involvement (ESI), and limited customer involvement, with speed and productivity as operational success measures. The communications web highlights the significance of knowledge management (KM). Clark and Fujimoto (1991) define NPD as information and knowledge-intensive work. The rational plan promotes early supplier and customer involvement, with performance being measured in profit, sales revenue and market share, and is prevalent in fast clock-speed industries, such as the fast fashion, with companies such as Benetton, Zara and H&M. Increasingly cross-functional teams, the preferred mode for organising NPD, are effective vehicles for the synergistic combination of complementary knowledge (Madhavan and Grover, 1996). In this research, NPD is viewed as a knowledge creation process through the syndication of diverse streams of knowledge.

Emerging technologies and complex product development are driving companies to adopt new NPD processes (Rycroft and Kash, 1999). Technology improvement and consumer behavior in many markets are driving rapid displacement of products. For example, seventy percent of Hewlett Packard’s products are less than two years in the market; forty percent of Staples’ office products change each year, and seventy percent of Zara’s in-store fashion clothing range, change every two weeks. As a result, global supply networks are required to provide increasing levels of structural and dynamic flexibility. For example, Apple Inc.’s SC can deliver a custom order manufactured in Shanghai, to a US based customer, within ninety hours, by integrating lean manufacturing, just-in-time-delivery and SC infrastructure planning (Chaudhuri and Chakraborty, 2009). The pace of new product diffusion is increasing, for example in 1997, with the initial iPhone launch, Apple Inc. required thirty-one months to achieve market coverage, within thirty-one countries. By 2012, for the iPhone 5 launch, Apple Inc. had reduced new product delivery lead-time to five months with similar market coverage. Fast clockspeed industries consider SC infrastructure planning as an integral part of NPD (Fine, 1998).

NPD performance influences organisational performance and often allows the organisation to meet or exceed the expectations of customers (Ng and Anuar, 2011).

Whilst it is accepted that design decisions regarding products and their associated SC are interrelated, it is not clear how these decisions interrelate (Zhang *et al.*, 2008). Limited work has been completed developing decision support models for concurrent SC and product design (Chiu and Okudan, 2011), considering the global issues in SC design (ElMaraghy and Mahmoudi, 2009). Contemporary NPD is about providing structural and dynamic SCC flexibility.

1.2.2. Supply chain configuration

SCC flexibility refers to flexibilities that add value from the customers' perspective, and are the shared responsibility of two or more functions within the SC (Vickery, 1999). Dynamic SCC flexibility reflects the ability to respond rapidly to variations in product volume and mix, whilst structural SCC flexibility reflect the ability to adapt to fundamental changes in the SC, for example a change in the 'centre of gravity', of the market (Christopher and Holweg, 2011). Structural SCC flexibility reflects a company's ability to adapt to environmental changes, however few companies succeed in building structural SCC flexibility (Christopher, 1998).

SCC encompasses decisions around "supplier selection, methods of manufacture and locations in the SC network to place appropriate levels of safety stock" (Amini and Li, 2011, p. 313), and will appear different depending on a company's position in the SC (Croxton *et al.*, 2001). SCC models are in general centered around inventory placement decisions with a focus on cost minimisation (Graves and Willems 2005; Bossert and Willems 2007). Graves and Willems (2005) address the configuration of SC's for new-to-market products, where the objective is to minimise the total manufacturing cost, for which the design has already been decided. Prior models do not consider intangible attributes such as the mirroring of business practices among SC partners and structural SC flexibility (Nepal *et al.*, 2005). Mentzer *et al.* (2001) consider the existence of different degrees of SCC complexity, distinguishing between a direct, extended and ultimate SC's. A direct SC consists of a focal company and its direct suppliers and customers; an extended SC includes suppliers of the direct supplier and customers of the direct customer, whilst the ultimate SC includes all organisations involved in upstream processes. The focus of this research is on the direct SC, and the focal or Original Equipment Manufacturer (OEM). Decisions covering product packaging design, transportation mode selection and transport network optimisation are outside the scope of this research.

1.2.3. Product planning

'Product planning involves decisions about a company's target market, product mix, project prioritization, resource allocation, and technology selection, by product' (Wheelwright and Clark, 1992). Product planning relates to the task of generating new product ideas. This task takes inputs from marketing, technical support, sales and engineering teams, and includes the analysis of competitor products and consumer needs. These planning factors have a significant influence on the probability of economic success (Wagner, 1975).

Many challenges confronting the global economy are associated with the increasing pace of globalisation, shown below in Table 1-1. Much disruptive product innovation is associated with how companies serve emerging markets, with globalisation forcing multi-tier SC partners to collaborate. OEM's rely on increasing numbers of supply sources each playing a role in getting products to market, leveraging global sources of technology and SCC innovation.

Table 1-1. Global gross domestic product distribution
Source: IMFBlog Obstfeld (April 19th, 2017)

		Projections	
	2016	2017	2018
World Output	**3.1**	**3.5**	**3.6**
Advanced Economies	**1.7**	**2.0**	**2.0**
United States	1.6	2.3	2.5
Euro Area	1.7	1.7	1.6
Germany	1.8	1.6	1.5
France	1.2	1.4	1.6
Italy	0.9	0.8	0.8
Spain	3.2	2.6	2.1
Japan	1.0	1.2	0.6
United Kingdom	1.8	2.0	1.5
Canada	1.4	1.9	2.0
Other Advanced Economies	2.2	2.3	2.4
Emerging Market and Developing Economies	**4.1**	**4.5**	**4.8**
Commonwealth of Independent States	0.3	1.7	2.1
Russia	−0.2	1.4	1.4
Excluding Russia	1.8	2.5	3.5
Emerging and Developing Asia	6.4	6.4	6.4
China	6.7	6.6	6.2
India	6.8	7.2	7.7
ASEAN-5	4.9	5.0	5.2
Emerging and Developing Europe	3.0	3.0	3.3
Latin America and the Caribbean	−1.0	1.1	2.0
Brazil	−3.6	0.2	1.7
Mexico	2.3	1.7	2.0
Middle East, North Africa, Afghanistan, and Pakistan	3.9	2.6	3.4
Saudi Arabia	1.4	0.4	1.3
Sub-Saharan Africa	1.4	2.6	3.5
Nigeria	−1.5	0.8	1.9
South Africa	0.3	0.8	1.6

Source: IMF, April 2017 *World Economic Outlook*.

Growth in multi-tier supply chains is reflected by Schumpeterian creative destruction and the average company tenure in the Standard and Poor's 500 Index®, which has reduced from seventy-five years in 1950, to a forecasted fourteen years by 2026. This trend is partly derived from the gradual obsolescence of the corporate form (Coase, 1937), and the increasing reliance on suppliers for product and SCC innovation. Using grounded theory, Noble and Kumar (2010) highlight that many product designers adopt a value-based view of design, with design thinking encompassing value creation (NPD) and value delivery (SCC). Research has so far discussed many positive effects that derive from the use of a modular service architecture, including decreased time-to-market by reusing components for different products (Böttcher and Klingner, 2011); increased variety and flexibility (Yang and Shan, 2009), and economies of scale and scope (Tuunanen *et al.*, 2012), all leading to cost-efficiency and strong competitiveness (Bask *et al.*, 2011). While there are currently no deterministic approaches to selecting optimal PA, this process can be guided. NPD thinking has emerged as a key enabler to managing global SCC.

1.3. RESEARCH METHODOLOGY

This section provides an overview of the research process. The Doctor of Business Administration (DBA) program at Cranfield School of Management is rigorous and milestone-driven. There are three projects that make up the DBA study. The modular structure includes a set of three individual research projects: each project is written up and presented to an academic panel at intervals for review. These review milestones form building blocks in the completion of the final thesis, allowing research questions to emerge progressively. The process dates relevant to this research are shown below in Figure 1-4.

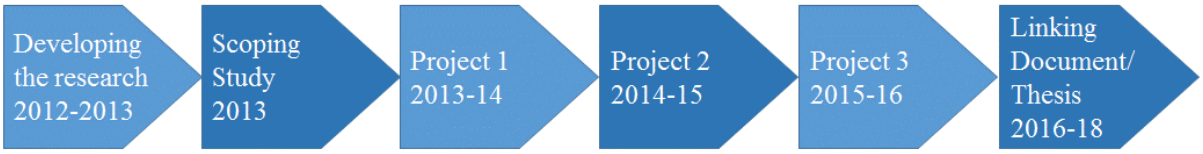


Figure 1-4. The DBA research process at Cranfield School of Management

The DBA methodology has certain disadvantages. With each project write-up including background, definition of the research question, overview of the literature, and methodology, there is a risk of introducing repetition in to the final thesis. Due to the individual projects, and the time lag with the research, some information may become misaligned, and redundant. To avoid this repetition, common material was moved to the linking document. The research development phase included a preliminary literature research, used to develop the review question (RQ0): "*What is the relationship between supply chain design and new product design which increases company competency?"*.

1.3.1. Theoretical domain

There is a lack of empirical research at the intersection of SCC and NPD, which led to the deduction of RQ0. This review question lends itself to the theoretical domain, where ‘relationships are the domain of theory’ (Whetten, 1989). This research is in the field of management control theory, and the sub-field of NPD management. Management control theory sits within the ‘grand theory’ of systems and control theory (Weiner, 1950; Von Bertalanffy, 1950).

Management control system design and use is positively related to new product performance (Davila, 2000). There is however a concern that excessive management control, or management control that is too formal or rigid can constrain or stifle NPD (Davila, 2000; Morris *et al.* 2006). On the other hand, management controls can curb profligacy and reduce excessive and wasteful NPD (Bisbe and Otley, 2004). Management controls should reduce risk, assist with strategy and goal alignment, decrease systems uncertainty and encourage risk tolerance and NPD experimentation (Davilla, 2000; Bisbe and Otley, 2004). Senge (1990) assesses how the systems method enables companies transform in to learning organisations, and considers systems thinking, personal mastery, mental models, building shared vision, and team learning as the basis for the development of core learning capabilities, developing reflective conversation, and understanding complexity to address value generation. Past research in operations management has frequently exhibited a focus on technique instead of knowledge orientation, and appears to be less integrative (Chase, 1980; Meredith *et al.* 1989).

Knowledge-based theory (KBT) is used to develop the mirroring the PM and SCCM constructs, building a mirroring framework based on the interrelationships between PM and SCCM attributes. KBT assumes that a key problem for companies is assembling and disseminating knowledge, across different domains of practice, focusing on tacit and explicit knowledge, and acknowledging that knowledge grows in value as it is shared.

1.3.2. Research Perspective

Ontology is the claim social research makes about the nature of social reality, that is what exists (Blaikie 1993). This has implications for epistemological criteria that determine what is knowledge, as opposed to beliefs. Research must consider what can be known and how to present this knowledge reliably. This research reveals a new approach to KM within NPD projects, correlating and combining NPD and SCC knowledge modules at the NPD concept phase. Ontology presents the states of combined static and dynamic NPD and SCC systems. Ontology also presents system behavior such as response and reaction (Chandra and Grabis, 2016). A KM reference model includes multi-disciplinary experience that enriches the company's intellectual knowledge base. This KM reference model creates a practical solution to the quest for knowledge sharing within and between projects and supports adherence to SCC standards and directives.

Positivism assumes that the social world exists externally, and its properties should be measured through objective methods (Easterby-Smith *et al.*, 1991). An epistemological implication of positivism is that knowledge is only of significance if it is based on observations of the external reality in the form of objective measures. Phenomenology assumes that reality is socially constructed and given meaning by people (Husserl 1946). Subjectivism is a similar ontological view where reality is a projection of human imagination (Morgan and Smircich 1980). This view assumes that human action arises from the sense people make of different situations, rather than a direct response from different stimuli (Easterby-Smith *et al.*, 1991). In this case the task of the social scientist should not be to gather facts and measure how often certain patterns occur, as is the approach under positivism, but to appreciate the different constructions and meanings that people place upon their experiences. Easterby-Smith *et al*. (1991) provide a comparison between positivism and phenomenology with respect to the basic beliefs of the researcher; the research strategy; and the preferred research method. The paradigm in this research is illustrated by the shaded boxes, shown below in Table 1-2. My beliefs are basically positivist considering my engineering background. This inclination to the positivist view undoubtedly influenced my selection of research topic but more significantly the research focus, strategy, and methods. This research focuses on the tangible attributes of PM and SCCM, rather than less tangible areas such as decision processes, personal motivations, and change management.

There are many views of ontology and epistemology but to explain the philosophical view adopted for this research it will suffice to explain the two extreme views. The approach to the research deviated from the pure positivist approach in several aspects. At least six aspects commonly associated with the phenomenological paradigm were adopted.

Table 1-2. Positivist and phenomenological paradigms
Source: Easterby- Smith et al. (1991)

	Positivist paradigm	**Phenomenological paradigm**
Basic Beliefs:	**The world is external and objective**	The world is socially constructed and subjective
	Observe is independent	Observer is part of what is observed
	Science is value-free	**Science is driven by human interests**
Researcher should:	**Focus on facts**	Focus on meanings
	Look for causality and fundamental laws	**Try to understand what is happening**
	Reduce phenomena to simplest elements	**Look at the totality of the situation**
	Formulate hypothesise and test them	**Develop ideas from induction from data**
Preferred methods include:	**Operationalising concepts so that they can be measured**	**Using multiple methods to establish different views of phenomena**
	Taking large samples	**Small samples investigated in depth or over time**

This research adapts a relativist research paradigm (Miles and Huberman, 1994). A key feature of this philosophical perspective is that causal explanations are sought, and multiple event evidence needs to be captured that presents examples of that explanation. This philosophy also considers that predictive certainty is not possible and that the most that can be expressed from a series of case studies are the ‘tendencies caused by the underlying generative mechanisms’ (Partington, 2002). A tendency denotes ‘characteristic ways of acting or effects of mechanisms which may or may not be actualised’ (Bhaskar, 1998).

1.3.3. Research strategy

‘The crucial issue for the researcher is how to discover, describe, explain and intervene in the phenomena under investigation’ (Blaikie, 1993). The primary research framework uses deductive methods shown below in Figure 1-5, and general statements to explain an instance. The primary motivation for developing deductive research is the development of new knowledge. No inductive theorizing was conducted during this research.

A scoping study was conducted to assess ‘*a-priori’* RQ0; refine the area of research, and deduce research question (RQ1). An SLR was conducted, during project one to establish thematic links between the three concepts; deduce working hypotheses or explanations for linking these concepts; develop a conceptual framework to support further research, where these provisional working hypotheses are tested during projects two and three. In addition, the SLR was conducted to identify gaps in the literature.

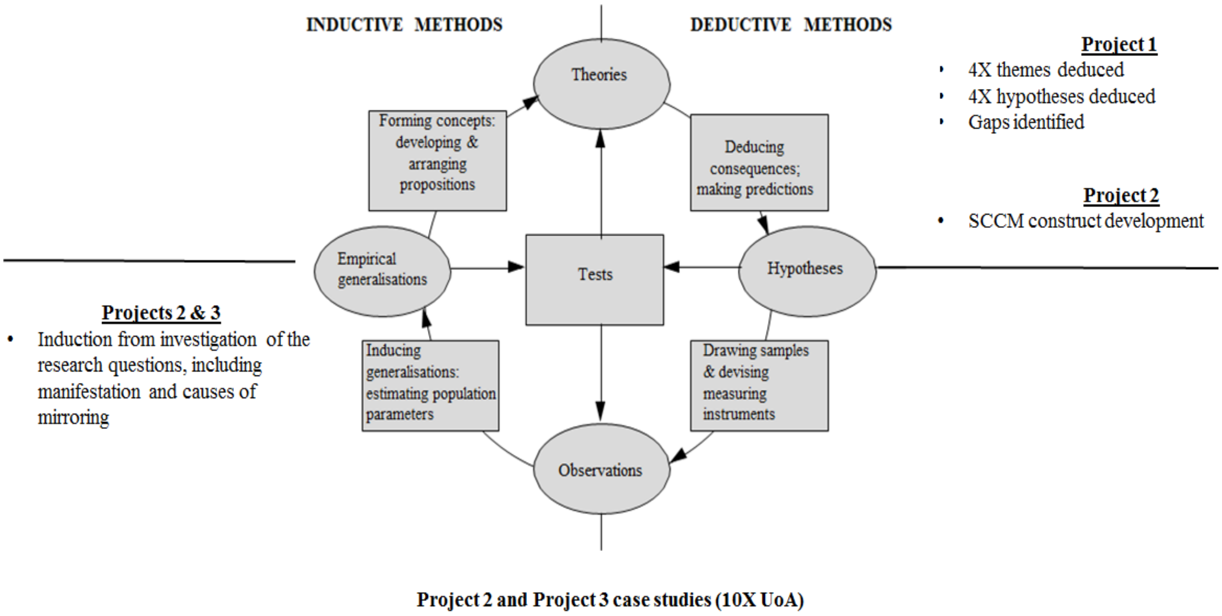


Figure 1-5. Research framework
Source: Wallace (1971), cited in Blaikie (1993)

The stages of this research are outlined below in Table 1-3. Four themes were deduced from the literature linking the key concepts. The modularity theme was identified as the strongest linking theme. The mirroring concept was deduced as a mechanism for linking product modularity and SCC modularity. Four research hypotheses were deduced from the literature, which require testing during projects two and three.

A conceptual framework was developed building on GST and KBT, to allow for empirical research, in to the linking mechanisms, and the identification of the causes of these links. This conceptual framework also supports testing the strength of the intervening mechanisms in support of mirroring of PM and SCCM.

Table 1-3. Research projects, questions, methods, and findings

	Project 1	Project 2		Project 3
Research questions	**RQ1.** What is the relationship between new product development, product planning and supply chain configuration prior to product launch?	**RQ2.** How can supply chain configuration modularity be conceptualised considering modularity principles and contemporary supply chains?	**RQ3.** How is the mirroring of product modularity and supply chain configuration modularity manifested?	**RQ4.** How do co-development, feedback control and feedforward anticipatory control affect the mirroring of modular product design and modular supply chain configuration, after product launch?
Hypotheses to be tested			**1.** Product architecture and supply chain configuration tend to be mirrored in terms of modularity.	**2.** Co-development (CD) of product architecture and supply chain configuration leads to enhanced mirroring between product modularity and supply chain configuration modularity. **3.** The mirroring between product modularity and supply chain configuration is enhanced by feedback control (FC), at the conceptual product development stage. **4.** The mirroring between product modularity and supply chain configuration is enhanced by feedforward anticipatory control (FAC), at the conceptual product development stage.
Methodology	Systematic literature review.	Case studies	Case studies	Case studies
Findings	Four themes link the first order concepts; 1. Modular design 2. Co-development of product and SCC 3. Early supplier involvement 4. Product and SCC life-cycle	There are two mandatory SCCM variables; 1. supply chain tiering 2. process postponement and three optional SCCM variables; 1. process standardization 2. process re-sequencing 3. place postponement	The mirroring concept draws on knowledge based theory and three principles of systems theory; 1. parallelism 2. life-cycle focus 3. process focus	1. PM and SCCM seek a mirroring state, over the product life-cycle 2. FAC of SCCM performance is key to the mirroring of the PM and SCCM constructs post product launch 3. CD of PM and SCCM is key to the mirroring of the PM and SCCM constructs post product launch.
Outcome	Conceptual framework for mirroring product architecture and supply chain configuration, and research hypotheses 1, 2, 3 and 4.	Supply chain configuration modularity construct and measures	Concept of 'mirroring' product modularity and supply chain configuration modularity, for improved product performance.	Framework for guiding the mirroring of NPD and SCC, at the product concept stage.

1.3.4. Scoping Study

RQ0 identifies a gap in research within product concept development, at the macro-level. The scoping study is a transitional assessment of RQ0, in a defined manner, surveying existing literature and informing the research gaps to be addressed during project one. PA decisions linked to business functions, shown below in Figure 1-6., are a key determinant of a products ability to deliver product variety and options at an affordable cost. The literature highlights that research in this area comes primarily from the SCC domain, where processes are developed to deliver product variety, in some cases these processes are outsourced. The scoping study identified a lack of focus on SCC decisions within the NPD process.

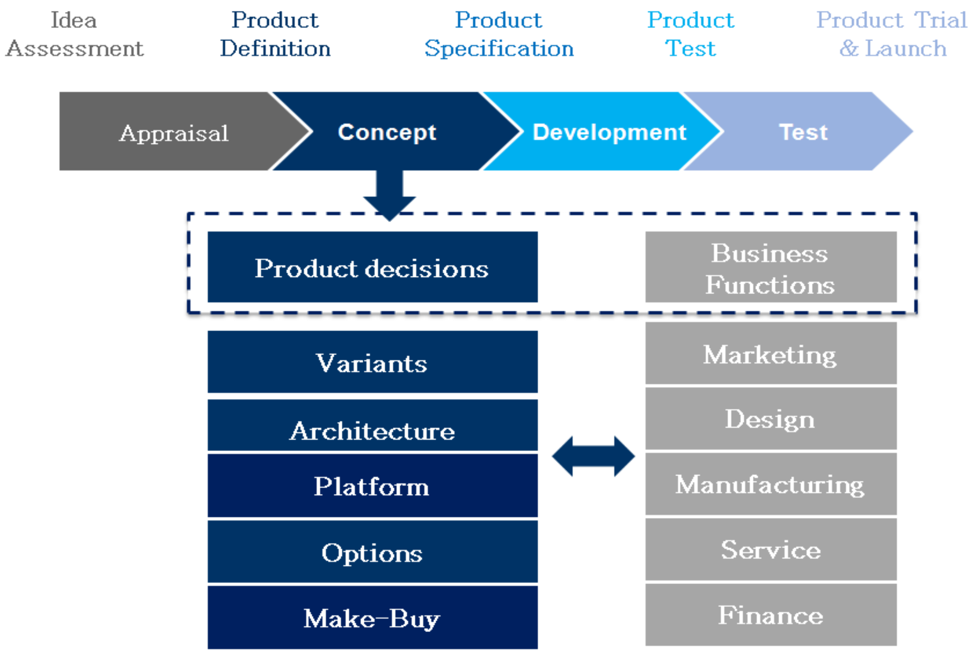


Figure 1-6. Product concept decisions

The initial focus of the scoping study was on design for affordability. This focus highlighted the benefits and barriers to frugal or reverse innovation[3], and the significance of product planning in managing price erosion and product succession within product platforms. This focus highlighted that traditional new product and process development processes act as a barrier to companies seeking to mainstream ideas from the developing to the developed world, with the largest hurdle to building reverse innovation being 'highly inflexible value chains' (Mukerjee, 2012). This early literature review discovered that academic research in to the relationship between new product concept development and SC planning is primarily focused on fast clock-speed industries. Vonderembse *et al.* (2006) identify the need to consider product life cycle during SC planning. Gligor *et al.* (2012) highlight the lack of SC planning decision-making at the product concept development stage.

Khiang Bay Boon *et al.* (2004) identify the requirement for form postponement design at the product development stage, and van Hoek (2001) calls for this postponement to be

[3] Reverse innovation is a term referring to an innovation seen first, or likely to be used first, in the developing world before spreading to the industrialized world, Hagel and Brown (2005)

brought to a more advanced methodological level, at the concept stage. Choi and Linton (2011) highlight risks associated with the over-delegation of control within the supply base, whilst Childerhouse *et al.* (2011) assess levels of early supplier involvement (ESI).

ESI implies that suppliers are involved during the early feasibility or concept stage to ensure supplier input to early design decisions (Eisto *et al*., 2010). Whilst research in fast clock-speed industry using three-dimensional concurrent engineering (3DCE) provides a framework for integrating product, process and SC design at the product development stage, it fails to focus on key SCC decisions required at the product concept development stage (Fine, 2000). Chiu Ming *et al.* (2011) consider limitations of SCC in the product development process, and identify the constructive influence of ESI.

Bonaccorsi (1994) stresses the need for a state of constant learning during NPD, and claim that integrating demand, supply and NPD will bring about a move from functional, 'I-shaped' skills to an increased demand for 'T-shaped' skill sets, employing people who understand customer requirements and can shape the integrated end-to-end value chain to meet these requirements. Clark and Fujimoto (1991) define NPD as information and knowledge-intensive work. Halldorsson *et al.* (2007) point to the lack of research and theory development in this area, and identify small-scale theories which are limited to a few concepts, for example the 'fit' model of products and SC developed by Fisher (1997) as appropriate to this research. A review of academic literature on innovation highlighted the 4P framework, which interlinks innovation in product, process, position and paradigm as relevant to this research (Tidd, Bessant and Pavitt, 2005). The four axes of this 4P framework model depict NPD, SCC, product planning and product market positioning.

The scoping study identified six existing process-oriented frameworks to ascertain whether NPD, SCC and product planning were integrated into an existing framework. The outcome of the scoping study was inconclusive, with none of these existing frameworks taking these three key concepts in to consideration.

This gap in understanding helped identify research question one (RQ1): *"What is the relationship between new product development, product planning and supply chain configuration prior to product launch?"*. The early involvement of SCC in the NPD process, taking product planning into consideration, offered a concrete direction for this research. My academic review panel agreed this was a suitable research direction.

1.3.5. Project 1 – Review of NPD, SCC and product planning literature

The purpose of this SLR is to understand prior research in the area of interest and gain an understanding of the themes that link NPD, SCC and product planning, at the concept stage, and SCC and product planning decisions which influence the performance of NPD.

In project one an SLR was undertaken to assess RQ1, and seek a theory or a set of theories that provide predictive value to this research. These theories need to provide the ability to predict relationships between the research constructs, and identify a contribution to theory. A SLR is defined as "a review that strives to comprehensively identify, appraise and synthesise all relevant studies on a given topic" (Petticrew and Roberts, 2006, p. 19). The purpose of the SLR methodology in management research is to search, review, extract and synthesise data in a transparent and replicable manner (Transfield *et al.*, 2003). Guidelines outlined by Transfield *et al.* (2003); Rousseau *et al.* (2008), and Denyer and Tranfield (2009) were followed in project one. An SLR is a method of identifying literature to which the research will contribute, contextualising the research within that literature, and building an understanding of theoretical concepts and terminology. The SLR involves question formulation, locating relevant academic research, research selection, analysis and synthesis, reporting the use of the results, and identifying areas of further research.

The SLR concentrates on peer-reviewed papers, published between 1995 and 2016, within Operations management. Applying a proven, systematic methodology to the literature resulted in a rigorous and reliable analysis of the extant literature to inform this research. The SLR deduces research hypotheses, and builds a conceptual framework to guide further research, shown below in Figure 1-7.

The approach taken was to imbue a deductive study with qualitative rigour while still retaining the creative, revelatory potential required for generating new concepts and ideas during the research. Fifty-nine peer-reviewed papers were selected for a critical literature review. These papers address theoretical and empirical research in to the relationships between NPD, product planning and SCC. Twenty-eight of the papers use the case study methodology. The UoA include supply network, company, industry, country and factory: no research selected products as the UoA.

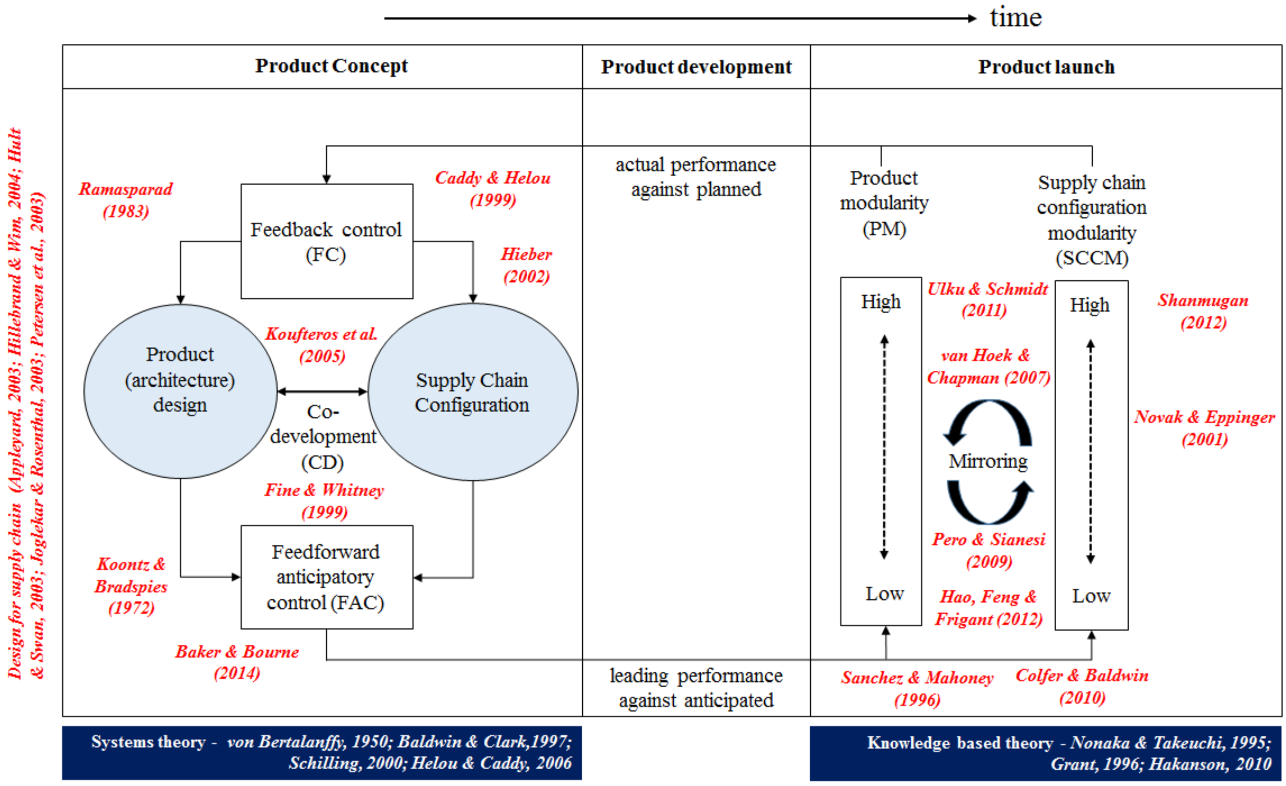


Figure 1-7. Conceptual framework

The literature research indicates a lack of SCC and NPD coordination as a reason for early-life product failures (Ellram, 2008; Chiu Ming-Chuan *et al*., 2011). Companies have embedded concurrent design thinking into their SCC processes (Khan *et al*., 2012) but previous research primarily considers SCC during the later detailed product development phase.

The thematic links between NPD, SCC and product planning at the concept stage, deduced from the literature are: 1) modular design; 2) early supplier involvement; 3) co-development of product and SCC, and 4) product and SCC life cycle, with modular design the dominant linking theme. Modularity was identified as an important design principle of complex product, process and organisational systems. The key constructs linking the modularity theme are: 1) product modularity; 2) supply chain configuration modularity, and 3) mirroring of these constructs at different levels of modularity. The systems model takes the circularity of PM and SCCM relationships in to consideration. The findings were integrated into a conceptual model, shown below in Figure 1-8. This framework focuses on testing the four hypotheses, mirroring PM and SCCM, post product launch. Hypothesis one indicates that PM and SCCM tend to be mirrored in modularity levels, post product launch, and this mirroring is desirable. Hypotheses two, three and four advocate the use of intervening systems mechanisms, to strengthen PM and SCCM mirroring, at different levels of modularity. The color coding in Figure 1-8 represents research questions and hypotheses tested in the three projects.

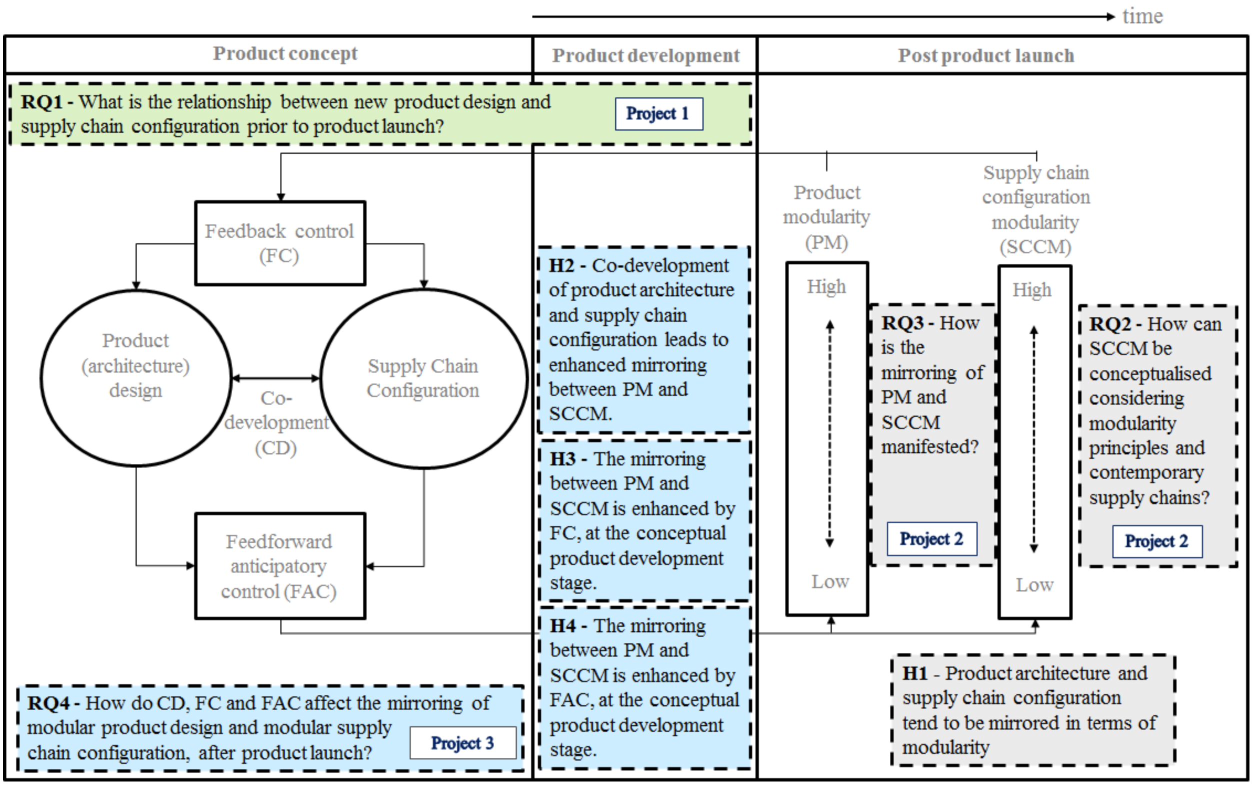


Figure 1-8. Research hypotheses
Source: Conceptual framework (see Figure 1-7.)

1.3.6. Case study design for projects 2 and 3

The research moved from interpreting existing studies, to structured interviews, and case studies, using qualitative methods of data analysis. Meredith *et al.* (1989) define that there is truth ‘out there’, independent of human experience, and ‘in here’, based on individual interpretation. Meredith *et al.* (1989) assert ‘the critical issue is between reliability and external validity; the most valid information is obtained by direct involvement with the phenomenon’.

This empirical research extends the work of Fine (1998), who argues that modular products should be delivered by modular supply chains. This research expands on the work of Graves and Willems (2005), who focus on integrating SCC decisions within PA decisions. This research investigates the findings of Fixson and Park (2008) who determined that the introduction of an integral PA (low PM) led to a vertically structured, near monopolistic SCC (low SCCM) dominated by a single company within the bicycle industry, with the claim by Ülkü and Schmidt, 2011) that matching integral PA with integral SCC networks is not observed in practice.

A semi-structured interview protocol was developed, prior to conducting the case studies. Questionnaires are useful when the research goal is to provide a description of the incidence or prevalence of a phenomenon (Yin, 2014). An early revision of the research questionnaire was tested using telephone interviews with three knowledge experts, shown in Appendix 3-2, Page 450. The interviews were structured around open questions, which allow for sharing of additional information. Case studies were deduced based on these semi-structured interviews, together with multiple data sources, informal meetings, and a review of secondary data, published reports, and research papers.

Modularity can be measured at product, system, sub-system and component level (Sosa *et al.*, 2007). Boundary conditions are set at the top three levels of the product bill of material (BOM), for the Units of Analysis (UoA) selected for the case research. Project two develops the SCCM construct, and explores the manifestation of PM mirroring with SCCM. The prevalent use of the case study approach, deduced in project one, led to this method being selected for the qualitative research. The case method is useful for: 1) exploring organisations; 2) interrogating relationships between concepts; 3) answering "*how*" and "*why*" questions; 4) non-manipulation of behaviour; 5) covering contextual areas, and 6) assessing system boundaries. In project two case research is used to explore the mirroring concept across four industry sectors, at different levels of PA. The case study method was used with five companies, and ten UoA, shown below in Figure 1-9.

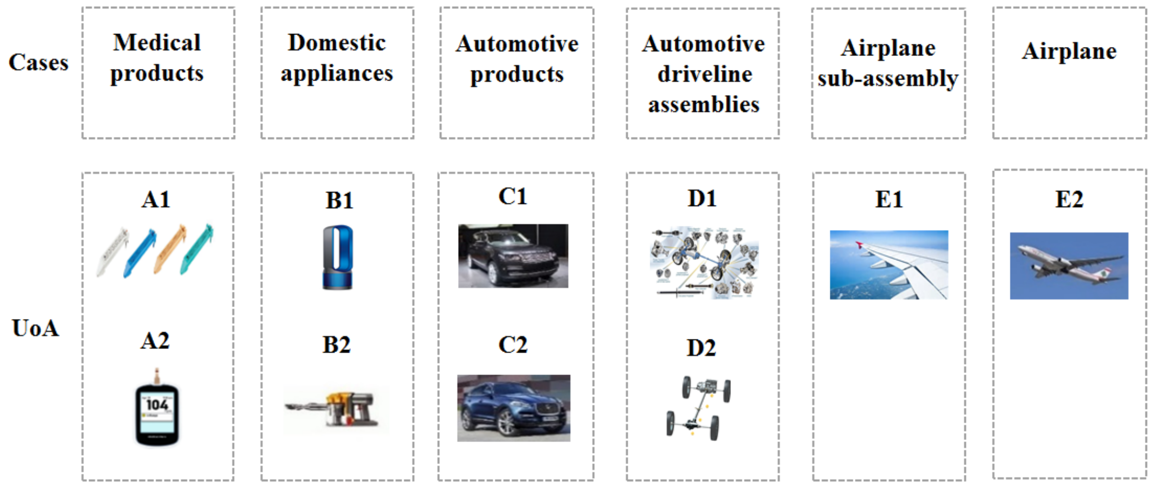


Figure 1-9. Units of Analysis
Diversity in terms of product complexity and SCC

1.3.7 Project 2 - Case studies to develop SCCM and explore mirroring

First, the project two methodological selection is discussed based on guidance from the SLR. Next the SCCM construct and the mirroring hypothesis are discussed. Finally, the PM and SCCM constructs developed during project two, are discussed

1.3.7.1. Methodological selection

Case study methodology was employed in over fifty percent of the academic papers selected in project one. Following Yin (2014) case study methodology was selected, to address the '*how*' question in research questions two and three, using semi-structured interviews as the primary data gathering method. The UoA are new-to-market products, within the medical device, domestic appliance, automotive and aerospace industry sectors. Within-case and across-case analysis is used to explain when and why the mirroring hypothesis holds, and might not hold.

1.3.7.2. SCCM construct

In practice there are various methods to decompose a system. The axiomatic design framework provides a building block for PM and SCCM, using design parameters (Suh, 1990). Suh's axiomatic domains; customer, functional product, SCC process, and physical domain and their interrelationships, are shown below in Figure 1-10.

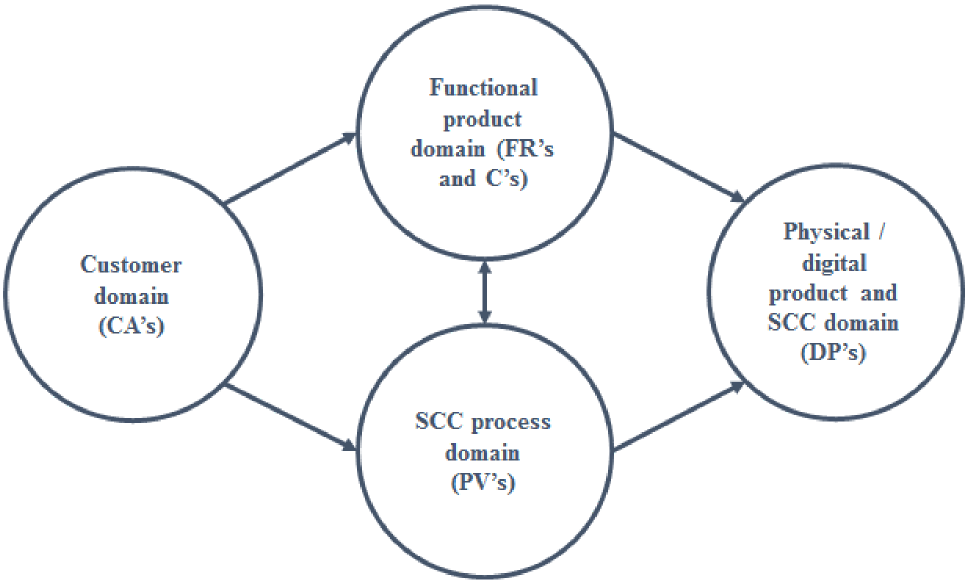


Figure 1-10. Axiom design framework
Source: Suh (1990)

The customer domain covers the needs or attributes (CA's) the customer is looking for in the end-product and SCC. These customer needs are mapped to functional product domains using functional requirements (FR's) and constraints (C's). The customer needs are mapped to the SCC processes characterised by SCC process attributes or variables (PV's). Finally, the functional product requirements and constraints and the SCC process variables are mapped to physical and digital product and SCC design parameters. The final two concepts are the independence axiom, which maintains the independence of the functional requirements; and the information axiom, which minimises the information content of the design. The SCC process variables are used to conceptualise the SCCM construct.

1.3.7.3. Mirroring hypothesis

Furlan *et al.* (2014) highlights that PM alone might not be sufficient to optimise transaction costs. Hayes and Wheelwright (1988, p. 135) argue that manufacturing process choice should support the company's products, and conclude that "a certain kind of product structure is matched with its 'natural' process structure". The hypothesis that a match between product structure and manufacturing process structure is related to performance has some empirical support (Miller and Roth, 1994; Hossein *et al*., 1996).

The mirroring hypothesis adopted from van Bertalanffy (1968, 1975) identifies a state of similarity (element of isomorphism) that allows the extension of one scientific discipline to other disciplines. Research hypothesis one advocates that an increased understanding of SCCM enhances NPD, and increases the probability of new-to-market product success. The mirroring hypothesis has potential for description, pattern matching, explanation, and prescription, of the mapping between these constructs. Mirroring does not suggest reflection of key constructs, but similarity and resemblance. The mirroring hypothesis predicts that the organisational patterns of a development project, namely communication links, geographic collocation, team, and company co-membership, will correspond to the technical patterns of dependency in the system under development.

This research advances a contingent view of the mirroring hypothesis, focusing on the causal links between PM and SCCM. It compares cases that confirm with cases that fail to confirm hypothesis one. Each mirroring factor is discussed in turn, highlighting theories or approaches that could be considered in conjunction, not in contrast with the modularity theory to explain hypothesis one. A contingent view of the mirroring hypothesis reconciles the two opposite views of hypothesis one, enhances the ramifications of hypothesis one in the theory of the company, and offers insights for practitioners.

Project two conceptualises the SCCM constructs, considering modularity principles and contemporary supply chains. Project two also assesses how is the mirroring of product modularity and supply chain configuration modularity is manifested and the levels of PM and SCCM present within each of the UoA. PM mirroring with SCCM is enabled through the mandatory modularity attributes: 1) module function sharing; 2) module interface coupling; 3) supply chain tiering, and 4) process postponement. The case research identified three causal links for mirroring PM and SCCM post product launch, through within-case and cross-case analysis. The findings of project two and project three are discussed in section 1.4., Page 32.

1.3.7.4. PM and SCCM attributes

The PM attributes were deduced from the literature, together with measures for assessing the levels of each attribute. Whilst a common theme throughout the SLR was the PM construct, the definition of modularity is not consistent. The PM attributes are measured on an ordinal scale, from high, to medium to low levels, shown in Appendix 1-1, Page 424. Separability and recombinability are two system-level attributes used in the measurement of the PM attributes or indicators shown below in Figure 1-11. The mandatory PM attributes include function sharing (Pahl and Beitz, 1996; Ulrich, 1995), and interface coupling (Baldwin and Clark, 2000; Fixson, 2005), consider functional product requirements, whilst the optional PM attributes data access, limited life, and product variety in use (Arnheiter and Harren 2005) consider customer needs and product constraints. The data access measure covers the product digitisation parameter, the limited life measure covers the reuse and extensibility parameters, and the product variety in use measure covers the reuse and reconfigure parameters.

A high level of DA modularity is represented by direct access devices, connected via communication channels. These modular direct access devices are in most instances easily replaceable. A medium level of DA modularity is represented by remote access ‘soft module’ devices using radio-frequency or near-field communication technologies, which are not necessarily directly accessible. A low level of DA modularity is represented by removable devices such as flash memory modules, which to not have direct access to the main product.

A high level of LL modularity is represented by modules or components with a low mean time to failure, and require ease of replacement. Certain low mean time to failure modules are less accessible and easy to replace, these are defined as possessing medium level of LL modularity. Modules or components with high mean time to failure are not susceptible to the need for regular replacement, and represent a low level of LL modularity.

A high level of PV modularity exists where product features are easily coupled with the main product. Medium PV levels require defined interfaces, but might not require physical interface coupling (IC), for example software downloads. Low PV levels typically exist where there is tight IC of the main product, and the design does not easily accommodate add-on modules. The PM measures were validated using pilot interviews, with design and SCC knowledge experts, see Appendix 3-3, Page 451.

Extant literature indicates that systems with higher levels of PM focus on goals such as life cycle and new product introduction rate (NPIR). This contrasts with systems with lower levels of PM, which focus more on integral PA, and the achievement of superior product technical performance. The level of PM embeddedness in PA relates closely to the concept of mass customisation (Mikkola 2003, 2006).

Five SCCM attributes or indicators deduced from the literature, are shown below in Figure 1-11. The mandatory SCCM attributes supply chain tiering (Hieber, 2002) and process postponement (Khiang *et al.*, 2004), consider SCC process attributes, whilst the optional SCCM attributes process flexibility (PF), process resequencing (PR) and place postponement (PP), consider both customer needs and SCC process attributes (Feitzinger and Li, 1997).

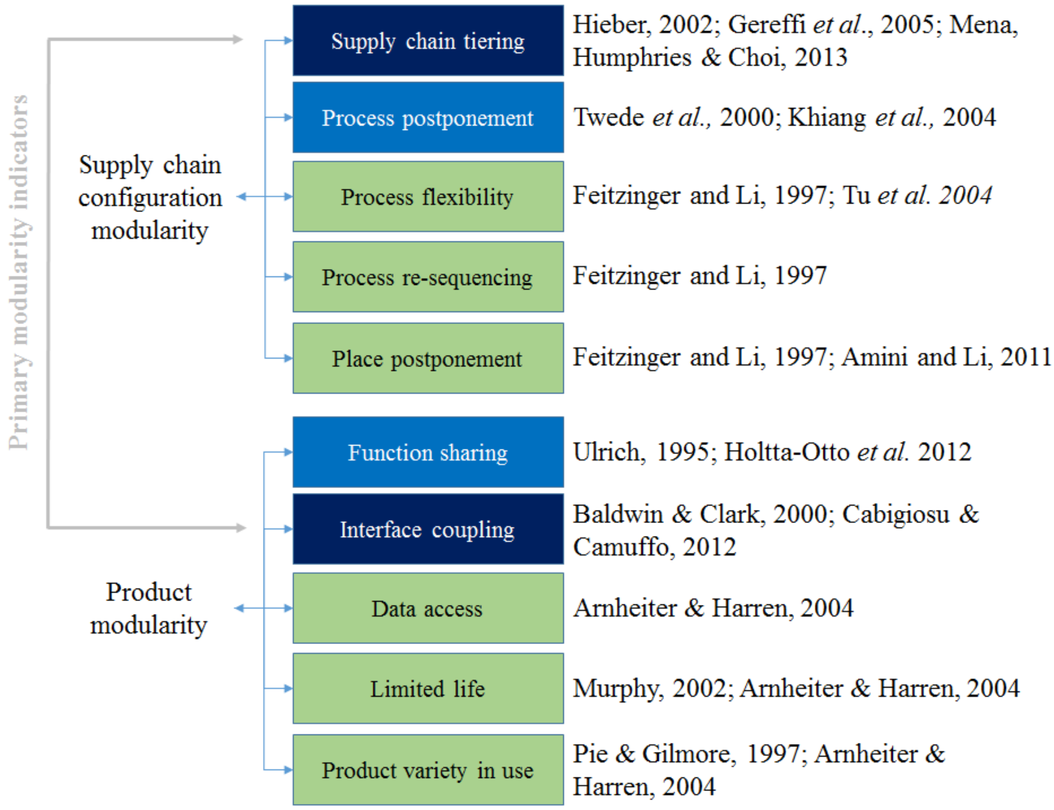


Figure 1-11. PM and SCCM attributes

Mandatory and optional SCCM attributes presented in Appendix 1-2, Page 425, were deduced from the literature, and tested during project two. The SCCM attributes are also measured on an ordinal scale, from high to medium to low SCCM levels.

The product planning concept was identified as a process of integrating NPD and SCC, thus the key concepts were reduced to NPD and SCC, in projects two and three.

1.3.8 Project 3 - Case studies to understand conceptual product development interventions

Project one deduced arguments for the use of intervening mechanisms at the concept stage to strengthen the mirroring PM with SCCM, post product launch. These intervening mechanisms take in to consideration the unidirectional nature of the NPD process, linking PA and SCC design. They address weaknesses in the Stage-Gate® process, and its primary focus on stage-gate reviews. namely its lack of early and frequent experimentation. Contemporary supply chains are required to provide early and rapid response to changes in the PA. The SLR reveals a lack of consensus concerning the influence of SCCM on PM (Antonio *et al*., 2007), which encouraged the empirical research in project two.

The case method and case studies selected for project two were extended to project three. During project three in depth interviews were conducted with ten respondents to investigate the level of involvement of intervening mechanisms, and their support for PM mirroring with SCCM.

1.4. RESULTS

This research has integrated concepts from GST and KBT theories to describe how PA and SCC knowledge can be integrated and aggregated at the concept stage of product design, increasing the probability of new to market products success, and increasing the NPIR.

1.4.1. Project 1 - Linking themes, mirroring concept and literature gap

Attainment of transparency in approach of search, analysis and synthesis, that is replicable, rigorous and scientific was achieved using a systematic literature review. The SLR selected fifty-nine papers for study. Four common themes and six factors are grouped together, following an axial coding approach (Strauss and Corbin) and coded by paper, using extraction data. Thirty-eight codes are identified as links between the key concepts (Miles and Huberman, 1994, p. 105), see Appendices 2-4, Pages 439-440.

During project one, a process of deduction was employed to develop the: 1) linking themes; 2) PM to SCCM mirroring hypothesis, and conceptual framework shown above in Figure 1-11, and 3) the literature gap. Several studies empirically support mirroring between OM and PM at different levels of analyses and in different industries (Schilling and Steensma, 2001; Sturgeon, 2002; Fixson and Park, 2008; Cabigiosu and Camuffo, 2012). This research extends OM to include external supply chain partners. The mirroring concept deduced in assessing the links between PA and SCC modular design, is also itself a phenomenon of theoretical interest, in this research.

Knowledge exchange and learning have been highlighted as central to design activities (Senge, 1990; Beckman and Barry, 2007). To manage interdependencies at module boundaries agents must perform information processing activities including communication, mutual observation, learning, and joint decision making. In other words, agents should couple their organisations even if the transacted artefacts are modular (Puranam *et al.*, 2012). KBT was selected to explain what knowledge exchange is required to mirror PM and SCCM (Grant, 1996), with KBT used to reveal the benefits of mirroring PM with SCCM, shown below in Table 1-4.

Table 1-4. Product and SCC mirroring

	Benefits of mirroring PM with SCCM
1	Increase in firm knowledge and protection of core intellectual property (IP).
2	IP management flexibility with PM and SCCM knowledge accessible on a 'need to know' basis.
3	Parallel life-cycle management of the bill of material (BOM) and bill of process (BOP).
4	Reduced supplier switching costs, should an Original Equipment Manufacturer (OEM) decide to multi-source, for security of supply, or other competitive reasons (Colfer, 2007).
5	Collaborative and early involvement of core supplier IP at product concept stage, with key suppliers assigned architectural chunks within the PA (Rechtin, 1991).

Several authors have classified existing literature on modularity from the engineering standpoint (Fixson, 2003; Gershenson *et al.*, 2003; Salvador, 2007). Campagnolo and Camuffo (2010) were the first to classify modularity from the perspective of management studies. Their research identifies three streams of literature clustered around three UoA: 1) product design modularity; 2) organisational design modularity; and 3) production system modularity. In this research the production system has been extended to encompass SCC, encompassing a network of facilities and activities that perform the functions of material procurement, the movement of material between facilities, the manufacturing of products, the distribution of finished goods to customers, and after-market support for product sustainment. Whilst the PM construct is well defined in the literature the SCCM construct lacks definition and requires further conceptualisation.

1.4.1.1. Linking Themes

The SLR identified four themes linking SCC, NPD and product planning: 1) modular design (Ulrich, 1995; Baldwin and Clark, 2000); 2) early supplier involvement (Ragatz *et al.*, 2002; Choi and Linton, 2011); 3) product and SCC life cycle (Novak and Eppinger, 2001; Salvador *et al.*, 2002; van Hoek and Chapman, 2006, 2007; Doran *et al.*, 2007; Dekkers *et al.*, 2013), and 4) co-development of product and SCC (Griffin, 1993; Swink *et al.*, 1998; Wikner and Rudberg, 2005; Lau and Yam, 2007). All four themes are incorporated in to the conceptual framework, shown in Figure 1-7.

The strongest theme is modular design, which is an important design principle of complex product, process and organisational systems. Hypothesis one indicates that PM and SCCM tend to be mirrored in modularity levels, post product launch, and this mirroring is desirable. The key constructs linking the modular design theme are: 1) product modularity; 2) supply chain configuration modularity, and 3) mirroring of these constructs at different levels of modularity. The findings show that hypothesis one is contingent on six distinct factors: 1) level of PA complexity; 2) codifiability of PM and SCCM knowledge; 3) co-development of PM and SCCM; 4) level of SCC process capability within the supply network; 5) FAC for open loop SCC, and 6) strategic inventy positioning, within the SC.

1.4.1.2. Mirroring Concept

The mirroring concept is deduced from the SLR. The SLR determined that a viable theoretical base for empirical research is the area of management control systems. The findings of the SLR reveal that a systems perspective contributes towards a greater understanding of NPD and SCC design, implementation and management (Helou and Caddy, 2006). A configurable system encapsulates interdisciplinary knowledge, which can be domain dependent and independent. Both NPD and SCC systems are defined by the systems theory framework (Dekkers, 2005).

There are noteworthy modular products supplied using supply chains configured with a 'mirrored' level of modularity. Mirroring does not suggest an exact reflection of PM and SCCM construct attributes, but similarity and resemblance. When Henry Ford entered the automobile industry in 1908, this was already a crowded marketplace with over three-hundred companies, competing in this sector. Most of these companies operated 'craft-shops' delivering high levels of PM and high levels of SCCM. Ford's success was built on a systemised and automated production and distribution system, with low levels of PM mirrored with low levels of SCCM. When faced with the challenge of increasing the production of the Lancaster airplane, during WWII, Roy Lancaster implemented high levels of PM, and established high levels of SCCM, delivering forty-nine airplanes weekly with an order to delivery lead-time of three days. With high levels of PM, SCC functions are designed into physical modules that can be combined in subsequent designs. A related concept 'reusable engineering', takes portions of previous SCC designs as the basis for new SCC designs. A further example of mirrored PM and SCCM is the iPod. There were more than thirty MP3 audio digital players in the market, at the time of the iPod launch in 2001. The iPod was conceived as part of an eco-system with iTunes being a personal computer and the iPod as small independent pods. Success of the iPod was based on a low PM levels built with a low level of SCCM. A single manufacturer originally manufactured the iPod (low SCCM), mirroring the low level of PM. The product's low levels of PM, is controlled by an integrated operating system (iTunes).

Two research questions are developed in project two, to address the mirroring hypothesis. Research question two (RQ2): *"how can supply chain configuration modularity be conceptualised considering modularity principles and contemporary supply chains?"* was developed to build and empirically test the SCCM construct. Research question three (RQ3): *"how is the mirroring of product modularity and supply chain configuration modularity manifested?"* was developed to guide and test the mirroring of the PM and SCCM constructs. Hypotheses two, three and four advocate the use of intervening mechanisms, to strengthen PM and SCCM mirroring, at different levels of modularity.

There are examples of products and SC configurations, for example the Polaroid camera, and Chrysler's production system that failed, due to insufficient consideration of PM mirroring with SCCM (Fine, 1998). Polaroid's instant photography business employed low levels of PM and SCCM. No parts, including lenses could be adapted from other cameras. All supply facilities were in the Boston area; with many of these facilities owned by Polaroid and managed by a tight knit team of managers and technical experts. During the 1980's Polaroid outsourced camera assembly facilities to Scotland and China. Since product design remained integral (low level of PM), the interfaces among parts remained distinctive, complex and tightly coupled. With Polaroid engineers required constantly to support the US, Scotland and China assembly facilities this slowed their ability to launch new products. The Polaroid company filed for bankruptcy, in 2001.

1.4.1.3. Literature gap

The SLR helps determine the research question, required to study the linking of NPD and SCC. Whilst modular design is the strongest thematic link between these concepts a review of extant literature, found limited research on the impact of modularity on system performance. Holtta *et al.* (2005) offer a single paper discussing modularity and performance for engineered systems and products. Comparing a laptop and desktop computer and a cell phone and desk phone, technical performance constraints such as light weight and compactness led to more integrality but did not provide a qualitative measure of modularity versus performance.

The NPD literature states that inter-functional coordination helps to ensure a clear and unified vision by aligning different technical competencies to ensure compliance with common goals (Cooper and Kleinschmidt, 1994; Brown and Eisenhardt, 1995), however the NPD literature lacks a focus on SCC, at the concept stage of NPD.

Deduced from the SLR is the difficulty in discerning causality in the relationship between NPD and SCC. Causal ambiguity makes it cumbersome to determine whether well performing companies, engaged in SCC planning or whether rigorous SCC leads to superior NPD performance. It could be that successful companies with slack resources and better capabilities engage in SCC optimisation. Consequently, my claim of a positive impact of SCC on performance is tentative and requires further research.

The SLR identified a weakness of the Stage-Gate® process, namely its lack of early and frequent experimentation. One of the myths of product and process development is the ‘right first time’ principle (Thomke and Reinertsen, 2012). NPD is a dynamic and iterative process, and evolves as new knowledge is generated and shared. It is in the best interests of the company to implement processes that encourage and foster knowledge generation across different disciplines. Limited research was found on the intervening mechanisms used to strengthen PM and SCCM mirroring. Research question four (RQ4) aims to test the strength of systems-based intervening mechanisms in mirroring the PM and SCCM constructs. The emphasis can be on fast response modelling focused on fast feedback control (FC) and feedforward anticipatory control (FAC), rather than a first pass success. There is a requirement for intervening mechanisms to support the Stage-Gate® phase process rather than replace it (Cooper, 2008).

Traditional PM measures produce a real number between zero and one, that can be used to compare relative modularity amongst multiple designs. These traditional measures focus on coupling whether between design parameters or interfaces amongst modules. It was determined that these measures are insufficient in capturing the benefits of modularity. Previous work identified two component and module interface types (Ulrich, 1995). Other work used a matrix approach to capture the existence of module interfaces (Stryker *et al.*, 2010). Current research on measuring product reconfigurability and extensibility is limited.

‘Despite the emphasis on modularity in academic literature, it is not the dominant strategy for managing integration’ (Anderson *et al.*, 2007). Whilst PM is identified in literature as a key component of PA design; ‘empirical studies demonstrating the PM effect on NPD performance are scant’ (Danese and Filippini, 2010). Nascent research has placed limited focus on the role and benefits modular-based practices play in the mirroring of product and SC architectures.

A product cum SC architecture model is emerging as a new UoA (Zott *et al.*, 2011). Business models seek to explain how value is created and captured. In addition, these models emphasise a system-level, holistic approach to explain how companies ‘do business’.

1.4.2. Project 2 – SCCM dimensions and manifestation of mirroring

The SLR led to a focus on mirroring modular-based processes in NPD and SCC, enhancing SCC value and encouraging NPD experimentation. The SLR deduces that this research should focus both on the stage-gates, and between the stage-gates. This focus was incorporated in to the interview questionnaires for project two. The literature guidance was considered when selecting the research methods for the empirical research in projects two and three.

In a theory-testing setting the “arguments should be closely linked to the data, and build on a small number of existing theories” (Boer *et al.*, 2015, p.6.). In the case of this research the relevant theories are GST and KBT. Secondly, the NPD and SCC attributes should align with the relationship the theory predicts. Thirdly, boundary conditions are clearly stated such that it is clear to what degree data supports or fails to support a given hypothesis. Finally, a good theoretical argument makes it clear how the results could be used to either falsify or confirm, the research hypotheses.

The benefits of modularity in product design have been widely recognised and qualitatively captured (Gershenson *et al.*, 2003). In an era of increasing product and SCC complexity the modularity concept is recognised as a means of managing new product design considerations, in high technology organisations, as shown below in Table 1-5.

Table 1-5. Technology and organisational modularity
Source: Schilling (2000)

Modularity concept	Technology and organisation considerations
Domain specific	X
Hierarchically module nesting	X
Internal and external integration	X
Knowledge encapsulation	X
System decomposability	X
Module recombinability	X
System expandability	X
Module as homologue	X

When decision-makers state they want a product to be more modular they are indicating that there are one or more aspects of modularity that they want captured in a new design. Agreed upon benefits of modularity include flexibility, reusability, reconfigurability and extensibility. Mirroring of PM and SCCM, focuses on product value the benefits of improved product delivery, flexibility, and increased customer service (Lau *et al*., 2007); cost efficient product variety (Worren *et al*., 2002); and mass customisation (Duray, 2004). Product systems are deemed modular, when they can be decomposed into modules and components that may be mixed and matched in multiple configurations. Modularity is a strategy for organising complex products and processes efficiently and effectively (Blaikie, 1993). It is not only necessary to mirror products and SCC processes, but also the supply network configuration (Feitzinger and Lee, 1997). Organisational systems become modular when they substitute tightly integrated for loosely coupled forms (Schilling and Steensma, 2001). For instance, when a company utilises contract manufacturing it is using an organisational form that is more independent than building manufacturing capabilities in-house: the company can switch between contract manufacturers that perform different functions, and the contract manufacturer can similarly work for different companies (Sturgeon and Lee, 2001). Codifiable knowledge is shared with these full or partial ‘turn-key’ suppliers. As companies couple organisational components that lie outside of the companies’ boundaries, the entire SCC system becomes increasingly modular. Using loosely coupled structures enables companies to achieve greater process agility in scope and scale (Schilling and Steensma, 2001).

1.4.2.1. SCCM Dimensions

Supply chain tiering is the main indicator of SCCM because it spans the SCC, whereas process postponement is confined to a single SCC tier and is only present where there are high levels of custom configuration.

Structural PA and SCC analysis at the concept stage encompasses SC inventory requirements, across all tiers of the SC. PM mirroring with SCCM supports strategic inventory positioning. When transportation and inventory holding costs are significant, companies may choose to locate inventory close to suppliers reducing coordination, quality, and overall logistics costs. Geographical proximity offers safe delivery, and lower transportation costs (Lau and Yam, 2005). Communication proximity improves the sharing of demand information, enabling companies to better foresee demand fluctuations, reducing safety stock level and stock-out risk. Finally, when it is expensive to maintain final product inventory, PM allows for process and PP on receipt of the customer order (Salvador *et al.*, 2002). UoA A1 and B1 which are finished products are built to forecast, with low PRP capability. In the case of UoA A1 and B1 it is economic to maintain an inventory of finished products. Were this not to be the case these UoA would require product postponement strategies (Howard and Squire, 2007).

1.4.2.2. Manifestation of mirroring

To reduce co-ordination costs, this research suggests PM mirroring with SCCM. All ten UoA had a low to medium level of PM, shown in Table 3-4, Page 199. There is research explaining why medium to low PM drives medium to low SCCM. This will be discussed in Section 1.5. Prior research ruled out different research settings as responsible for the contrasting views of the mirroring hypothesis (D'Adderio and Pollock, 2014, p. 1814). These authors argue that the discrepancy between product and organisational architectures derives from contingent factors 'that ultimately impinge on the ability of modular design rules to bring about modular organisations'.

The originality of the model proposed is in the tagging of knowledge modules that mirror PM with SCCM, through a granular analysis of these constructs. One reason for the early specification of these interfaces, at the product concept stage relates to ESI. *"The motor manufacturer and filter manufacturer are specified in very early. We don't tell them what the concept is, but we will tell them we need a filter that provides a certain face velocity, this is the amount of air that gets through the filter itself",* interviewee for unit of analysis (UoA) B1, in project two.

Mirroring is manifested through product interface coupling and supply chain tiering. A high level of mirrored modularity is manifest as loose product interface coupling in PM and a high level of SC spread with low legal and economic involvement, by the company. Product interface coupling is closely related to function sharing (loose interface coupling is associated with low levels of function sharing), supported by all but one UoA (E2).

PM mirroring with SCCM is evident for six UoA (supporting hypothesis one). A high level of mirroring is manifested as loose product IC and a high level of SC spread with low legal and economic involvement, by the focal company. Four UoA; B1, C1, C2 and E2 challenge hypothesis one. These four UoA are technologically dynamic products. Loose IC with low levels of FS is supported by all UoA, except for E2. SCT the main indicator of SCCM, spans the SC whereas PRP is confined to a single SCC tier and is only present where there are high levels of custom configuration.

Mirroring is manifested primarily through product module IC and SCT. Higher levels of product assembly for example C1 and C2 have medium level IC, due to the many interface types connecting the modules. E2 however exhibits a low PM level, due to the tight coupling required with the airplane system. Medium PM level assemblies such as A1, A2, B2 have medium level of SCT and lower level assemblies D1, D2 and E1 have lower levels of SCT respectively. B1 is an exception in that it exhibits tight coupling. A high level of mirroring is manifested as loose product IC and a high level of SC spread with low legal and economic involvement, by the focal company. SCT is the main indicator of SCCM since it spans the SC whereas PRP is confined to a single SCC tier and is only present where there are high levels of customer configuration. The substantive contribution of project two is the identification of three linking mechanisms between PM and SCCM; propensity to decouple modules within the PA and SCC; ESI at concept development, and a product and SCC life cycle focus, at concept development.

Project two identified the benefits of PM mirroring with SCCM, include an increase in company knowledge; improved management of intellectual property (IP); reduced supplier switching cost and improved product life cycle management. There is a resurgence in interest in the role of modularity in addressing the increasing challenges of product technology life cycle. For example, with "*the cordless vacuum cleaner, the digital motor is being continuously upgraded with increasing power and can be accommodated in the same chassis. While higher PM is typically higher cost than lower PM, it is normally better from a product life cycle perspective",* interviewee for UoA B2. NPD requires multi-disciplinary teams, and continuous knowledge exchange, at the concept stage. There is an increasing interest in academic research on SCC knowledge generation and exchange, which supports this focus on multi-disciplinary design, see Appendices 4-13 and 4-14, Pages 484 and 486.

Sosa *et al.* (2004) show high PA complexity can restrict companies in grasping component interdependencies causing a lack of mirroring between PM and OM. This research builds on the work of Sosa *et al.* (2004) reviewing different levels of PA. For complex PA, design coordination costs may become high as in the case of aerospace (Argyres, 1999) and automotive (Fine *et al.*, 2005) industries. Standardised interfaces embed the necessary information to coordinate different actors efficiently (O’Sullivan, 2003; Danese and Romano, 2004), and reduce the need for high coordination costs by isolating the hardly transferable technological knowledge in innovative product design (Schmickl and Kieser, 2008) and tacit knowledge (Kotabe *et al.*, 2007) within product modules. Mapping component and product functions reduces the interdependency between organisational units, hence containing coordination costs. Galvin and Morkel (2001) assert that the specialisation of companies on specific modules enables them to make their processes more efficient, resulting in lower sourcing costs. Sanchez and Mahoney (1996) state that modular product design boosts component specific learning within organisations. This is relevant in the case of UoA E1, which required a twenty-year investment, to bring the technology to the NPD concept stage.

PM and SCCM mirroring is evident for six UoA (supporting hypothesis one) however four UoA challenge this mirroring hypothesis. B1 was launched into a pre-existing medium modularity SCC (previously used for modular products) but the product was highly integral (high function sharing and tight module interface coupling) driven by the product specification, yet there was no early involvement from suppliers and SC life cycle was not taken into consideration. C1, C2 and E2 offer a high level of customer configuration supported by high levels of process postponement and high SCT spread (with low OEM-supplier involvement) all indicating high levels of SCC modularity. However, the interface coupling is not loose as might be expected.

A rationale for paired PM and SCCM modularity is the strategic flexibility offered, shown in Table 3-18, Page 239, for attributes PV and PP. With UoA’s C1 and C2, a pre-condition of these high-end luxury vehicles is the ability of PM mirroring with SCCM to respond under competition and customisation pressures, to specific customer requests (Christensen *et al.*, 2002; Cheng, 2011). The focus with UoA C2 is to produce standard SKU’s and provide customisation within the distribution network. Downstream suppliers of ‘stand-alone’ custom configuration functions enable upstream suppliers to reach market without incurring the exorbitant fixed costs of forward integration. Organisational decoupling enabled by PM helps the OEM to mitigate operational risks and meet changing customers’ needs. A further rationale for paired ‘high PM–high SCCM’, with

UoA C1 and C2 is that product development teams can mitigate unexpected problems by keeping them local. Further, these OEM’s can more easily provide new product configurations to customers by combining their capabilities with other development groups. Research hypothesis one which advocates the mirroring of PM and SCCM was addressed in project two, by answering research questions two and three.

With UoA B1, a relatively low PA complexity does not show a high level of PM – SCCM mirroring, post product launch. This UoA operates in an open system, with weak data feedback. B1 and A1 and B1 also exhibit medium levels of FAC of SCC requirements at the concept stage. The assessment of SCC at the product concept stage is at a medium level for these two UoA. Open systems which do not have digital or software control require FAC intervention.

With UoA B1, the intense interdependencies among the components (low PM) increase the coordination efforts that are needed to maximise the synergy between components and minimise product errors (low SCCM), Gokpinar *et al.* (2013). Moreover, a new integral PA (low PM) may cause a shift towards coupled supply chains (low SCCM). This is the situation with the UoA B1, where the OEM has contracted a Primary Systems Assembler (Integrator) to integrate manufacturing and distribution.

For product with a medium level of PA complexity, as in the case of UoA D1 and D2, the high level of PM mirroring with SCCM reduces supplier product quality risk. Subsystems having a few interdependencies are less vulnerable (Gokpinar *et al.*, 2013).

PM mirroring with SCCM is manifested through three linking mechanisms:

a. Propensity to decouple (PD)
   PD refers to an inclination or natural tendency for modules to separate, at their interfaces, which define the spatial, informational, material, energy or structural connections or coupling of one module to another within a product (Sosa *et al.* 2007). The degree of coupling is used to identify which modules are loosely and tightly coupled to the other modules in a product. This assessment can be used by designers

and SCC decision-makers to guide future design decisions regarding which modules to target when trying to improve a product's modularity, and mirror PM with SCCM.

A low propensity to decouple modules leads to a high proximity in SC tiering whereas a high propensity to decouple leads to a lower proximity in SC tiering. A lower propensity for module decoupling in general leads to a higher proximity of SCT, where these products are inclined to be produced and delivered by a vertically integrated SC, whereas a higher propensity for module decoupling in general leads to a lower proximity in SC. These products are inclined to be produced and delivered by vertically and horizontally dis-integrated SC's. A high PD is evident for six UoA, but less evident for UoA B1, C1, C2 and E2, leading to weak levels of mirroring or these four UoA. Modules and systems intersect with one another in these products but do not overlap as congruently in the case of the air purifier, automobiles, and airplane.

b. Early supplier involvement (ESI)

ESI exists in all UoA, within regulated industries, but not with domestic appliances which reside at a lower level of regulation. ESI where interface coupling is tight focuses on application specific design inputs; ESI where interface coupling is medium focuses on early supplier selection and qualification and a broader spread of the SCT. The empirical research identified that ESI, propensity to decouple (PD), and the life cycle view are strong primary causal links between module IC and SCT. Whilst knowledge codification (KC) supports the mirroring of PM and SCCM, is not a causal links between IC and SCT.

McIvor *et al.* (2006) emphasise the potential negative effects of high capability dispersion within the supply network. Such dispersion may reduce the capacity of the companies to sense and seize new market opportunities. This claim is supported by the lack of ESI with the domestic appliance company. When the companies in a supply network are extremely specialised, they tend to follow different knowledge trajectories. The focus of each company may become too narrow to recognise and seize market trends since they lack inclusive capabilities to align product design with changing market needs (Gadde and Jellbo, 2002). In such a situation, a system integrator is required to achieve a good environmental fit, within the whole supply network. Gadde and Jellbo (2002) exemplify the shift in the outsourcing strategy of OEMs such as Honda and GM. These OEMs focused on their core competency for higher operational efficiency and relied on the specialised capabilities of their suppliers for outsourced modules. OEMs today seek to retain and integrate dispersed capabilities. System integrators and integration mechanisms are required to align dispersed capabilities along the supply network providing medium to high SCCM. Similarly, Airbus adopted integration mechanisms, joint design tools, project teams, and concurrent engineering (CE), to develop the A380, allowing Airbus to align a large amount of dispersed capabilities throughout the supply network (Frigant and Talbot, 2005).

ESI is a form of vertical collaboration between SC partners in which the manufacturer involves the supplier at an early stage of the product development process (Mikkola and Skjott-Larsen, 2006). ESI exists with all eight UoA, within regulated industries, but to a lower extent with domestic appliances B1, and B2 which operate to a medium level of regulation. Where module IC is tight ESI focuses on application specific design input. Where module IC is medium ESI focuses on early supplier selection and qualification and a broader spread of SCT. Ragatz *et al.* (2002), and Choi and Linton (2011) believe that the focus of ESI should not be limited to single buying/supplying organisational units, but should extend to the extended SC.

The US Food and Drug Administration (FDA), International Standards Organisation, National Highway Traffic Safety Administration (NHTSA), Federal Airline Association and the Association of European Airlines, together with other regulatory agencies work towards standardisation, and compliance to standards. In the domestic appliances sector there are regulations on power consumption, customer labelling, and environmental compliance, the levels of regulation are less defined than with the other industry sectors where for example material characterisation, and equivalence testing are required.

High levels of ESI did not lead to high levels of mirroring for C1, C2 and E2, for the reasons discussed under hypothesis four. Where IC is tight (B1, D1, D2, E1, E2) ESI focuses on application specific design inputs, utilising supplier innovation. Where IC is medium ESI focuses on early supplier selection and qualification and leads to a broader spread of SCT. ESI is a strong linking mechanism for low to medium complexity products, and lower level sub-assemblies.

c. Product and SCC life cycle

For new to market products life cycle planning focuses on specific requirements of the life cycle, following user needs and technology capability readiness. Life cycle objectives determine the type of modularisation. For new-to-market products life cycle planning focuses on specific requirements of life cycle, with life cycle objectives determining the type of modularisation used. Life cycle planning focuses on specific requirements following user needs and technology capabilities (Abernathy and Utterback, 1978; Ülkü and Schmidt, 2011; Chandra and Grabis, 2016; Cabigiosu and Camuffo, 2017).

The one optional PM attribute that had a link with SCC was data access (DA). Smart connected devices are allowing products to be accessed through the SCC life cycle, leading to inter-connected and intelligent supply chains. The one SCCM attribute effected by the SCC life cycle is SCT. There is a high level of mirroring between DA and SCT, for four UoA C1, C2, D1, and E2. Whilst DA is not available for UoA A2, B1, B2, the participants referred to future revisions of these UoA which will contain DA sensors. There is also a focus within these companies on further use of smart manufacturing technologies (Industry 4.0).   C1, C2 and E2 offer a high level of custom configuration supported by high levels of PRP and high SCT spread (with low OEM-supplier involvement) indicating high levels of SCCM. Module IC is not loose as might be expected. In the case of automotive and airplane the sheer number, and types of module interfaces combined with the need for high levels of functional performance plus the fact that many modules are not subject to custom configuration implies that loose IC is limited to a medium level. B1 was launched into a pre-existing SCC with a medium level of SCCM (previously used for modular products) but the product was highly integral (high FS and tight module IC) driven by the product specification. There was limited SC life cycle consideration, during the product concept stage.

The interface type plays a key role in the mirroring of PM and SCCM. Product modules are connected by informational, spatial, material, energy and structural interface. Each interface type will differ depending on the product. Informational interfaces transfer signals and controls; material interfaces transfer airflow, oil, fuel or water; energy interfaces transfer heat, vibration, electric, or noise energy; structural interfaces transfer loads or containment, whilst spatial interfaces cover physical adjacency for alignment, orientation, serviceability, assembly or weight (Stryker *et al.*, 2010). SCC modules are connected by informational, spatial, material, energy and structural interfaces (Baldwin, 2008). SCC modules equal the nodes or tasks-cum-agents in the SC network. A substantive contribution of project two is the identification within the product life cycle, of differences in PM mirroring with SCCM, for analyser and prospector companies. Analyser companies tend to be fast followers where prospector companies take a more aggressive new product-market position within broadly defined markets, and tend to be industry pioneers in the creation and development of new SC technologies. “Analyser companies maintain a secure market position within a core market . . . but also seek new market positions” (Walker and Ruekert, 1987, p. 16). Prospectors are often the first to adopt new concepts and new tools when the opportunity arises, with the notion constantly to push performance boundaries. Their aim is always to have the most innovative SC operations. In the case of the company that designs and manufactures D1, D2 and E1 sub-assemblies this company is highly innovative and constantly bringing advanced module technologies to market in the form of advanced composite solutions (E1), and advanced metallic solutions (D1 and D2); a low level of PM and SCCM is appropriate for these sub-assemblies. In the case of the domestic appliance company., which focuses on bringing innovative technologies to market, including advanced cyclone, digital motor, and filtration technology (B2); filtration technology and advanced acoustics (B1); these products tend to have lower levels of PM at product launch, with PM increasing over the life of the product, as product enters volume markets. There is an acknowledgement that PM should be increased, allowing for late stage product customisation, this will lead to PM mirroring with SCCM, for B1.

Knowledge sharing commences with the customer requirements definition (Campagnolo and Camuffo, 2009; Cabigiosu *et al*., 2013). In the case of UoA A2 the test strip forms a critical part of the product subsystem. The test strip is comprised of active biologics and a measurement algorithm for measuring the level of glucose deposited on the test strip. In the case of UoA B2 the power sub-system is a key measure of the customers' product perception. This product took 5,127 attempts to create the first no-loss-of-suction vacuum cleaner (O'Brien, 2015) using a digital motor, powered by a DC battery. Products A2 and B2 have a high level of customer requirements specification, supported by the fact that whilst they are new-to-market products they are follow-on generation product variants. UoA A1 and B1 which have a high level of knowledge codifiability illustrate a high level of PM mirroring with SCCM.

Products with lower levels of knowledge codifiability such as C1 and C2 illustrate a low to medium level of mirroring.

1.4.3. Project 3 – Conceptual product development interventions impacting on mirroring

Following development of the SCCM construct, and PM mirroring with SCCM manifestation in project two, the research was extended to understand the effectiveness of concurrent development (CD), feedback control (FC) and feedforward anticipatory control (FAC) intervening mechanisms in re-enforcing the mirroring process. Project three explored the development of an integrative framework, mirroring PM and SCCM constructs, using these intervening mechanisms, focusing on knowledge exchange between NPD and SCC. Research question four: *"how do co-development, feedback* *control and feedforward control systems, applied at the conceptual stage of product development, affect the mirroring of modular product design and modular supply chain configuration?*", is deduced from the literature in project one.

CD, FC and FAC mechanisms were evaluated for their feasibility, usability and utility (Platts, 1993), in strengthening the mirroring process. In-depth interviews were conducted with NPD and SCC experts, and case research was conducted with the same companies and UoA, as project two. The research hypotheses were tested with the five companies across these ten UoA, shown in Figure 1-9, Page 26. Testing these hypotheses requires the study of the NPD process at the product concept stage, and the capture of mirroring outcomes, post product launch, shown below in Figure 1-12. Hypotheses two, three and four were validated during project three, but not tested, due to the time limitations of the DBA.

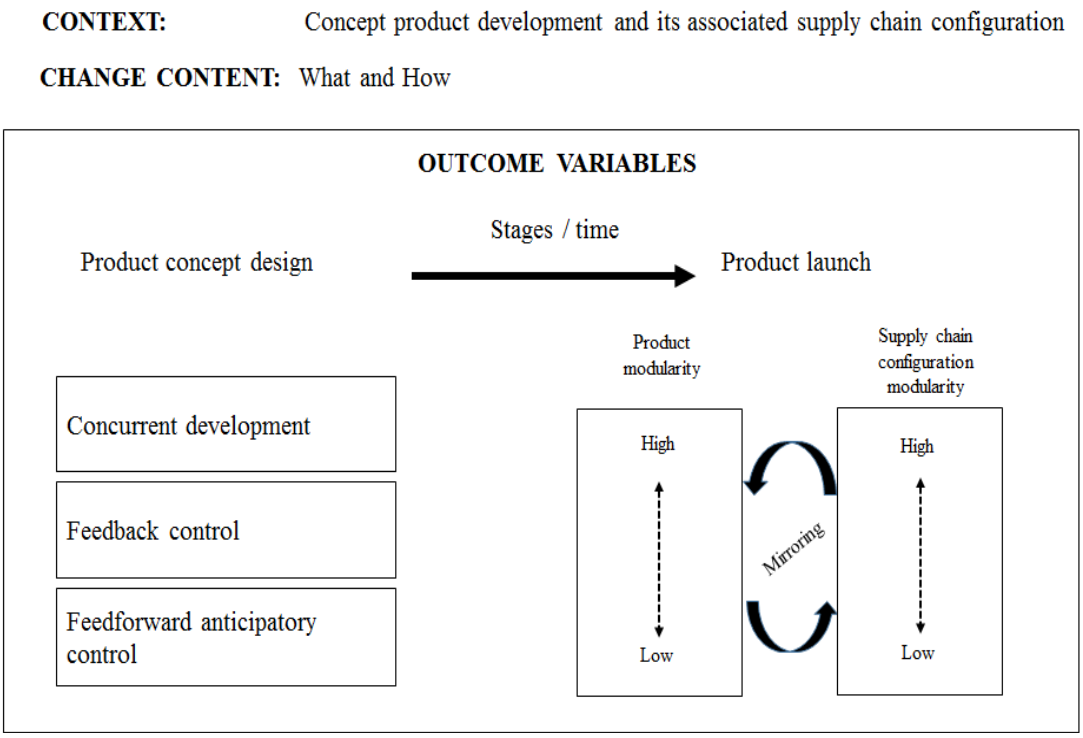


Figure 1-12. Meta-level analytical framework
Source: Pettigrew (1992)

1.4.3.1. Co-Development (H2)

Hypotheses two indicates that co-development of PA and SCC leads to enhanced mirroring PM and SCCM. A review of the literature highlighted three levels of each attribute or variable, for the intervening mechanisms. The levels for CD are shown in Appendix 1-3, Page 426. Often SCC involvement commences post the concept stage of NPD. In other cases, there is limited involvement of SCC functions, with participation often limited to material and supplier selection. Where CD is a core competency, as stated in the interviews, this does not always mean that there is early supplier, internal and external customer involvement.

Research hypothesis two is based on three core principles: 1) integration; 2) parallelism, and 3) continuous development. Eight UoA show strong support for hypothesis two, which proposes that CD leads to enhanced mirroring between PM and SCCM. This is supported by the literature, as shown in Appendix 3-12, Page 459. B1 and B2 show a lower level of support for this hypothesis at the concept stage. The conditions for supporting hypothesis two, which is a re-emerging area of SCC research (Chandra and Grabis, 2016) are: 1) Early definition of process capability requirements; 2) Innovation capabilities within the supplier base; 3) Knowledge codification and knowledge hiding as a means of protecting IP, and 4) Use of the Technology Release Level (TRL) methodology at the concept stage.

The domestic appliance company has in-house design capability. These domestic appliance products are primarily focused on mechanical design, with tight geometric interface tolerances. This focus allows for a lower level of CD at the concept stage, protecting core product IP.

Co-development is evident in all instances where PM is mirrored with SCCM. Two of concurrent development's guiding principles, integration and parallelism (Burton *et al.*, 1988; Baregheh *et al.*, 2009) support the development of mirroring of PM with SCCM. Complex and innovative PA require a tight integration between the units that develop the different modules (Sosa *et al.*, 2004). If managers do not recognise this need and build thick boundaries among development units, coordination is likely to be impacted, and errors or performance penalties may ensue.

1.4.3.2. Feedback Control (H3)

Eight of the ten UoA support hypothesis three, which proposes that the mirroring between PM and SCCM is enhanced by FC. FC is closely related to CD for closed-loop systems. Quality, delivery, capacity and price determination are considerations in closed-loop product and SCC performance assessment. The higher the level of FC the higher the level of mirroring, as with UoA C1, C2, D1 and D2. There are inbuilt communication patterns between the PA and SCA teams in the case of this automotive alliance, supporting FC.

FC attributes or variables deduced from the literature are measured at three levels, shown in Appendix 1-4, Page 427. Hypothesis three states that FC of PA and SCC leads to enhanced mirroring between PM and SCCM. UoA A1 and B1 exhibit a lower level of support for this hypothesis. Whilst A1 and B1 are first generation final level assemblies, there are components within these designs which are in the market, in previous designs. These components offer performance data which could be fed back to the NPD team. The conditions for supporting hypothesis three are: 1) a KM process is in place to accumulate and feedback component and module level performance data, and 2) codified knowledge, ESI and innovation sharing are present.

1.4.3.3. Feedforward Anticipatory Control (H4)

Hypothesis four supports a life cycle focus at the concept stage. FAC attributes or variables deduced from the literature are measured at three levels, shown in Appendix 1-5, Page 428. Hypothesis four states that FAC of PA and SCC leads to enhanced mirroring between PM and SCCM. Six UoA support hypothesis four, which proposes that the mirroring between PM and SCCM is enhanced by FAC. These six UoA with the strongest FAC levels appear to undergo a low rate of product change, where change occurs on a stepped basis. “Products which have FAC intervention experience step-change improvements in SCC productivity metrics” (Baker and Bourne, 2014, p. 46).

A2, B1, C1 and C2 provide moderate support for hypothesis four. UoA A1, B1 and E2 which illustrate a low level of PM mirroring with SCCM have open-loop SCC, and benefit from FAC. A1, B1 and E2 have strong property rights in place enabling these companies to disaggregate their supply chains. This enables these companies to extract core technology and specialisation gains from key suppliers. A1 relies on global precision metal and plastics suppliers; B1 relies on precision tooling and key filter technology suppliers, and E2 relies in a global network of technology partners. Patents enable research-intensive and production-intensive companies to enter a variety of contractual arrangements, reconfiguring their SCC supply to maximise specialisation gains.

1.5. CONTRIBUTIONS TO RESEARCH

The findings of this research reveal a deeper understanding of SCC. Unpacking these findings involves a review of the research hypotheses.

The substantive contribution to theory is the development of the SCCM construct and discovery of the manifestation of PM mirroring with SCCM, identifying causal linkages between PM and SCCM, which support mirroring of these constructs. The substantive contribution to practice is the development of a mirroring framework model, using CD, FC and FAC intervening mechanisms.

Many operational benefits are revealed in this this research, which are attributed to 'high PM - high SCCM'. Cohen and Levinthal (1990) argue that interactions between individuals with diverse and specialised knowledge increases a company's ability to innovate. Kogut and Zander (1992) introduced the concept of 'combinative capability' to describe the competitive importance of integrating knowledge from multiple sources. Data-driven, and decision-enabled SCC processes require integration especially concerning exchange and joint utilisation of decision-making data (Deokar and El-Gayar, 2011).

There is, at present no single theory around which product and SC systems designers might reasonably unite, in terms of PM mirroring with SCCM. Viewpoints and methods invoked by designers tend to be loosely defined. There are many potential advantages of a single theory, particularly with complex systems. The mirroring hypothesis uses configuration entropy as a unifying concept, since systems are either tangible or are perceived to reduce complexity, by the nature of the way we define them. This seeks understanding by examining complex NPD and SCC systems. It avoids pejorative viewpoints about ‘right’ and ‘wrong’ or ‘control’. The principles of modularity, mirroring, connected variety, cyclic progression, preferred patterns and knowledge sharing, were developed throughout this research. Together, these principles form a framework for mapping NPD and SCC, and provide a framework for PM mirroring with SCCM. KM is proposed as a theoretical foundation for building knowledge-based information systems.

Marra *et al.* (2012) identify that outsourcing, NPD, decision support, and risk management are all relevant to SCC. The KM framework developed in this research addresses decision-making challenges in a distributed environment. To prognosticate trends and opportunities in SCC, one only must review some of the vital issues driving the development of manufacturing and logistics in the twenty-first century (Lasi *et al.*, 2014; NRC 199). There is an opportunity for improving SCCM knowledge, by modularising it in a similar manner to PM. The dynamic nature of SCC and the requirement for the concurrent exchange of knowledge between SC practitioners and product designers is addressed by KBT with a focus on module interfaces, and the mirroring PM and SCCM at the product and SCC interfaces.

In OM researchers often design and execute theory development work according to the precepts of the traditional scientific method, which often leads to engagement in progressive extensions of existing knowledge as a way of discovering new knowledge. This orientation most often trains our attention on refining the existing ideas we use to navigate the theoretical world. This approach has dominated the conduct of theory and research in the OM field for many years. These precepts, as widely applicable as they might be and as undeniably useful as they often are, do not encourage the kind of originality we would most like to see (Corley and Gioia, 2011). Advances in knowledge that are too strongly rooted in what we already know delimit what we can know. In organisational study, one of the main consequences of the traditional approach is that we most often focus our attention on construct elaboration. While recognising and appreciating that studying organisations via construct elaboration and measurement has served us well in the relatively short history of the OM field, there remains the sense that something is missing, something which hinders our ability to gain a deeper knowledge of organisational dynamics. It is not the intention of this research to elaborate on PM and SCCM, but to explain the desired effects of mirroring these constructs and propose a means of achieving this mirroring. Focusing too much on refining our existing constructs too often amounts to sharpening the wrong tools for gaining bona fide understandings. What we need instead are new tools. In this work, those new tools are the SCCM construct and a framework for mirroring PM and SCCM.

The theoretical domain of this research expresses a relationship between the NPD and SCC constructs. The operational domain examines a corresponding relationship between PM and SCCM attributes. Theory, or the construct relationships in the theoretical domain, is invaluable in classical confirmatory research since it pre-specifies the composition and structure of the constructs and can guide hypotheses to be tested in the operational domain. The results of these tests can confirm or modify theory, leading to robust theory that can withstand scrutiny in multiple contexts. The SLR reveals key theoretical perspectives, shown below in Table 1-6.

Table 1-6. Theoretical perspectives underlying the SLR

<table>
<tr><th colspan="3">Underlying themes</th><th colspan="5">Theoretical perspectives considered</th></tr>
<tr><td>1</td><td rowspan="2">Modularity</td><td>Modular design</td><td rowspan="5">Transaction cost theory (TCT)</td><td rowspan="5">Network theory (NT)</td><td rowspan="5">Agency theory (AT)</td><td rowspan="5">General systems control theory (GST)</td><td rowspan="5">Knowledge-based theory (KBT)</td></tr>
<tr><td>2</td><td>Integral design</td></tr>
<tr><td>3</td><td colspan="2">Co-development</td></tr>
<tr><td>4</td><td colspan="2">Life cycle</td></tr>
<tr><td>5</td><td colspan="2">Early supplier involvement</td></tr>
</table>

GST addresses the composability and decomposability of systems. Nickerson and Zenger (2004) argue that, when problems are fully decomposable, independent companies can efficiently work in parallel, coordinated by markets. However, as the sub-problems become interdependent and non-decomposable, it is often more efficient to bring the search process within the purview of a single company. Effective across-company collaboration, it is argued, requires a modular technical architecture using hidden information. Clearly delineated task boundaries and codified interface standards are needed to make formal transactions and third-party dispute resolution effective. Consistent with mirroring, the boundaries of companies will correspond to, or mirror the modules in the technical architecture. Causality may run in either direction, from technical architecture to company boundaries or from company boundaries to architecture. Recent contributions to the cross-company theoretical literature do not challenge the mirroring hypothesis, but rather add new concerns to prior theoretical arguments. Wolter and Veloso (2008) point out that obsolescence risk and the need to preserve outside options create forces causing fragmentation: as a result, companies and industries experiencing modular or radical innovations may have a propensity to break apart. Helfat and Campo-Rebado (2009) show that vertically integrated companies may choose to remain integrated even when the underlying technical system is modular, if they anticipate that the designs will later become re-integrated.

KBT assumes that the key problem for organisations is to facilitate flows of information and assemble the requisite stocks of knowledge. Relative to markets, companies have superior capacity for central planning (Alchian and Demsetz, 1972) and rich contextual communication (Arrow, 1974; Monteverde, 1995).

Increasing customer expectations and the digital-physical dimension can be addressed by focusing on a solution oriented rather than product oriented SC. A system of systems approach is required to design complex SC networks. This is especially true as SC's assume global proportions, recognising the concept-to-fruition notion of product and service delivery (Chandra and Grabis, 2016).

1.5.1. Contributions to Practice

Modularity involves rethinking the operation of a company and devising new methods for integrating knowledge across the company. This involves responding rapidly to changing customer requirements and the ability to deliver these requirements in a short time-frame. This research reveals that a framework for mirroring PM with SCCM decisions is desired at the product concept stage.

The aerospace company has been using modularity as part of their operations since the company's formation. Modularity was required because of the company mergers which created this trans-national enterprise. Product modules are made by each partner, with the wings being assembled in the UK. The main sub-assemblies are shipped to France, and Germany where they are assembled, in to the final airplane. This arrangement forced the use of modularity allowing the division of the airplane into distinct modules which could then be developed by different companies. The resultant modular design offers substantial productivity advantage, over the competition.

Knowing which situations PA and SCC design shape each other is important for product and SCC designers. This review cautions managers to take into consideration the contingent factors identified in this research, carefully analysing the presence and strength of these factors and their impact on optimised SCC. There are evident risks in failing to recognise the effects of contingency factors on the mirroring between SCC and PA. Finally, risks can be related to operational and logistics concerns. When logistics costs are of paramount importance, a high integration between buyers and suppliers in terms of geographical proximity and in terms of information sharing is needed regardless of the architecture of the products (Howard and Squire, 2007). The risk is to develop arm's length relations with distant suppliers of modular components at the expense of coordination, quality, and overall logistics costs. This emphasises the requirement for a mirroring framework, at the concept design stage.

1.6. LIMITATIONS

While this study contributes to research and practice, it has limitations. The first limitation is the accuracy of the database search engines themselves. EBSCO Business Source Complete and ProQuest ABI/Inform are the primary databases used. These databases provide full-text access to these articles, in addition to journal and non-journal articles and reports such as business case studies, industry reports, and conference proceedings. These databases are intuitive and effective in narrowing the literature searches. Systematic literature review papers were limited to peer reviewed academic and conference proceedings, this search did not consider non-English speaking authors or non-peer reviewed papers. Given that this is a nascent area of research it might be appropriate to extend the literature research to non-peer reviewed Journals and conference proceedings. The research is limited to ten UoA, offering diversity in terms of product type and the level of the BOM researched.

Positioning this research in the literature Furlan and Camuffo (2014) state that the mirroring hypothesis does not hold for technologically dynamic components and modules and their supply relationships, this is supported by the findings on hypothesis one. This research was limited to the top three levels of the product BOM. It is necessary to go to a lower level of the BOM to support or challenge this proposition. Cabigiousa and Camuffo (2017) state that high levels of PM reflect high levels of ESI. The selected UoA however illustrate low to medium levels of PM, limiting the ability to support or challenge this proposition. In the next Section I will discuss opportunities for further research.

1.7. OPPORTUNITIES FOR FURTHER RESEARCH

This section addresses opportunities for further research.

1.7.1. Context awareness of SCCM

The agenda for future research in mirroring must recognise that SC's increasingly serve their customers by providing solutions (Cavalieri and Pezzotta, 2012), combining physical and digital products as well as services. Linked to physical and digital SC relationships is the subject of inventory ownership, and the fusion between strategic and tactical inventory financing decisions. This further area of research is driven by an increasing need to analyse supply responsiveness, using PM mirroring with SCCM.

1.7.2. Levels of PM and SCCM Mirroring

Further development of the SCCM construct is required to gather further empirical evidence on the relationships between the five contingent factors, outlined in project three. An extension of the analysis on PM mirroring with SCCM could include modelling of the contingent mirroring factors: 1) the complexity of the product architecture; 2) customer requirements definition at the concept stage; 3) SCC performance assessment at the concept stage for closed-loop SCC; 4) the level of SCC process capability within the supply network, and 5) FAC at the product concept stage.

1.7.3. Module Reusability, Reconfigurability and Extensibility

An area of further research could include looking at the impact of PM mirroring with SCCM for different module typologies. One of the underutilized methods of reducing variability is design reuse. Reuse eliminates variability in completion time, and reduces capacity utilisation. Knowing the extent to which a product or SCC module is reusable offers increased PA and SCC agility. Eliminating combinations of modules (due to pair-wise constraints) when calculating the number of reconfigurations would advance the fidelity of this analysis. Ultimately the number of reconfigurations will be a balance between user requirements and cost.

The extensibility factor is used to compare the built-in architectural design options for upgrading, or adding functionality to a product. This factor could be used to evaluate SCC redesign effort associated with product improvements.

1.7.4. Longitudinal Study

The study considered interventions at the conceptual product development stage and PM and SCCM, after product launch. Over the duration of this research if was observed that PM mirroring with SCCM evolved over the product life cycle. It was not possible to study the evolution of PM and SCCM, and the impact of the three intervening mechanisms CD, FC and FAC over time. A longitudinal study could be conducted to investigate how PM and SCCM mirroring evolves post product launch.

1.7.5. Company size

Miller (1987) suggests the SCC structural imperative is relevant to large organisations that enjoy patent and other trade protections. All the case companies in this research are large organisations, with extensive patent portfolios. The odds of successful knowledge transfer in large enterprises, and accordant gains in innovation, are greatest where agglomeration effects are present, as in the case of MNC's. Whilst the research focused on multi-national and transnational companies, a study of small and medium enterprises would be beneficial to understand the relationship between PM and SCCM in smaller scale organisations.

SYSTEMATIC LITERATURE REVIEW

PROJECT 1

2.1. INTRODUCTION

This introduction discusses the rationale and background for the systematic literature review (SLR), the specific purpose of the project and the structure of this paper. The SLR enables an assessment of the quality of individual studies, allowing results of different studies to be evaluated together when these are inconsistent.

2.1.1. Rationale for the project

The SLR was preceded by a scoping study, which identifies and defines the scope of this research. The objective of this SLR is to systematically interrogate existing research literature, address and further refine the research gap identified during the scoping study and subsequent reading. The identified research gap is the limited research on SCC integration with NPD at the product concept stage, which leads to research question one: *"What is the relationship between new product development, product planning and supply chain configuration prior to product launch?"*.

The SLR is defined as "a review that strives to comprehensively identify, appraise and synthesise all relevant studies on a given topic" (Petticrew and Roberts, 2006, p. 19). Tranfield *et al.* (2003) describe the purpose of the SLR in management research is to methodologically search, review, extract and synthesize data in a transparent and replicable manner. Attainment of transparency in approach can be achieved by SLR (Denyer and Tranfield, 2009). This approach seeks to minimise researcher bias. It is important to this research that the research methodology succeeds in providing relevant, unbiased and transparent recommendations to the practitioner community.

While SCC is important to NPD success, it is not clear to what extent SCC knowledge at the NPD concept stage contributes to a company's competitive advantage. The area of research represents three overlapping domains, NPD, product planning and SCC, shown below in Figure 2-1. The SLR contributes to this research by: 1) identifying the linking themes between these concepts; 2) developing the mirroring construct; 3) integrating these concepts, using a knowledge-based view, and 4) developing a conceptual theoretical framework for further research. Project, one is positioned to assess the mechanisms that link these concepts at the NPD concept stage.

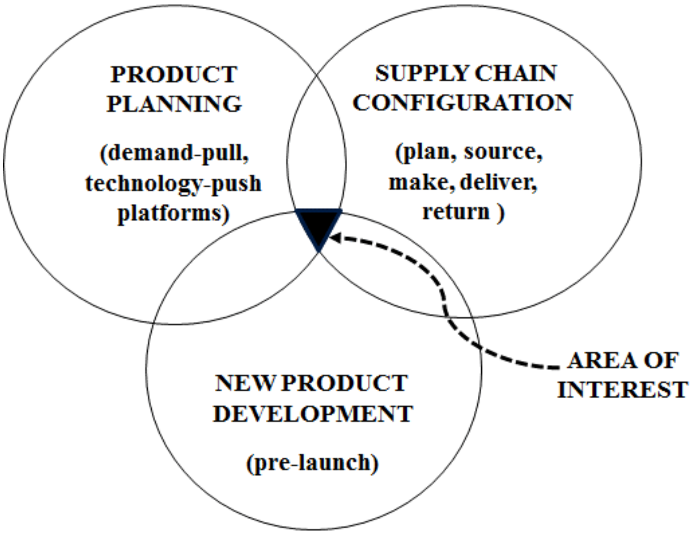


Figure 2-1. Literature domain for the SLR

This SLR identifies four themes that link these concepts; modularity, ESI; co-development of PA and SCC, and a life cycle planning approach to product and process design (Novak and Eppinger, 2001; Salvador *et al.*, 2002; van Hoek and Chapman, 2006, 2007; Doran *et al.*, 2007; Dekkers *et al.*, 2013), with modularity being the strongest of these themes.

2.1.1.1. Research context

There is a growing realisation that SCC value creation begins at the product design drawing board (Krishnan and Ulrich, 2001). PA and its eco-system are largely determined at this stage. While NPD outcomes have been the focus of much research, there is a lack of a comprehensive taxonomy to assist academics and practitioners mirror PA and SCC concepts. This is in no small part due to the complexity and the lack of knowledge sharing between these two domains. Whilst the NPD process has been extensively researched, see NPD definition in Section 2.2.2, Page 67, the SCC definition in Section 2.2.1, Page 65.

SCC is defined along multiple dimensions, these include horizontal extent, vertical extent, objectives and criteria, decisions made, and parameters. SCC has its foundations in SC flexibilities that directly impact on a company's customers. These flexibilities add value from the customers' perspective, and are the shared responsibility of two or more functions within the SC, Vickery *et al.* (1999). Structural SC flexibility refers to a company's ability to adjust their SC organisation to changes in the environment. SC infrastructure planning incorporates SCC, make-or-buy decisions, product life cycle (PLC) planning, and supplier selection (Huan *et al.*, 2004). There are no comprehensive principles for designing structurally flexible SCs (Ksawery, 2012), except for SC infrastructure planning, shown below in Figure 2-2. Few companies succeed in building structural organisation flexibility (Christopher, 1998). Consequently, this area is attracting the attention of practitioners and academics.

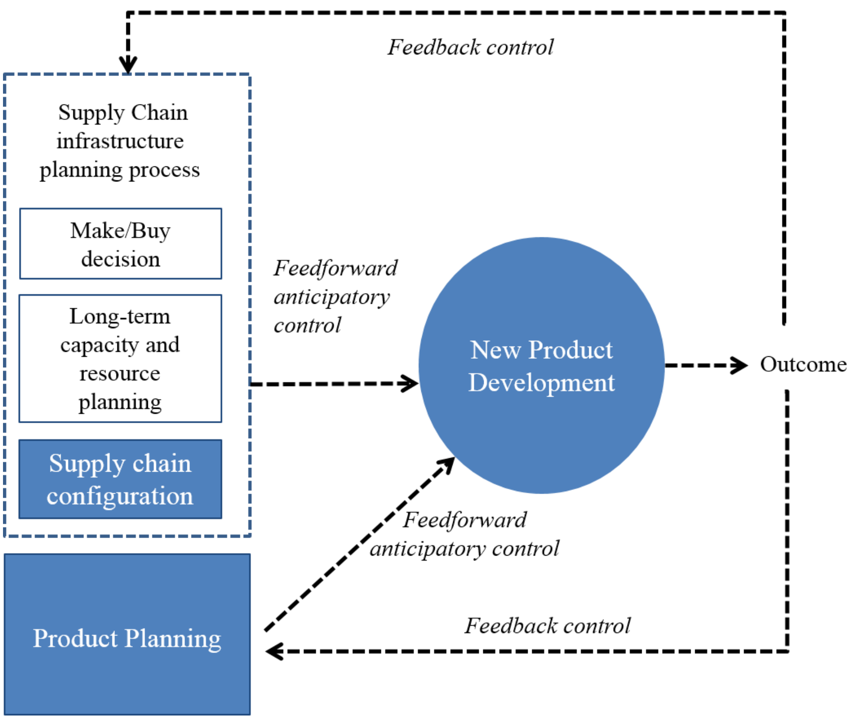


Figure 2-2. Scoping review reference model
Source: Huan et al. (2004)

2.1.2. Structure of the paper

The SLR is organised into six sections, following the process shown in Appendix 2-1, Page 430. Following the definition of the key concepts Section 2.3. outlines the research methodology, including the research protocol; Section 2.4. provides an account of the research findings; Section 2.5. discusses the results, and Section 2.6. provides a synthesis of the results.

2.2. REVIEW QUESTION

In high-tech sectors hyper-competition is increasing the need for a more integrative NPD and SCC. The pressure to launch new-to-market products concurrently or ahead of competitors, is motivated by the emergence of global buyer segments, fear of technological obsolescence, and the need for industry leadership in product innovation (Li *et al*., 2003). The a priori review question: "*What is the relationship between supply chain design and new product design which increases company competency?",* requires insight on the SCC integration with NPD, through systematic inquiry (Pawson *et al*., 2003). The first step in the development of the review question is the definition of the key concepts.

2.2.1. Supply chain configuration

Huan *et al*. (2004) indicate that SCC falls into the category of strategic SCM. Strategic decisions require an understanding of the dynamics of the SC and the development of objectives for the whole chain (Gopal, 1992). Configuration models may be classified into macro models which describe behavior of the whole system with emphasis on strategic decision-making; micro models which are designed to investigate behavior of individual entities involved in the system, and coordination models which are usually designed to coordinate the interactions between macro and micro level models. These models are domain dependent and are designed to solve specific problems. In this research SCC is defined by Amini and Li (2011, p. 313), as "encompassing decisions including the selection of suppliers and manufacturing modes; and locations in the supply chain network to place appropriate levels of safety stock", at a macro-level.

SC network design has recently received increased attention among researchers. SC network involves the number, location, capacity level and technology of the facilities, together with transportation channels and decisions around the levels of inventory required to meet demand. While many high-tech companies have built dynamic SCC, flexibility offering efficient manufacturing and distribution, only a minority of companies have successfully built structural flexibility into their SCs. Structural SCC flexibility challenges current SC network design thinking (Christopher, 1998), and is the ability of the SC to adapt to fundamental change. If the 'centre of gravity' of the SC changes, can the system change? (Christopher and Holweg, 2011). Companies are required to challenge previous thinking and consider: 1) local-for-local alternatives to global sourcing and centralised manufacturing; 2) economies of scope, and scale; 3) increased bandwidth and competency, through asset sharing, and 4) a real options approach to SC decision making. Dell Corporation (Kapuscinski *et al.*, 2004), and Zara (Ferdows *et al.*, 2004) are amongst the few companies that have successfully managed to extend their capabilities to manage demand-driven exogenous turbulence. Dell manages the demand for its components by adjusting prices whilst Zara has developed a vertically integrated 'rapid-fire' SC, capable of rapid response to fashion demand changes, by drawing upon what can be best described as a cluster of small 'modular' factories closely located, in Northern Spain.

Porter (1985) introduced the concept of the value chain, which describes a series of primary activities that add value to the output of the company. Whilst the focus of Porter's model is on the focal company, value is not only by the focal company in the network, but by all entities that are inter-connected. SCC will appear different, depending on a company's position in the network (Croxton *et al.*, 2001). The value chain has been described as the underlying framework of the SC (Skjøtt-Larsen, 1999). Mentzer (2001) considers the existence of different degrees of SC complexity distinguishing between direct, extended, and ultimate SC's. A direct SC consists of a focal company and its direct suppliers and customers; an extended SC includes suppliers of the direct supplier and customers of the direct customer, whilst the ultimate SC includes all organisations involved in the upstream and downstream flows of products, services, finances, and information from the ultimate supplier to the ultimate customer. This research focuses on the extended SC. Competitive advantage can be short-lived, as in the case of Crocs (Marks *et al.*, 2007). Ideas and practices of SCM have largely emerged over a period of relative stability. Until recently, these ideas and practices have not been tested in more turbulent conditions. A new business model is required to deal with turbulence in the SC, shifting to adaptable SCC structures.

2.2.2. New product design

NPD definitions generally focus on either the producer or the customer, where producer-driven definitions are technology-driven, whilst customer-driven definitions are customer-demand driven. Some NPD definitions place emphasis on the different phases of NPD, from concept generation, product planning, product/process engineering, pilot production to ramp-up (Wheelwright and Clark, 1992). There appears to be an assumption in these definitions that products should follow a stage gate process from idea to launch, but this has some disadvantages Cooper (2008), as will be seen in this research. Many companies have embedded concurrent design thinking in their NPD and SCC processes (Khan *et al.*, 2012), however prior research primarily considers SCC during the detailed NPD phase, after the PA has been defined. The focus of this research is to improve the effectiveness of the NPD process, incorporating SCC at the product concept design stage for new-to-market products.

Ulrich and Eppinger (2008) categorise product development into four project types: 1) new product platforms; 2) derivatives of existing product platforms; 3) incremental improvements to existing products, and 4) fundamentally new products. A further new product typology is the classification of breakthrough, platform and incremental products (Wheelwright and Clark, 1992; Pero *et al.*, 2010), shown below in Figure 2-3.

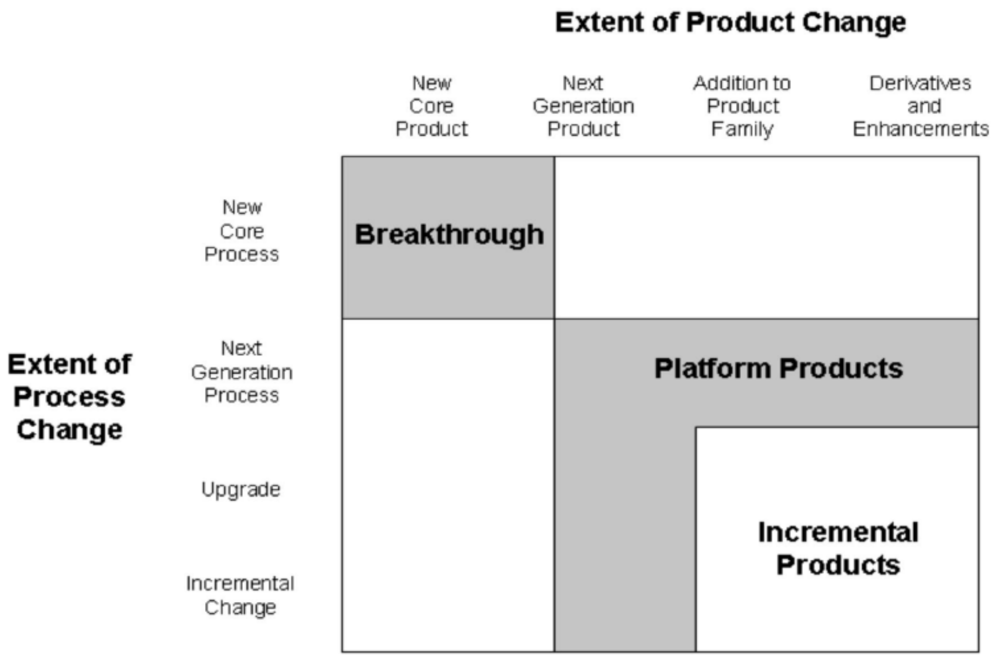


Figure 2-3. New product typology
Source: Wheelwright and Clark (1992)

Krishnan and Ulrich (2001, pp. 1-21) define NPD as "the transformation of a market opportunity and a set of assumptions about product technology, into a product available for sale". Johne and Snelson (1988) suggest that the options for new and existing product lines centre on altering the attributes around either design and engineering, R&D, production management, marketing or economics. Product platform is defined as "a set of final products that are offered by a single company, are partially substitutable in their demands, possess similarities in their functionality, and share the same common design and assembly process" (Salvador *et al.*, 2002, p. 553). Products may share similarities in components used, and associated manufacturing and SCC processes, despite having distinctive market and functional features. This similarity and dissimilarity across the product range has a significant impact on optimal SCC (Huang *et al*., 2005).

New products can be classified as new-to-world, new-to-market and new-to-company, shown below in Figure 2-4. New-to-world product innovations are often transformational, in these cases customers are not always the best guide to NPD success. Griffin (1997) identifies seventy percent of new products as being improvements, cost reductions and additions to existing lines. Research indicates that only ten percent of new products are new-to-market and company (Booz *et al.*, 1982). The size of each circle in Figure 2-4. denotes the number of product introductions relative to the total.

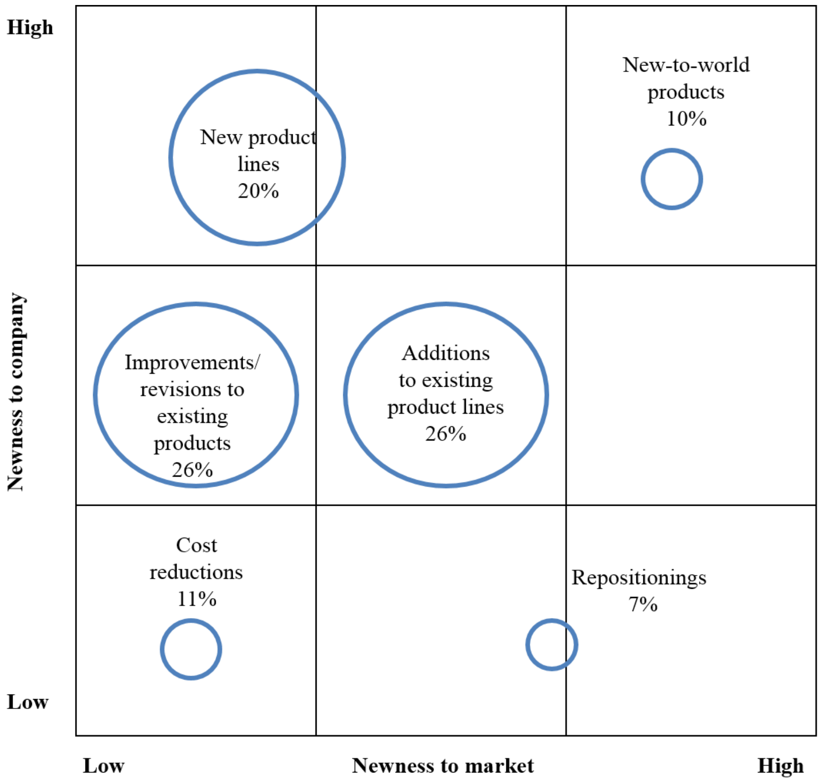


Figure 2-4. New product classification
Source: Booz, Allen and Hamilton (1982)

Since high-tech products have an increasing level of digitisation and software control, the working definition of NPD for this research is 'a differentiated product solution which incorporates a tangible product'.

2.2.3. Product planning

Product planning relates to how companies generate new product ideas, based on inputs from external and internal stakeholders, including marketing, sales and engineering. New products also have different SCCs due to demand patterns, customer locations and market sizes (Butler *et al*., 2006). Product planning involves decisions about the company's target market, product mix, project prioritisation, resource allocation, and technology selection, by product. These decision factors have a significant influence on the probability of product economic success (Mansfield and Wagner, 1975).

There are many examples of NPD failure, where companies perform inadequate product planning. Christensen and Bower (1996) utilise data from the disk drive industry to determine that successful company's sometimes do not recognise technological and, or market shifts because product planning is biased towards existing markets. The working definition of product planning adopted for this research is taken from Wheelwright and Clark (1992), where 'product planning involves decisions about the company's target market, product mix, project prioritisation, resource allocation, and technology selection'.

2.3. METHODOLOGY

The objective of the scoping study is to research the review question, and develop the scope of this research. As discussed in the linking document there is a dearth of empirical research in this area, which led to research question one. The SLR which is a systematic approach to reviewing OM and social science literature, provides a comprehensive overview of academic literature relating to research question one. The SLR sought to review and catalogue the literature that is available and relevant to SCC, product planning and NPD, and act as a foundation for subsequent research. The SLR highlights conceptual, analytical, simulation, statistical and hybrid models, which deal with the decision-making aspects of SCC.

This Section describes the methodology applied; the stages of the SLR process, search strings and databases, inclusion and exclusion criteria, quality criteria, data extraction, synthesis and presentation of the results. The SLR is based on published peer-reviewed papers from academic journals. The starting point for the literature search is the decision on which articles should be retrieved, ensuring that as many relevant peer-reviewed academic papers as possible are located. The search strategy relates directly to the research question and is based on the inclusion and exclusion criteria regarding study design, participants, interventions, outcomes, and language. The SLR protocol was approved by my academic review panel, see Section 2.3.4., Page 89.

The exploratory research in project two addresses research question two: "*how SCCM can be conceptualised considering modularity principles and contemporary supply chains"*, and research question three: "*how is the mirroring of PM and SCCM manifested"*, deduced from project one. This exploratory work identifies relevant and potentially counter-intuitive phenomena that cannot be explained well enough by existing theory, and reveals a need for further testing, to 'explain why something is likely to happen' (Sutton and Staw, 1995). The confirmatory work in project three puts hypotheses two, three and four developed in project one to the test, in specific contexts, to refute, amend, expand or confirm their application as new theory, and define the realm of their applicability. Project three addresses mechanisms, which support the mirroring of PA and SCA. This research tests the mirroring of PA and SCC. The value of any theoretical contribution is determined by its utility, in informing practice and or future research.

2.3.1. Scoping study

The scoping study which relates to the review question enables the systematic gathering and examination of information, to establish strengths, weaknesses and gaps in academic research (Davis *et al.*, 2009). This scoping study was designed to identify the research studies available (Grant and Booth, 2009); identify the current state of understanding of the topic (Anderson and Joglekar, 2005), and determine the value of undertaking an SLR (Arksey and O'Malley, 2005).

The purpose of the scoping study is to ensure that an appropriate research topic has been identified and that research question one is appropriate. The scoping study looks at existing NPD models and frameworks which relate to the mirroring of PA with SCA. Research question one was developed by focusing on current NPD frameworks, and reviewing their suitability in solving the business problem, or lack of SCC integration with NPD. The initial scoping review focused on the development of a frugal innovation framework for aligning NPD and SCC, for new-to-market products, embracing the idea of design for 'radical affordability', using the principles of reverse innovation [4].

Reviewing the barriers to reverse innovation highlighted the significance of 'product planning' in managing profit margin erosion, for existing products. It highlighted that traditional new product and process design processes and inflexible value chains act as a barrier to companies seeking to mainstream ideas from the developing world to the developed world (Mukerjee, 2012). Connecting NPD, SCC and product planning requires a focus on design for affordability and sustainability, whilst considering market competitive intensity (Jaworski and Kohli, 1993).

The scoping study reviewed demand management (DCM) which underpins the philosophy that organisations need to manage processes where value is created, delivered and communicated (Christopher and Ryals, 2014), shown below in Figure 2-5. Cooper (1986) stresses the three stages of DCM should be completed prior to the product concept stage-gate® exit. A demand chain emphasises the needs of the marketplace and designing the chain to satisfy these needs following; provision of customer insight in selecting the value to be delivered; provision of the value that is to be delivered and communication of the value hypothesis specific to target markets. Whilst the product concept must take customers' needs into consideration, the demand chain is outside the scope of this

[4] Reverse innovation is a term referring to an innovation seen first, or likely to be used first, in the developing world before spreading to the industrialized world, Hagel and Brown (2005)

research. The scoping study surveyed existing process-oriented SCM frameworks, to ascertain their coverage of PA mirroring with SCA (Cooper *et al.*, 1997; Fine, 1998; Bowersox *et al.*, 1999; Mentzer, 2001).

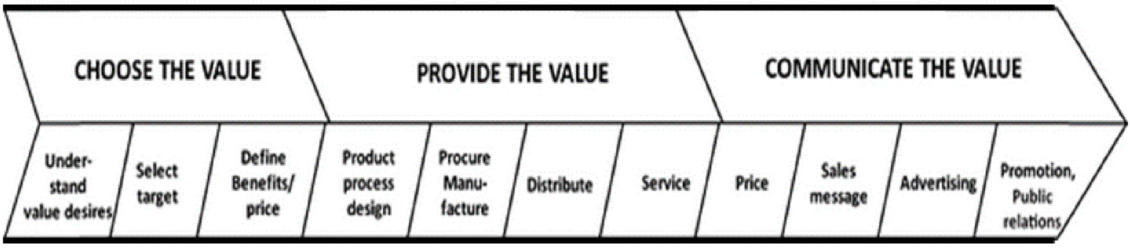


Figure 2-5. McKinsey value delivery system model
Source: Christopher and Ryals (2014)

The supply chain model framework introduced by the Global Supply Chain Forum (GSCF) is built on eight key business processes that are both cross-functional and cross-organisational in nature (Lambert, 2008). The eight processes are customer relationship management, supplier relationship management, customer service management, demand management, order fulfilment, product development and commercialisation, manufacturing flow management, and returns management. GSCF define SCM as 'the integration of key business processes from end user through original suppliers that provide products, services, and information that add value for customers and other stakeholders' (Lambert *et al.*, 2000). Implementation of this framework is performed through SC network, SC business processes, and management components. Whilst this framework provides the structure for developing and bringing new products to market jointly with customers and suppliers (Rogers *et al.*, 2004), it does not address SCC considerations.

The Stage-Gate® NPD process (Cooper, 2001) incorporates open innovation, the flow of ideas, IP protection and technology innovation (Chesbrough, 2003). With eighty percent of PLC cost determined during the product design phase (Dowlatshahi, 1996), it is imperative to understand the interdependencies between PA and SCA, prior to Stage-Gate 3, in the Stage Gate® model, shown below in Figure 2-6. Whilst the Stage-Gate® system provides a structured approach to NPD, it does not adequately address SCC considerations.

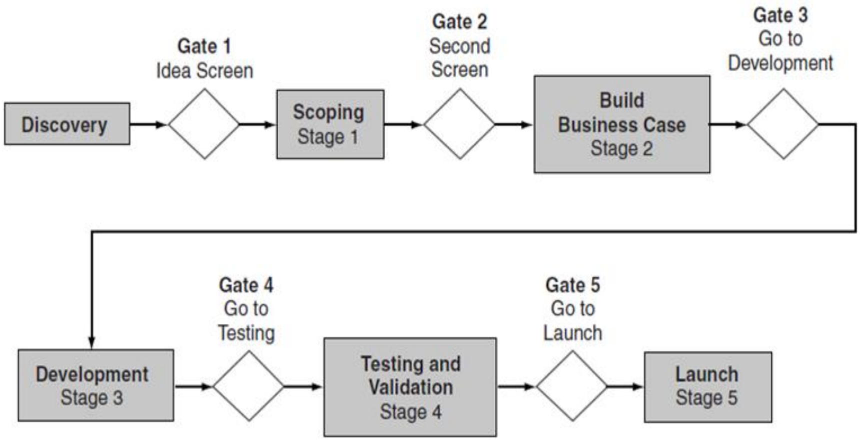


Figure 2-6. Stage Gate® process
Source: Cooper (2001)

The Supply-Chain Operations Reference (SCOR) framework (Supply Chain Council, 1997) includes five business processes; plan, source, make, deliver and return. The SCOR model was developed by the Supply Chain Council (1997) using the Analytical Hierarchical Process (AHP) framework. Whilst SCOR does not address NPD considerations, the accompanying DCOR framework covers NPD, shown below in Figure 2-7. SCC is one of the sub-processes of the SC infrastructure, contained within the SCOR framework. SCOR, as a process reference model developed specifically for integrated SCM has experienced limited success (Stewart, 1997).

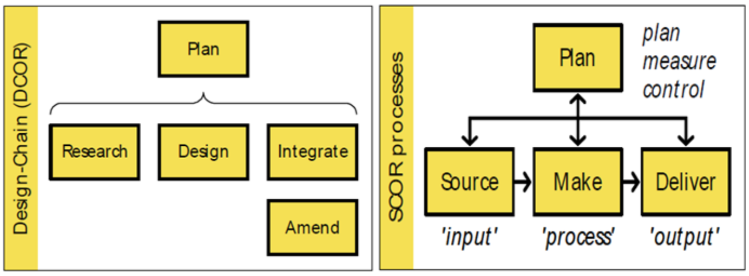


Figure 2-7. DCOR and SCOR framework
Source: Supply Chain Council (1997)

The SLR focuses on the infrastructure planning process (P0), as outlined in the SCOR framework, shown below in Table 2-1. An objective of the SCOR model is to improve the mirroring of the marketplace and the SC., as outlined in Section 2.5.1, Page 138.

Table 2-1. SCOR configuration framework

	Process category Supply chain operations reference model (SCOR) processes			
	Plan	Source	Make	Deliver
Process type				
Planning	P1	P2	P3	P4
Execution		S1-S3	M1-M3	D1-D3
Infrastructure	P0	S0	M0	D0

Notes: P0 - Plan infrastructure; P1 - Plan supply chain; P2 - Plan source; P3 - Plan make; P4 - Plan deliver; S0 - Source infrastructure; S1 - Source stocked products; S2 - Source make-to-order products; S3 - Source engineer-to-order products; M0 - Make infrastructure; M1 - Make-to-stock; M2 - Make-to-order; M3 - Engineer-to-order; D0 - Deliver infrastructure; D1 - Deliver stocked products; D2 - Deliver made-to-order products; D3 - Deliver engineered-to-order products

At the infrastructure planning stage, the focus is on product and SCC design collaboration, focused on product and SC design frameworks, required to successfully develop new products, focused on fulfilling target customer needs, incorporating key elements of SCC. All features of the SCC which impact on the 'delivered' cost or quality, must be incorporated at the product concept design stage.

High-tech products contain increased levels of software, where product features can be software-enabled. Product planning decisions are implemented using four common strategies: commonality, modularity, postponement and scalability (Zhang *et al.*, 2008). Commonality is based on configuring a range of products using a relatively low variety of components. Higher commonality generally leads to higher standardisation and lower SC complexity, but decreases the degree of differentiation among the various product variants. Modularity is based on combining different modules to obtain variety. Hence, deciding on the right mix of module components and the degree of commonality required for developing the optimal modular platform is important, at the concept stage.

Since the SCOR framework lacks a focus on NPD, its usefulness is limited to framing, or visualising product features at the NPD concept development stage, shown below in Figure 2-8.

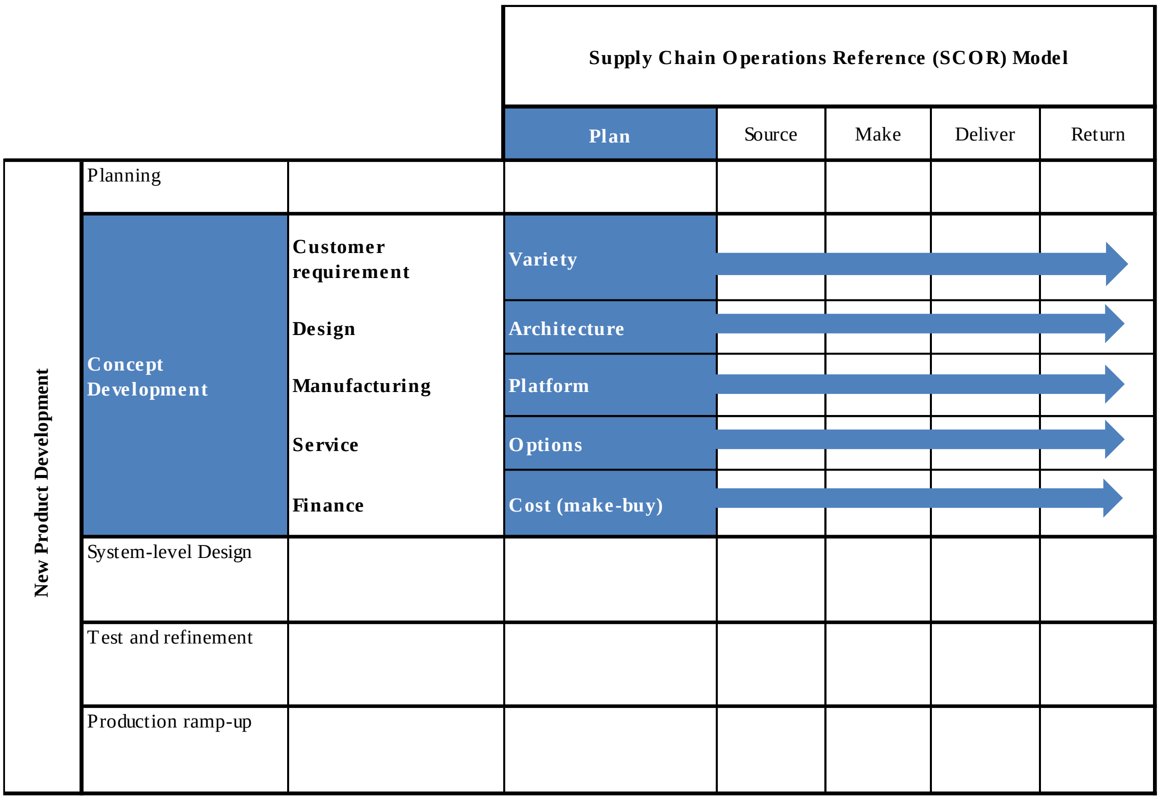


Figure 2-8. SCOR model relating to NPD concept

A fourth framework includes: 1) customer relationship management; 2) product development management, and 3) SCM (Srivastava, 2007). In this framework, the product development is the process where there is greatest requirement for cross-functional involvement (Srivastava, 2007).

A fifth framework (Bowersox *et al.*, 1999) considers operational, planning and control contexts. This framework includes plan, acquire, make, deliver, product design or redesign, capacity management, process design or redesign, and measurement business processes. A detailed description of these processes was not provided, limiting the value of this framework, in this evaluation.

A sixth framework (Mentzer, 2001) presents an SCM framework which focuses on inter-company and cross-company SC relationships. Although business processes are mentioned the processes that require implementation are not delineated. For this reason, this framework is excluded from the evaluation.

Finally, the CE framework has sought to mirror NPD with the product delivery process, with varying degrees of success over the past twenty years. One of the drawbacks of CE is the product performance outcome is not known until the end of the project. Fine (1998) identified shortcomings of 2DCE in SCC design and presented a three-dimensional 3DCE model, shown below in Figure 2-9.

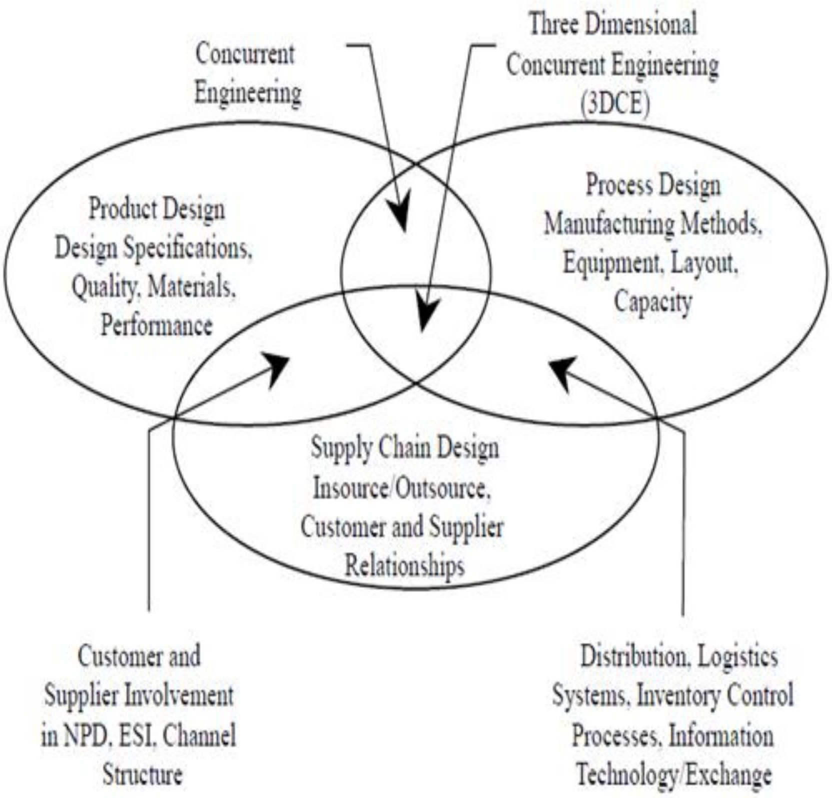


Figure 2-9. 3DCE framework
Source: Fine (1998, p. 146)

Fine's 3DCE framework proposes that only certain product, manufacturing and SC decisions need to be made concurrently, by integrated product teams (Fine, 1998). Whilst 3DCE appears to be a promising approach, few researchers have developed this framework (Fine *et al.*, 2005; Fixson, 2005), shown below in Table 2-2. The source is a Scopus database search conducted on Sept. 6th, 2013. The 3DCE model remains at a conceptual stage, it lacks a theoretical definition and has not been extensively explored in OM literature (Marsillac and Roh, 2014).

Table 2-2. Literature Search History

	pre-1990	1991-2000	2001-2005	2006-2010	2011-2013
Concurrent Engineering	94	4669	5466	9081	2957
3D Concurrent Engineering (3DCE)	0	1	8	24	1

A weakness of 3DCE is its engineering bias, and lack of customer involvement in the product innovation and diffusion process. The core 3DCE concept definitions are shown below in Table 2-3.

Table 2-3. 3DCE concept definitions
Source: (Marsillac and Roh, 2014)

Core 3DCE concepts	Definition	Author(s)
Product design / development	A deliberate process involving hundreds of decisions, with the intent of developing a tangible, physical product	Krishnan and Ulrich (2010)
Manufacturing process	The activities responsible for the production of tangible, physical products	Hayes and Wheelwright (1979) Skinner (1985)
Product design and manufacturing	The inter-dependencies that arise from the processes influence of product characteristics and the process activities required to produce them	O'Driscoll (2002) Fixson (2005) Forza *et al.* (2005)
Supply chains	Complex partner interactions with the purpose of conveying materials, products, information and capital from source to consumer and back	Fisher (1997) Christopher and Towill (2002) Lee (2004)
Product design and the supply chain	The inter-dependencies that arise from the influence of product characteristics on the supply chain activities required to convey them	Fisher (1997) Vonderembse *et al.* (2006)
Manufacturing process and the supply chain	The inter-dependencies that arise from the influence of process characteristics on the supply chain activities that follow	Saad and Gindy (2007) Cagliano *et al.* (2008)

‘Despite the undeniable appeal and importance of co-coordinating decisions across product, manufacturing process and SC design to science and practice, we know very little about how to do so to maximise operational, SC and company performance’ (Rungtusanatham and Forza, 2005). SCM World offer a model for the relationships between product, supply and demand, shown below in Figure 2-10. This model however lacks a focus on SCC and product planning, and does not offer a framework for mirroring PA with SCA.

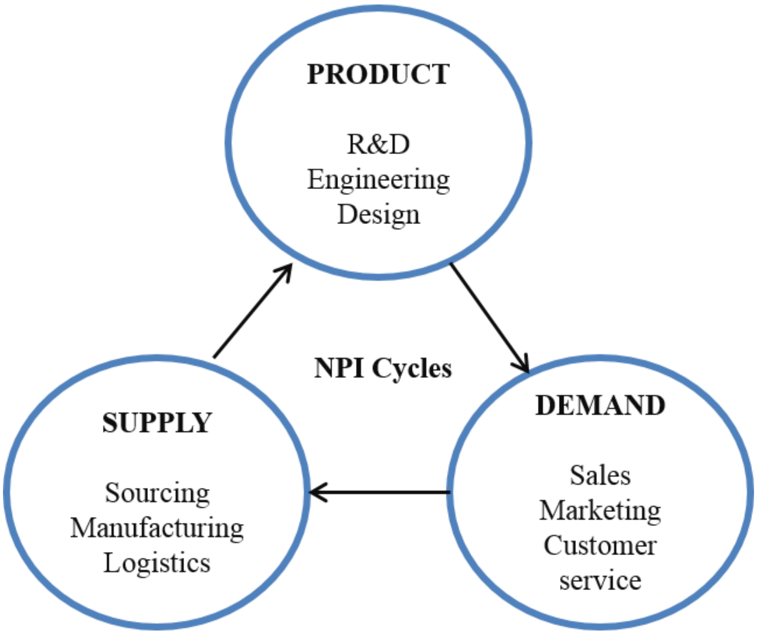


Figure 2-10. NPI value creators
Source: SCM World (March 2013, p.1.)

Product complexity challenges PA and SCC mirroring (Novak and Eppinger, 2001) and requires the adoption of innovative product design and development processes (Rycroft and Kash, 1999). There is growing recognition that specifying a set of business model elements, and relationships, is like giving a business model designer a box of Lego blocks (Bürgi *et al.*, 2004). A focus on innovation, and product variety is driving a requirement for business model change, offering a framework for implementing innovation-led change (Linder and Cantrell, 2000). Amit and Zott (2001) perceive the business model as a locus of innovation, while Mitchell and Coles (2003) see business model innovation as a source of competitive advantage. There is evidence that companies offering innovative designs such as Apple Inc., follow the four stages of innovation framework, shown below in Figure 2-11 (Tidd *et al.,* 2005). The horizontal axis represents NPD and SCC design, the vertical axis dimensions ‘Position’ and ‘Paradigm’ represent product positioning, and product platform development. The paradigm dimension is represented for example by the i-tunes platform developed by Apple Inc., integrating Apple devices across a common IT platform, offering digital content, device software and support. The position dimension is represented by Apple's drive for strong market share in each market sector.

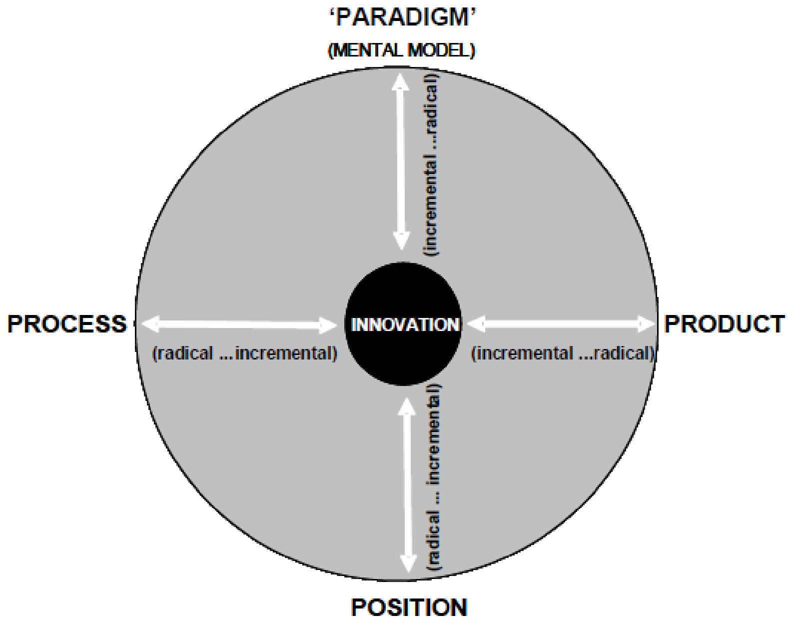


Figure 2-11. Innovation space
Source: Tidd et al. (2005)

SCC innovation focused on the demands of lean in the 1980s (Womack *et al.*, 1990); supply networks and the resource-based view in the 1990s (Womack *et al.*, 1990; Jarillo and Stevenson, 1991; Nishiguchi, 1993), and outsourcing (Lee, 2004); decision support tools (Blackhurst *et al.*, 2005), and sustainability (Srivastava, 2007), in the 2000s. During the 2010s the focus has shifted to cloud-based IT platforms (Wu *et al.*, 2015); trade-offs between sustainable and economic factors (Brandenburg, 2015); reliability (Yildiz *et al.*, 2016), and integrated SC reconfiguration frameworks (Chandra and Grabis, 2016, p.83). The scoping study highlights the usefulness of change models, mapping the migration to effective SCC design. Change models can be classified at four levels; realisation, renewal, extension and journey models, shown below in Figure 2-12. This scoping study identifies the need for a business model change, involving an extension or journey model.

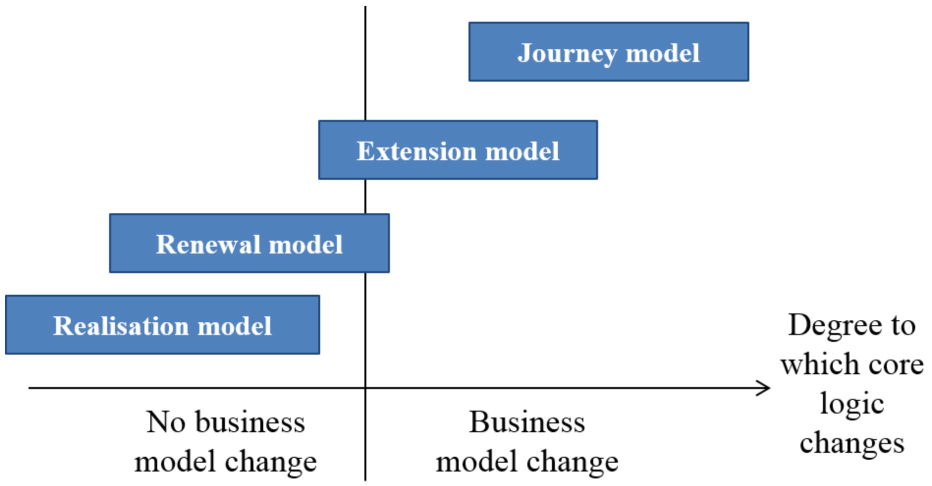


Figure 2-12. Change models
Source: Linder and Cantrell (2000)

There is empirical evidence that supports the relevance of business model innovation, shown below in Figure 2-13. This research illustrates the positive relationship between business mode innovation and business profitability.

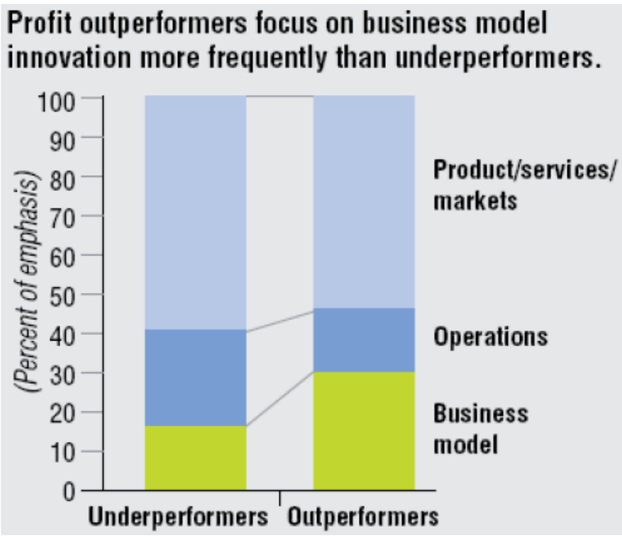


Figure 2-13. Business Model innovation
Source: SCM World (March 2013, p.1)

2.3.2. Preliminary literature review

I initially identified the following sources of literature that were potentially relevant for my SLR, shown below in Table 2-4. These sources included broad categories such as academic research and practitioner-oriented articles and Journals. On-line databases ProQuest, EBSCOhost, JSTOR, Web of Science, CRES and the Cranfield University library catalogue were used for accessing academic publications.

Table 2-4. Initial literature sources

Source	Value to the review
Academic Journals	Primary source of published academic research
Academic texts	Secondary source of published academic research
Conference papers and proceedings	Primary source of un-published academic research
Practitioner research reports	Primary source of practitioner oriented data
Material requested from practitioners in the field	Tertiary source of in-process academic research

A preliminary literature review identified literature addressing PA and SCC decision-making as central to the review question, shown below in Table 2-5. A sample of papers discussing PA and SCC were selected for critical analysis during the scoping review. The benefits of SCC at an early stage of NPD are documented in the NPD oriented and SC oriented literature (Fine *et al.*, 2005). The NPD oriented literature is based on the ‘constraints’ anticipation concept, applied to SCC related issues, whilst the SCC oriented literature is concerned primarily with how to design, plan and manage the SC, based on new product features.

SC literature has traditionally examined procurement and value-adding activities, without explicitly defining product development. The preliminary literature review identifies the need to mirror SCC with NPD, ensuring product availability at the product launch date (van Hoek and Chapman, 2006). Khan *et al.* (2012) identify a positive correlation between

SC responsiveness and SC resilience after aligning product design and the SC. Make-or-buy decisions, long-term capacity and resource planning are components of the SC infrastructure planning process (Stewart, 1997), these operational factors are excluded from the scope of this SLR. Nascent research has focused on PA and SCC attribute mirroring (Abdelkafi *et al.*, 2010; Pero *et al.*, 2010; Stavrulaki and Davis, 2010).

Table 2-5. Selected preliminary academic papers

Approach (orientation)	Authors (year of publication)	Product architecture	Supply chain configuration
New product development	Fine (1995)	X	X
	Brown and Eisenhardt (1995)	X	X
	Ulrich (1995)	X	
	Lee and Sasser (1995)		X
	Erens and Verhulst (1997)	X	
	Lee and Tang (1998)	X	X
	Hsuan (2001)	X	
	Novak and Eppinger (2001)	X	X
	Krishnan and Ulrich (2001)	X	X
	Fixson and Clark (2002)	X	
	Peterson *et al.* (2005)	X	X
	Fixson (2005)	X	
Supply Chain configuration	Fisher and Ittner (1999)	X	
	Randall and Ulrich (2001)		X
	Salvador *et al.* (2002)	X	X
	Fixson and Clark (2002)	X	
	Fixson (2005)	X	
	Graves and Willems (2005)	X	X
	Hoetker (2006)	X	X
	Doran *et al.* (2006)		X
	Ro *et al.* (2007)		X
	Pero *et al.* (2010)		X
	Ulku & Schmidt (2011)	X	X
	Dekkers *et al.* (2013)	X	X

A preliminary literature review identified five academic papers which highlight the significance of SCC mirroring with NPD at the concept stage, shown below in Table 2-6. These papers were published between 2000 and 2005. In sectors as diverse as aerospace, automotive, telecommunications and fashion, product development has become a collaborative, SC-based process that is critical to competitive performance (Bidault *et al.*, 1998). These papers illustrate the diverse approach to research in this area.

Table 2-6. Preliminary critical literature review

	Paper Title	Authors	Year of Publication	Journal
1	Optimizing the Supply Chain Configuration for New Products	Stephen C. Graves, and Sean P. Willems	2005	Management Science, Vol. 51, No. 8, August 2005, pp. 1165-1180
2	Sourcing by Design: Product Complexity and the Supply Chain	Sharon Novak and Steven D. Eppinger	2001	Management Science, Vol. 47, No.1, January 2001, pp. 189-204
3	Supplier integration into new product development: coordinating product, process and supply chain design	Kenneth J. Petersen, Robert B. Handfield and Gary Ragatz	2005	Journal of Operations Management, Vol. 23, Iss. 3-4, 2005, pp. 371-388
4	Product Development Decisions: A Review of the Literature	V. Krishnan, V., and Karl T. Ulrich	2001	Management Science, Vol. 47, No.1, January 2001, pp. 1-21
5	Towards a General Modular systems theory and its application to inter-firm product modularity	Melissa A. Schilling	2000	Academy of Management Review, Vol. 25, Iss. 2, pp. 312 -334

Three of the papers look cross-industry, at material selection, supplier selection, supplier integration and inter-company modular systems, while two papers focus on supplier, part, and process selection, and the role of asset specificity in the make-buy decision. An analysis of these five papers is shown below in Table 2-7.

The PLC has an impact on SC strategy (Aitken *et al.*, 2003). Vonderembse *et al.* (2006) acknowledge the need to consider the PLC during the SC planning phase, and point to gaps in the research on PLC in the product concept development stage.

Table 2-7. Critical literature review assessment

	Paper Title	Authors	Phase of NPD	Area of Supply Chain Configuration	Context	Research Methodology	Theme
1	Optimizing the Supply Chain Configuration for New Products	Stephen C. Graves, and Sean P. Willems	Product Development	Supplier, part, process and transportation (options) selection	Mature PC company Tiered supply chain Mature Industry Fast Clockspeed Competitive market-place	Target Costing Model development	Concurrent development
2	Sourcing by Design: Product Complexity and the Supply Chain	Sharon Novak and Steven D. Eppinger	Product Concept	Vertical Integration (insourcing) and the role of asset specificity	Luxury automotive sector Study of components in eight vehicles over five overlapping five year periods from 1980 - 1995, in eight companies	Qualitative survey	Modular design
3	Supplier integration into new product development: coordinating product, process and supply chain design	Kenneth J. Petersen, Robert B. Handfield and Gary Ragatz	Product Development	Supplier selection and integration	A study of supplier selection, and integration across automotive, electronics, computer, chemical, consumer products, and semiconductor industries, in Asia, Western Europe, US/Canada and South America.	Questionnaire survey	Early supplier involvement
4	Product Development Decisions: A Review of the Literature	V. Krishnan, V., and Karl T. Ulrich	Product Concept development, and market launch	The authors focus on supplier and material selection, design of the production sequence and project management decisions within a single firm.	The authors selected cases from the electronics, computing, software, text books, bicycles, and aerospace industries, to assess inter-firm modular systems	Literature review	Modular design
5	Towards a General Modular systems theory and its application to inter-firm product modularity	Melissa A. Schilling	Product Concept	The authors focus on inter-firm modular systems, drawing on systems research from many disciplines.	The research looks at systems research within many disciplines. The authors refer to research on technological, social and biological modularity. They use selected cases from electronics, computing, software, text books, bicycles, and aerospace.	Literature review	Modular design

Given the growing complexity of products in many fields and the growing acceptance of time as a competitive factor (Stalk, 1988), companies must use the capabilities of suppliers more effectively during NPD. Supplier involvement in NPD varies greatly depending on the suppliers' capabilities, and willingness to collaborate in the NPD process. Wynstra and Pierick (2000) identified four types of supplier involvement in NPD; strategic development, critical development, arm's length development and routine development. Research by Brown and Eisenhardt (1995) indicate that supplier involvement and performance associated with ESI in NPD is inconclusive and in many respects, imprecise. McCutcheon *et al.* (1997) establish that the supplier-buyer linking process during the component development task is more important than the actual technical outcome, at least in shaping the opinions of product designers. Whether the OEM is prepared to use that supplier in NPD projects is more related to the cooperativeness of the supplier than to the supplier's contribution to technical success. Moreover, in the eyes of the respondents, much of the contribution to technical success could be attributed to the supplier's cooperativeness, through a more complete understanding of the problems of the product developers, and their quick response and willingness to mesh smoothly with the agenda of the product developer. Research on ESI in the NPD process tends to exclude the dynamics and factors influencing supplier involvement, supplier design responsibility and buyer/supplier communication (Hartley *et al.*, 1997). The movement of activities earlier in the NPD process requires a re-examination of the total supply network (McIvor *et al.*, 2006).

This preliminary review was limited to the relationship between NPD, product planning and SCC prior to product launch. There is a clear lack of a framework for aligning these three concepts. Perceived gaps in academic research are identified, shown below in Table 2-8.

Table 2-8. Perceived gaps in academic research

	Paper Title	Authors	Approach	Weaknesses of the research	Influencers	Theme
1	Optimising the Supply Chain Configuration for New Products	Stephen C. Graves, and Sean P. Willems	Target Cost model development	Weak consideration of supply networks; inventory allocation; supply constraints and uncertainty around supply and demand.	Sourcing decisions Inventory decisions	Concurrent development
2	Sourcing by Design: Product Complexity and the Supply Chain	Sharon Novak and Steven D. Eppinger	Review of the relationship between product complexity and vertical integration	Research does not consider the governance structure; ownership structure and information exchange within Keiretsu relationships.	Asset specificity	Modular design
3	Supplier integration into new product development: coordinating product, process and supply chain design	Kenneth J. Petersen, Robert B. Handfield and Gary Ragatz	Review of the Tier structure in supply chains, and a study of the coordination of ESI	There is no examination of how relational rents are distributed among alliance partners; given the poor track record of many alliances, further research might examine the factors that impede the realization of relational rents.	Early supplier integration	Early supplier involvement
4	Product Development Decisions: A Review of the Literature	V. Krishnan, V., and Karl T. Ulrich	Study of product development, decisions from product, product portfolio, and product architecture perspectives	Relatively little attention has been paid to the product development supply chains.	Product Architecture	Modular design
5	Towards a General Modular systems theory and its application to inter-firm product modularity	Melissa A. Schilling	Focus on product modularity, within the product architecture, and inter-firm.	The researchdoes not identify explicit links between modularity constructs.	Product Architecture	Modular design

Current SCC models focus primarily on inventory investment and location decisions and the minimisation of total SC costs (Graves and Willems, 2005; Bossert and Willems

2007). While some studies seek to balance the need for product availability with the need for minimising costs, other studies highlight the complexity of multi-echelon SCs, questioning the validity of less complex models. Prior models do not consider the mirroring of business processes among SC partners and structural SC flexibility (Nepal *et al.*, 2005). The preliminary thematic review identified many theoretical perspectives which require further research, shown below in Table 2-9. A research agenda was proposed to address perceived research gaps, using the SLR methodology.

Table 2-9. Preliminary thematic review

	Paper Title	Authors	Theory	Origins of primary theory	Secondary Theory	Origins of secondary theory	Theme
1	Optimizing the Supply Chain Configuration for New Products	Stephen C. Graves, and Sean P. Willems	Emerging multi-tier supply chain theory	Mena, Humphries and Choi (2013)	Resource based view	Barney (1991)	Concurrent development
2	Sourcing by Design: Product Complexity and the Supply Chain	Sharon Novak and Steven D. Eppinger	Transaction Cost Economics	Coase (1937) Williamson (1975, 1985)	Property rights approach	Grossman and Hart (1986)	Modular design
3	Supplier integration into new product development: coordinating product, process and supply chain design	Kenneth J. Petersen, Robert B. Handfield and Gary Ragatz	Resource-dependency stream of organization theory	Pfeffer and Salancik (1978)	Transaction Cost Economics and Behavoural theory of firms	Coase (1937) Williamson (1975, 1985), Dyer and Singh (1998)	Early supplier involvement
4	Product Development Decisions: A Review of the Literature	V. Krishnan, V., and Karl T. Ulrich	Scientific method, inductive approach		Modularisation and Value transfer theory	Doran *et al.* (2007)	Modular design
5	Towards a General Modular systems theory and its application to inter-firm product modularity	Melissa A. Schilling	Systems Theory	Simon (1962), von Bertalanffy (1969)	Functionalist Control	Wiener (1950)	Modular design

Whilst the scoping study indicates the lack of mirroring between NPD and SCC activities as a reason for NPD under-performance (Ellram *et al.*, 2008) and the notion that this lack of mirroring between NPD and SCC is one of the key reasons for product failure Chiu Ming-Chuan *et al.* (2011), there remains a gap in knowledge as to the strength of this hypothesis. This gap requires an in-depth SLR.

2.3.3. Research question one

The scoping study identified a research gap, in SCC integration with NPD at the product concept stage, which lead to research question one; *"What is the relationship between new product development, product planning and supply chain configuration prior to product launch?"*. This gap requires an understanding of prior research on the themes linking

NPD, SCC and product planning, at the concept stage, and the SCC and product planning decisions which influence the performance of NPD.

2.3.4. Systematic literature review protocol

The SLR methodology uses the approach developed by Tranfield *et al.* (2003) and Petticrew and Roberts (2006). An SLR is an evidence-based approach which originated in the medical science field. Its aims are to improve decision making (Tranfield *et al*., 2003). Management reviews are typically narrative reviews that provide mainly descriptive accounts of the literature. These reviews differ significantly from SLRs which adopt "a replicable, scientific, and transparent process" and provide an "audit trail of reviewer's decisions, procedures and conclusions" (Tranfield *et al.*, 2003, p. 209). An SLR attempts to reduce reviewer bias and provide a critical account of the available evidence. The objective of this critical account is to provide a solid research foundation and develop research hypotheses contributing to academic literature, and practice. SLRs facilitate the identification of common, general and conclusive evidence (Tranfield *et al.*, 2003). SLRs also provide opportunities to challenge existing knowledge and established schools of thought (Petticrew and Roberts, 2006).

In this Section I will outline the SLR protocol. The academic review panel members from Cranfield School of Management, provided expert guidance on the SLR protocol.

2.3.4.1. Academic review panel

My review panel consisted of subject matter, theory and methodology experts ensuring the quality, reliability, and validity of the systematic review process and outcome. The panel reviewed the scoping study, approved the protocol, and provided guidance on inclusion/exclusion criteria of research studies (Tranfield *et al.*, 2003), shown below in Table 2-10. Dr. Carlos Mena Madrazo who was a panel chair during project one and project two, took a position as Assistant Professor in the Department of Supply Chain Management at Michigan State University, and was replaced on my panel by Dr. Soroosh Saghiri, with Dr. Palie Smart taking the role of panel chair for project three.

Table 2-10. Academic review panel members

Panel Member	Title/Organization	Role
Dr. Heather Skipworth (Supervisor)	Lecturer, Centre for Logistics and Supply Chain Management/DCM. Heathers expertise is in Manufacturing and Management.	Heather's expertise provided feedback on all aspects of the systematic literature review, and empirical research
Dr. Palie Smart (Panel Chair 2014-17)	Lecturer, Doughty Centre for Corporate Responsibility/IPM.	Palie provided advice, literature recommendations, and research direction
Dr. Carlos Mena Madrazo (Panel Chair 2012-14)	Lecturer, and Director of the Centre for Strategic Procurement and Supply Management and head of the Executive Procurement Network (EPN).	Carlos provided support on the search methodology, and research direction
Dr. Soroosh (Sam) Saghiri	Lecturer, Centre for Logistics and Supply Chain Management/DCM. Soroosh's expertise is in supply chain planning and supplier development.	Sam provided advice and literature recommendations
Ms. Heather Woodfield	Social Sciences Information Specialist, Kings Norton Library, Cranfield University.	Heather provided advise on literature searches and database management

2.3.4.2. Literature search strategy

The search strategy involved the identification of keywords, terms and phrases derived from the scoping study, the preliminary literature search, and discussions with panel members. The initial search of EBSCO and ABI/Inform (ProQuest) databases identified further articles through cross-referencing. A step-by-step search protocol was followed, shown below in Figure 2-14. Systematic data extraction and an assessment of data quality were performed. The literature search included conference proceedings from the CIRP Conference on Manufacturing Systems, and the Production and OM (POMS) annual conference proceedings. The CERES academic research database was reviewed for relevant UK academic papers, without locating any relevant research papers.

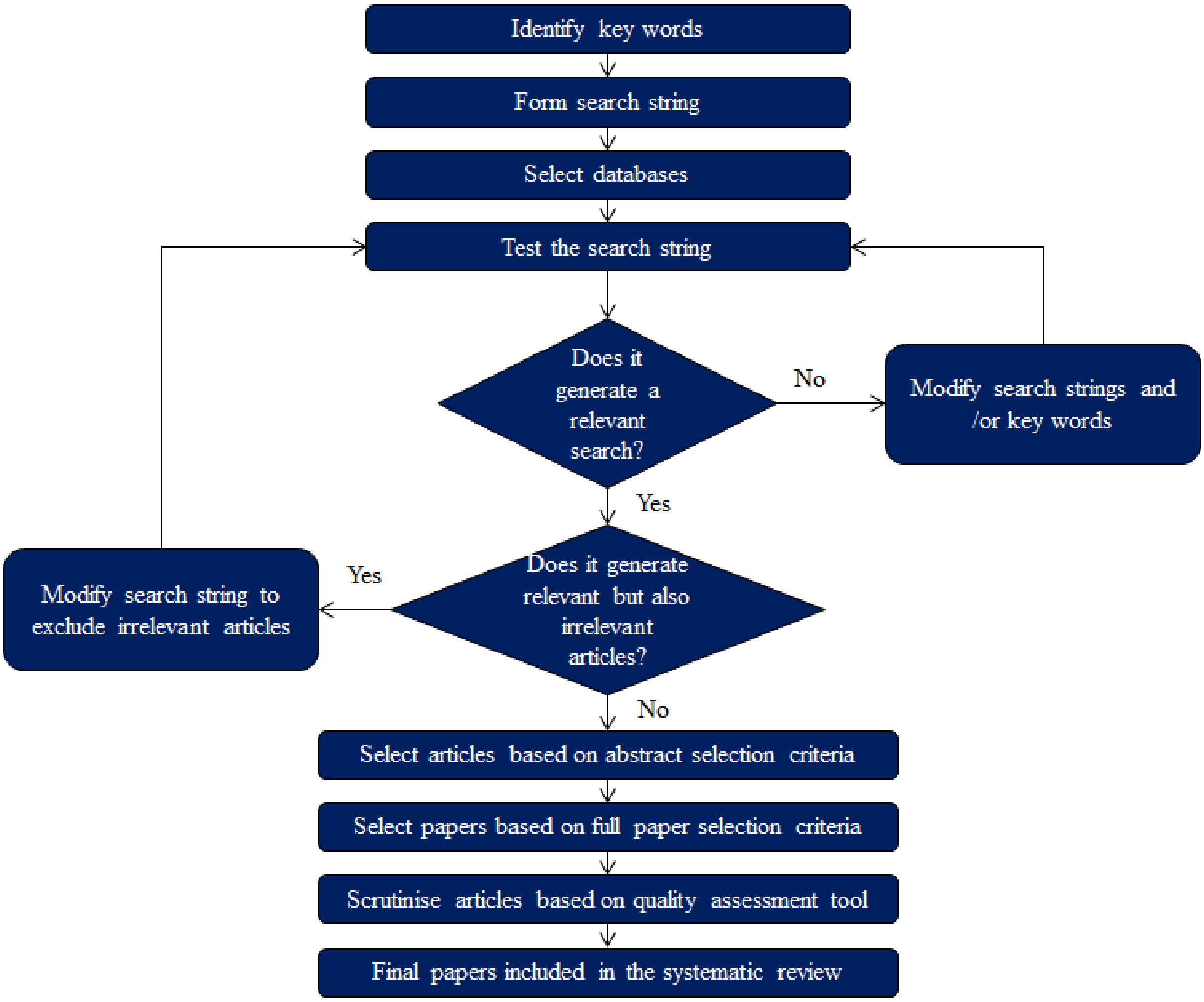


Figure 2-14. Search strategy

The review comprises of three concepts, NPD, SCC and product planning. To aid in the development of search strings, each concept domain was deconstructed into sub-domains, by reviewing highly cited academic papers, in this area of research, shown below in Table 2-11.

Table 2-11. Development of literature search strings

Author	Construct	Definition
Krishnan and Ulrich (2001)	New product development	The transformation of a market opportunity and a set of assumptions about product technology, into a product available for sale
Wheelwright and Clark (1992)	Product Planning	Decisions about the company's target market, product mix, project prioritization, resource allocation, and technology selection
Ülkü and Schmidt (2011)	Supply Chain Configuration	Design of supply chain depends on whether Product development is done internally by the manufacturer in an integrated supply chain or in collaboration with a supplier in a decentralized supply chain
Huang *et al.* (2005)	Supply Chain Configuration	Supplier selection, selection of transportation delivery modes, determination of inventory quantities and stocking points, manufacturing processes to use and production time
Amini and Li (2011)	Supply Chain Configuration	Selection of suppliers, manufacturing and transportation modes, as well as locations in supply chain network to place appropriate levels of safety stocks

The keywords were carefully selected to reflect a variety of opinions from a wide selection of academic papers. Search strings were selected to allow the literature search to locate academic articles which address the area of interest, regardless of the actual words used by authors, expressing the research domain. Key terms were built into expanded search strings. 'Product w/3 design' is an example of a search string as it picks up product design, design of new products, design for innovative product development. These phrases are used in practice, and in academic literature. The search strings were combined using an 'AND' statement, building the following search strings, shown below in Table 2-12. The search strings vary slightly between the primary EBSCO Business source and ABI/Inform (ProQuest) databases.

The SLR followed a twelve-stage process:

1. Initial search of the academic databases
2. Review of papers to select core papers
3. Selection of additional papers found from review of core paper references
4. Critical review and data extraction of core papers
5. Selection of additional papers from full core paper critical review references
6. Post full paper critical review and data extraction, coding development and saturation
7. Re-run of database searches
8. Presentation of summary findings of data deduced from relevant empirical studies
9. Development of the results
10. Synthesis of the results
11. Discussion of findings
12. Re-run of database searches, repeating stages 4 to 11 above.

The stages were approached in sequential order. During stage four many strong themes, modular design, and the importance of ESI became evident, from the data. The open coding development began during stage four. During stage six, after full text screening and the coding development, the ideas on synthesis were developed.

Table 2-12. Search strings

Concepts		Search terms	Search strings (EBSCO)	Search strings (ABI/Inform)
A	New product development	Product design, Product prototype, Product introduction, Product development, Product concept development, New product introduction, New product effectiveness, Technology management, Technology development, Clockspeed, Hypercompetition, Velocity	(Product* w3 (design or prototyp* or introduc* or develop* or effective*)) or (Technolog* w3 (manag* or develop*)) or clockspeed or hypercompetition or velocity	(Product* w/3 (design or prototyp* or introduc* or develop* or effective*)) or (Technolog* w/3 (manag* or develop*)) or clockspeed or hypercompetition or velocity
B	Supply chain configuration	Supply chain configuration, Supply chain planning, Supply chain infrastructure, Supply network, Supply base management, Infrastructure planning, Logistics capabilities, make/buy, Sourcing, Procurement, Capacity planning, Resource planning	(Supply w3 (configure* or planning or infrastructure or network* or management)) or ((infrastructure or capacity or resource*) w3 planning) or "logistics capabilities" or sourcing or procurement*	(Supply w/3 (configure* or planning or infrastructure or network* or management)) or ((infrastructure or capacity or resource*) w/3 planning) or "logistics capabilities" or sourcing or procurement or "make or buy"
C	New product planning	Product planning, product development, product line management, product ramp-up, product phase-in, product phase-out, make/buy	Product w3 (planning or development or line or ramp* or phase*) or “make or buy”	Product w/3 (planning or development or line or ramp* or phase*) or "product platform" or "target market" or "product mix" or "technology select*"
Results			197 results - 9th March, 2014 NPD, SCC and product planning	90 results - 8th March, 2014 NPD, SCC and product planning
			549 results - 9th March (EBSCO) NPD and SCC only	221 results - 9th March (ABI/Inform) NPD and SCC only
			2594 results - 17th March, 2014 NPD and product planning only	

The limiters for this review included published academic articles from 1st January 1995 to the 9th March 2014. The literature search commenced from 1st January 1995 as most academic research on SC has been conducted since this date, shown below in Figure 2-15. This method follows Burgess *et al.* (2006) and Giunipero *et al.* (2008), who observed that increasing publication in SCM has occurred since 2000. Limiters also included, English language and peer-reviewed academic articles. Process and services industries were excluded from the review.

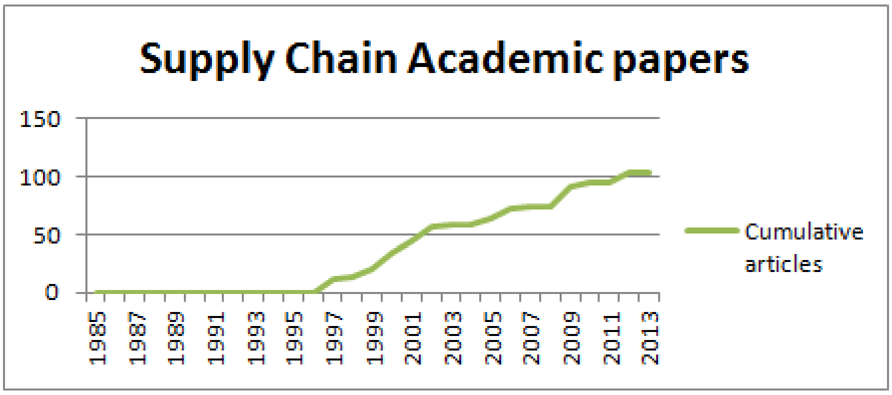


Figure 2-15. Chronology of Research papers on Supply Chain Management
Source: Dr Janet Godsell, Warwick Manufacturing Group

All the retrieved papers on NPD were published after the seminal paper by Brown and Eisenhardt (1995) in which the authors built a model of factors which affect the success of NPD. These authors studied innovation at macro (country and industry), and micro (company) levels, and identified three streams of academic research on product development; rational plan, communication web and disciplined problem solving. The rational plan adopts mainly an atheoretical approach; the communication web follows an information theory, and resource dependent route; and the disciplined problem-solving approach follows an information theory question. The authors highlight that in fast clockspeed industries, the disciplined problem-solving model, is the most appropriate.

In addition to the primary ABI/Inform and EBSCO databases, the Web of Science, Scopus, Zetoc and Sage Journal databases were accessed, shown below in Table 2-13. These additional database searches, located limited relevant academic articles.

Table 2-13. Primary databases

Database	Description
ABI/Inform (ProQuest)	Over 3,900 publications in business and economics.
EBSCO	Over 3,700 scholarly business publications.

The methodology used to search these databases follows that of Pittaway *et al.* (2004). These databases are comprehensive and index a vast amount of business literature. Even though there is a degree of overlap between the two databases it was worthwhile searching to avoid missing important publications. The initial database search located 296 academic peer-reviewed academic papers, extracted primarily from 2*, 3* and 4* Journals, shown below in Table 2-14. Following a critical review, using predefined quality criteria, shown in Appendices 2-2, Pages 431-434, this list was reduced to fifty-nine papers. Forty-six of these papers were published in the past decade, reflecting the increasing research focus on SCC and product planning integration within the NPD process.

Table 2-14. Database search results (I)

Data Base	EBSCO	ProQuest	Web of Science	Scopus	Zetoc	Sage Journals	Total Hits
papers located	197	90	6	3	0	0	**296**

The search criteria used in searching ABI/Inform and EBSCO are shown below in Table 2-15; the search criteria used for all the databases are shown below in Table 2-16, and the database search results are shown below in Table 2-17.

For the literature that passed the selection process, the Web of Knowledge database was used to conduct a ‘forward’ search of all citations. The papers were reviewed and assessed using the same inclusion/exclusion criteria. If Web of Science did not include the paper, Google Scholar was used to identify citations. Zetoc was used for alerting the researcher to up-to-date academic articles in this area of research.

Table 2-15. Search criteria for ABI / Inform and EBSCO databases

Search Criteria		
	ABI/Inform	EBSCO
Source	Scholarly Journals, Conference papers and Proceedings (Peer-reviewed)	Academic Journals (Peer-reviewed)
Doc. Type	Article, Conference paper, Dissertation / Thesis	Article
Databases	Business and Management	All
Language	English	English
Search modes		Find all my search terms
Date range	Do not include duplicate documents Jan 1, 1995 - Jan 13, 2014	Jan 1, 1995 - Jan 13, 2014

Table 2-16. Search criteria for all other database searches

Database	Search Criteria	In	Publication type	Document type	Period
ABI/Inform Complete via ProQuest	Search strings and keywords	Abstract, Complete text	Scholarly Journals (peer reviewed), Conference papers, Proceedings	Articles	Jan 1995-Jan 2014
EBSCOhost (Business Source Complete)	Search strings and keywords	Abstract, Complete text	Scholarly Journals (peer reviewed), Conference papers, Proceedings	Articles	Jan 1995-Jan 2014
Zetoc	Keywords	All Fields	Academic Journals	Articles	1995-2014
ScienceDirect	Keywords	All Fields	Academic Journals, and Books	Articles	All
Scopus	Keywords, Advanced search	Article title, Abstract	Articles or Conference papers	Articles	1995-2013
Web of Science	Keywords, Advanced search	Title Abstract	Academic Journals, and Conference papers	Articles	1995-2014
Sage Journals	Keywords, Advanced search	All Fields	SAGE Journals	Articles	1995-2014

It became apparent from the initial title and abstract review, that the concept of product planning was limiting the number of academic papers selected. A search was conducted of the combined SCC and NPD search strings, and of the combined product planning and NPD search strings, are shown below in Table 2-17. Title and abstract reviews were conducted on these papers.

Table 2-17. Database search results (II)

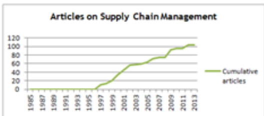
Database	Search criteria	Keywords					
		New Product Development	Supply chain configuration	Product planning	New Product Development + Product planning	New Product Development + Supply chain configuration	New Product Development + Supply chain configuration + Product planning
ABI/Inform	Full text, peer-reviewed, scholarly Journals, Articles and Conference papers, 1995-2014, English	32975	22169	9864	2594	221	90
EBSCO	Peer-reviewed Articles, Academic Journals, 1995-2014, English	258	3533	410461	4863	549	197
Zetoc	Journal search, All fields, 1995-2014	7425	38	35	342	21	0
Web of Science	Articles, Topic, English, 1995-2014	3901	120	39	464	54	6
Scopus	Article, Title, Abstract, Keywords, Academic articles, Social Sciences & Humanities subject area, 1995-2014	10747	64	36	1293	19	0
SAGE	Academic Journals, Abstract, 1995-2014	93	0	0	12	8	0

2.3.4.3. Literature assessment criteria

The selection criteria were developed in advance of conducting the SLR, to guide the selection of articles for inclusion, are shown in Appendices 2-2, Pages 430-433. These criteria were used for the initial screening of academic papers, at title and abstract level. Operationalising the search strings resulted in a total of two-hundred and ninety-six articles. To ensure that only relevant papers were reviewed, the articles were reviewed in a four-stage process, based on predetermined review criteria.

Firstly, the paper titles were reviewed to identify papers that related to research question one. Secondly, abstract screening was conducted to identify papers that contained relevant themes. Detailed inclusion and exclusion criteria shown below in Tables 2-18 and 2-19 were applied during these initial stages. Thirdly, the complete texts of the papers were reviewed. Finally, quality criteria were applied to assess these papers, shown in Appendices 2-2, Pages 430-432. There is a dearth of literature on this topic; hence relevancy to the research question was the key criteria. For paper selection there was no restriction applied to geographic regions, industry or methodology. Considering the research question, only empirical papers were included in the final sample. Panel recommendations were examined to identify other relevant literature. There were a few relevant articles located after the SLR, that were not picked up during the search; these additional papers were subjected to the same quality assessment, using the same inclusion criteria. Google scholar was searched using the final search strings without Journal constraints to capture relevant material in other journals.

Table 2-18. Literature inclusion criteria

Inclusion criteria				
No.	**Criteria**	**Reason for inclusion**	**Definitions of key constructs**	**Key terms and phrases**
1	Theoretical papers showing both internal and external validity	Provide the working assumptions to be used in the SLR report, supporting robust theory		
2	Scholarly Journals (peer-reviewed)	Provide the evidence and warrants to support research conclusions		
3	New Product Development, pre- product launch	Central construct in the area of research	**(New Product Development)** The transformation of a market opportunity and a set of assumptions about product technology, into a product available for sale; Krishnan and Ulrich (2001).	Product design, Product prototype, Product introduction, Product development, Product concept development, New product introduction, New product effectiveness, Technology management, Technology development, clockspeed, Hypercompetition, Velocity
4	Aspects of Supply Chain Configuration relating to New Product Development	Supply Chain Configuration and New Product Development are two of the constructs in the area of research	**(Supply chain configuration)** Encompasses decisions including selection of suppliers; manufacturing and transportation modes; as well as locations in supply chain network to place appropriate levels of safety stocks; Amini and Li (2011).	Supply chain configuration, Supply chain planning, Supply infrastructure, Supply network, Supply base management, Infrastructure planning, Logistics capabiltiies, Sourcing, Procurement, Capacity planning, Resource planning
5	Aspects of Product planning relating to New Product Development	Product planning and New Product Development are two of the constructs in the area of research	**(Product planning)** Product planning involves decisions about the firm's target market, product mix, project prioritization, resource allocation, and technology selection; Wheelwright and Clark (1992).	Product planning, product development, product line management, product ramp-up, product phase-in, product phase-out
6	Include papers which include both New Product Development and Supply Chain configuration	These are two of the three primary constructs		
7	Include papers which include both New Product Development and Product planning	These are two of the three primary constructs		
8	Time period 1995 to date	Supply chain academic research commenced circa 1995		
9	Research type	Empirical, conceptual and methodological papers		
10	Social Science	The social science field incorporates area's of management science		
11	Business and Management	Covers the area of interest		

Except for the research by Brown and Eisenhardt (1995), it was decided not to include papers which considered only the individual concepts of NPD, SCC, and product planning. As of 14th June 2014, this paper had been cited 3,197 times and takes a cross-industry perspective on NPD research following three streams; rational plan, communication web, and disciplined problem solving, with all three streams relating to SCC.

Table 2-19. Literature exclusion criteria

Exclusion criteria		
No.	**Criteria**	**Reason for exclusion**
1	pre-1995	Supply chain academic research commenced around 1995
2	Papers which just include one of the three constructs; new product development, supply chain configuration, and product planning	The relationships between these three constructs is covered in the research. They are not being reviewed independently
3	Research type	Pure mathematical model papers
4	Languages other than English	The relevant academic research journals are published in English
5	Physical, Life, and Formal sciences (mathematics and logic) are not relevant to this research	The research area is covered by the social science field which incorporates management science

Texts that passed through the searches were included in the review. Conducting this research provided a set of texts to review and synthesise.

2.3.4.4. Data analysis

This SLR is an exploratory piece of research since it is not clear what literature is available addressing research question one. I expected that identifiable themes would emerge from the literature and provide the basis for developing a conceptual model. This is a deductive exercise, with the themes deduced from the SLR.

SCC has attracted significant attention in literature. The SLR covers those papers which consider SCC prior to product launch. Few papers refer specifically to the design concept stage, but rather to the entire product design phase. Pashaei and Olhager (2015) explore concurrent product and SC design and identify outsourcing, supplier selection, supplier relationships, distance from focal company, and alignment as key research themes, within concurrent design.

NVivo was considered as a tool to automate coding of the literature themes, however it was decided to use open coding and content analysis to interrogate the literature, in search of themes and causal links between SCC, NPD and product planning, shown in Appendix 2-1, Page 431. Thirty-eight codes were identified as links between the key concepts (Miles and Huberman, 1994, p. 105), are shown in Appendices 2-4, Pages 439-440. Data extraction sheets were used to document the key attributes of each paper, and identify the core themes and sub-themes, are shown below in Table 2-20. The checklist facilitated data collection, encouraging comparison between the academic papers, is shown in Appendices 2-5, Pages 441-444. As new themes emerged these were added to this checklist.

Table 2-20. Data extraction sheet

Data Extraction Sheet
Citation/Description
Title:
Author(s):
Journal:
Year:
Keywords:
Research objective/Question:
Methodology
Sample selection, size and characteristics:
Data sources/ Data collection methods:
Methods of analysis:
Theme
Context
Intervention/Strategy
Mechanism implied by theory
Outcome
Results
Key findings:
Limitations and Suggestions for future research:
Contribution to Research Question
Positive impact:
Negative performance:
No impact:

2.3.4.5. Data synthesis

Taking the findings, a descriptive analysis was completed, prior to the findings being consolidated into linking themes. Table 2-21 outlines the elements that were developed for each paper:

Table 2-21. Data synthesis procedure

Synthesis
Key contribution(s) to research question
Research domain
Theoretical foundation
Linking mechanisms
Practical application
Limitations

The key papers were imported into the checklist, and emergent coding was applied to allow a more a critical synthesis of the research. A critical synthesis is a narrative that tells a trustworthy story answering the question and informing the reader what the findings mean (Popay *et al.*, 2006). The stages of synthesis are outlined, are shown below in Figure 2-16.

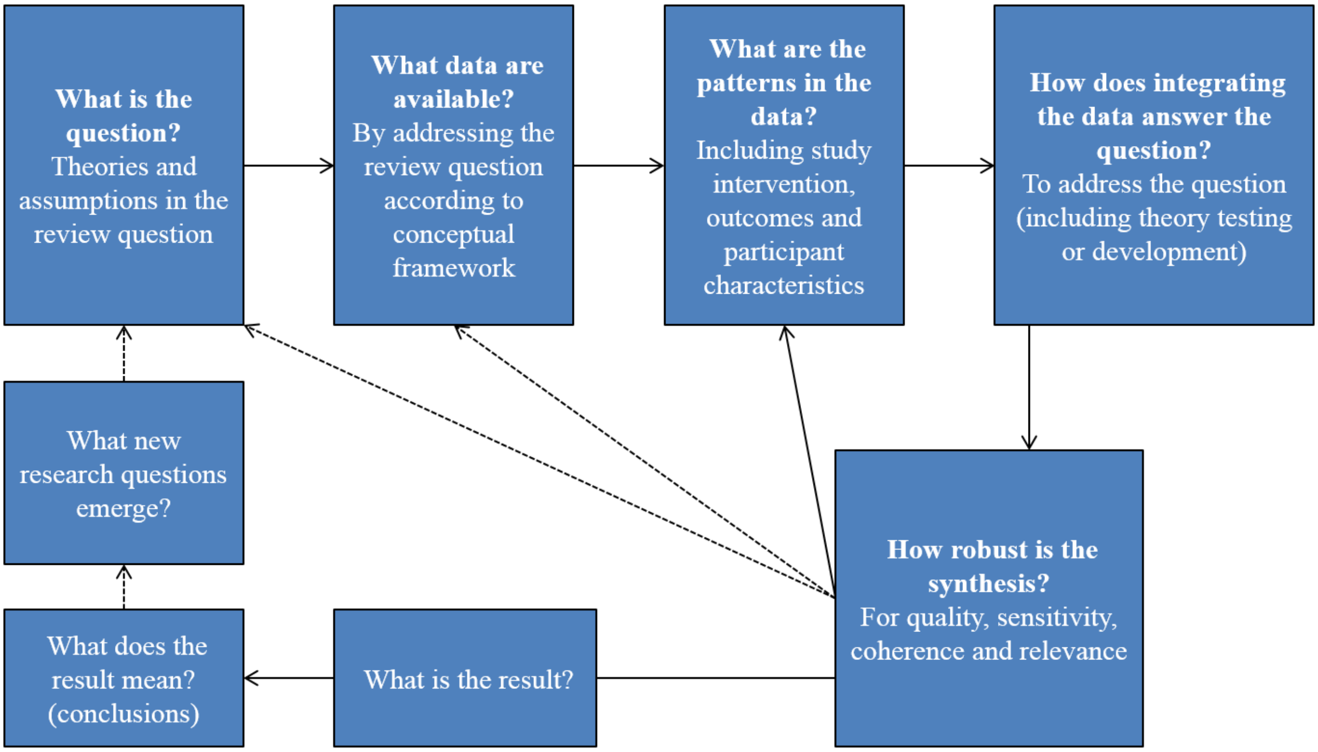


Figure 2-16. Stages of synthesis
Source: Popay et al. (2006)

A descriptive quantitative analysis of the body of papers reviewed is presented in Section 2.4.2. This analysis identifies the year of publication, industry sector, research methodology and geographic location of the research. The descriptive analysis is followed by a thematic analysis identifying the key themes linking the key concepts, see Section 2.4.3. This thematic analysis provides the foundation for the conceptual framework developed from this SLR.

2.3.5. Results

After selecting papers based on the title, abstract and complete text, these papers were appraised for quality, following the criteria outlined in Appendices 2-2, Pages 419-422. All relevant papers had to meet the quality criteria to be selected for the review stage. Integrated research on SCC, NPD and product planning is emerging and is spread across journals with different journal rankings.

The literature search provided interesting insights. Due to the nascent nature of this research there was a high number of relevant papers in lower ranked journals. Journal ranking was not included in the quality appraisal criteria because of this fact. All criteria were scored on a scale of zero to three. A minimum average score of one was applied in selecting papers for the final sample. This minimum score was selected to provide a sizeable number of academic papers. The search and evaluation process resulted in a final sample of fifty-nine articles, see Figure 2-17, and Appendices 2-3, Pages 435-438.

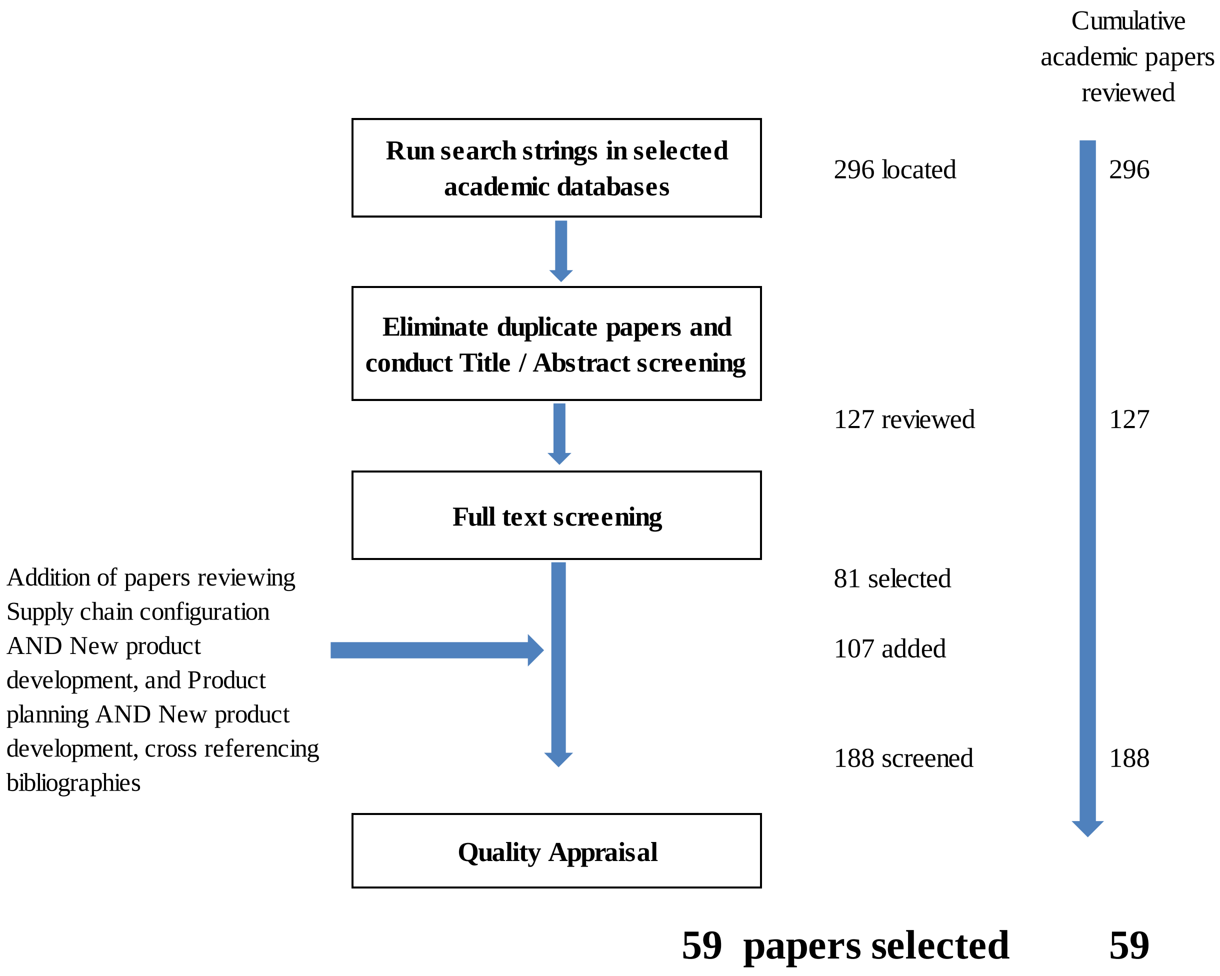


Figure 2-17. Literature search results

Of the 169 papers eliminated after the initial search, 17 were duplicates. Titles, abstracts and full texts were screened for relevance before quality appraisal was completed. Relevant data from all fifty-nine_articles were extracted into a standardised data extraction form, shown in Table 2-20. The extraction sheets for the final fifty-nine papers are catalogued in Appendices 2-5, Pages 429-432.

2.3.6. Limitations of the SLR protocol

All research is subject to limitations. The limitations which have potential impact on the quality of this SLR are covered in this Section. The first limitation is the accuracy of the database search engines. The search engines EBSCOhost and ABI/inform use different Boolean search strings, and therefore produce different results. A second limitation is the exclusion of practitioner sources to focus only on peer-reviewed academic research. This focus best serves my research in understanding how my review question is documented in the academic literature.

To serve the purpose of being a broader based systematic review I maintained an up to date review of the practitioner sources throughout the research timeframe. As the practitioner content is vast, there is not sufficient time to find and evaluate all practitioner data, but a sample of this data. By focusing on the academic Journals relevant to the research domain it was possible to remain up to date with academic research throughout the entire timeframe of this research.

2.3.7. Conclusions

The SLR process can produce reliable knowledge, enhancing the management knowledge base (Tranfield *et al.*, 2003). This project provided confirmation of the research using a more rigorous and transparent method, than the scoping study and preliminary literature review.

Project one, provided in-depth experience of the research experience overall. Defining the research question, designing the methodology, collecting and analysing the data and writing the synthesis are all activities in any research project regardless of whether it is primary or secondary research. In the subsequent sections I discuss my findings in addressing the review question and research question one.

2.4. FINDINGS

First the structure of how the results are presented is discussed. This is followed by a thematic review, of the primary themes which link the key concepts. Finally, the results and conclusions of the SLR are presented.

2.4.1. Structure of findings

The structure of the SLR research process is shown in Appendix 2-1, Page 431. Following the descriptive account of the SLR results, level-one coding of the data was completed, as shown in Appendices 2-4, Pages 439-440. Using content analysis, the results are interrogated for key constructs and construct attributes discovered from the scoping study. The aim of this content analysis is to provide clarity and unity.

2.4.2. Descriptive overview

Due to the limited number of academic papers located, the search was not limited to 4* and 3* academic journals; seventy-three percent of papers are drawn from 4* and 3* academic journals, with many of the selected papers published in OM, Product Innovation, Supply Chain and Strategic Management Journals. Only Supply Chain Management: An International Journal contained more than five relevant academic papers, shown below in Table 2-22.

Table 2-22. Journal characteristics

Journal Name	Frequency	Cranfield Ranking
Academy of Management Review	1	4*
California management review	2	4*
Journal of Operations management	4	4*
Journal of Product Innovation management	1	4*
Management Science	3	4*
Strategic Management Journal	1	4*
European Journal of Operations Research	5	3*
IEEE Transactions on Engineering Management	3	3*
International Journal of Management Reviews	1	3*
International Journal of Operations and Production Management	2	3*
International Journal of Production Economics	5	3*
International Journal of Production Research	5	3*
Production and Operations Management	3	3*
Supply Chain Management: An International Journal	7	3*
European Business Review	1	2*
Journal of Manufacturing Technology management	1	2*
Journal of Purchasing and Supply management	1	2*
Production Planning and Control	1	2*
Harvard Business School Case	1	Not Ranked
Industrial Management and Data Systems	4	Not Ranked
International Journal of Customer Relationship management	1	Not Ranked
Intechopen.com	1	Not Ranked
Intehweb.com	1	Not Ranked
Journal of Engineering and Technology management	1	Not Ranked
Journal of Intelligent Manufacturing	1	Not Ranked
Proceedings CIRP Conference on Manufacturing Systems 2013	1	Not Ranked
Proceedings POMS 21st Annual conference	1	Not Ranked

Forty-six out of the fifty-nine papers selected were published in the last thirteen years, reflecting an increasing focus on this area. The number of available papers peaked in 2005, these are shown below in Figure 2-18.

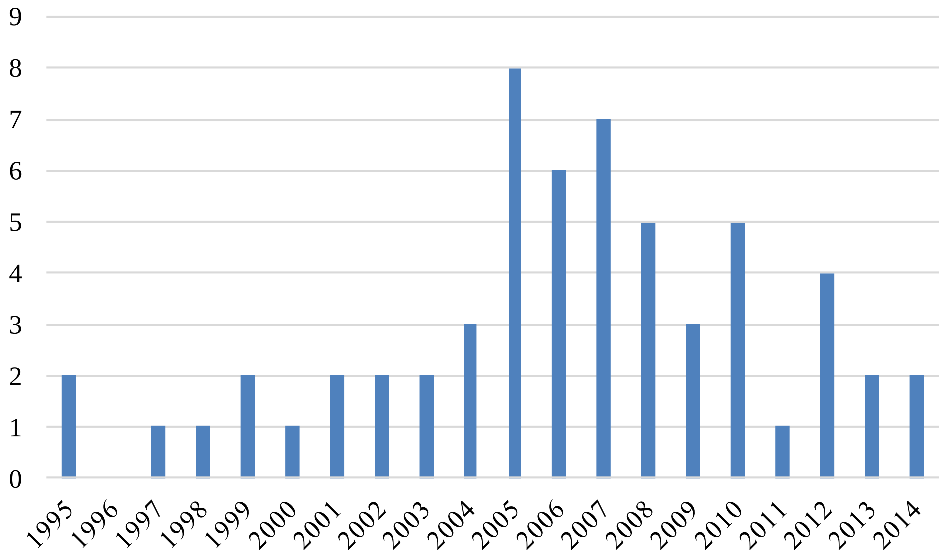


Figure 2-18. Chronological distribution of academic papers

Contextual variables such as technology, industry type, geography, and culture, all have the potential to shape aggregate NPD outcomes. These contextual variables can be studied at a macro and micro level. This SLR studied the UoA for each academic paper, shown below in Table 2-23. The UoA analysis highlights the growing interest in supply networks; this has been observed by authors, including Harland (2013). In total, twenty-six papers studied SC networks, fourteen papers discussed SC networks in the US, four addressed global networks, and all other networks studied involved single countries outside the US.

Table 2-23. Units of Analysis

Unit of Analysis	No. of papers	%
Network	26	44%
Company	17	29%
Industry	13	22%
Country	2	3%
Factory	1	2%
	59	

On a global level, academic research has investigated several different areas. These areas include vertical integration and sourcing (Novak and Eppinger, 2001); NPD and supplier involvement (Johnsen, 2009; Handfield *et al.*, 1999); fast fashion design and SCC (Ghemawat and Nueno, 2006); SCM and PLC (Fandel and Stammen, 2004); SCM and product recovery (Srivastava, 2007), and PM and SC integration (Lau *et al.*, 2010). On a regional level, academic research has examined NPD and SCM (Pero *et al.*, 2009), SC integration and product design (Lau *et al.*, 2007). On a country level, academic research is more focused on individual companies; the impact of PLC on SC design (Aitken *et al.*, 2003); NPD and SC mirroring (Pero *et al.*, 2010); engineer-to-order (Gosling and Naim, 2009); product platform and SCM (Mikkola and Skjøtt-Larsen, 2006); product standardisation and SC design (Baud-Lavigne *et al.*, 2012), and supplier involvement in NPD (McIvor *et al.*, 2006).

Forty-nine percent of the studies were performed in the US, see Table 2-24, most of the early research on SCC and NPD emanated from the US. Fourteen percent of research papers were in China and Hong Kong and fourteen percent pursued global research. The concentration of research in these countries is reflective of the move by US multinationals into global markets and the outsourcing of certain elements of business to off-shore locations. A total of twenty-seven percent of the papers did not identify the geographic location of their research, shown below in Table 2-24.

Table 2-24. Geographical distribution of research

Country/Region	Number of papers	%
Australia	1	2%
Taiwan	1	2%
Canada	1	2%
France	1	2%
Sweden	1	2%
Netherlands	1	2%
Italy	1	2%
Denmark	2	3%
UK	5	8%
China/Hong Kong	8	14%
Global	8	14%
USA	29	49%
Total	59	

A summary of the literature reveals that research at the individual company level usually occurs at a country level, whilst research at an industry and network level is performed at regional and global levels. Almost a third of the studies focused on a single industry with the automotive sector receiving the most research attention, closely followed by the computing and electronics sectors. Lau and Yam (2007) focused on NPD and SC co-development; Chiu and Kremer (2014) focused on centralised versus decentralised SC design; Zhang *et al.* (2008) focused on platform products and manufacturing supply chains, and Huang *et al.* (2005) focused on product information and SC dynamics. The studies spanned a minimum of ten industry sectors, shown below in Table 2-25.

Table 2-25. Industry typology

Industry type	No. of papers	%
Automotive	6	10%
Electronics	3	5%
Lighting	1	2%
Computing	5	8%
Clothing / Fashion	3	5%
Earth moving equipment	2	3%
Bicycles	1	2%
Semiconductors	1	2%
Hearing aids	1	2%
Furniture	1	2%
Cross sector study	19	32%
Not industry specific	16	27%
Total	59	

Industries that experienced globalisation earlier, for example the automotive sector, received greater academic focus, reflecting the scope of globalisation. It is not surprising that, given the influence of globalisation, many of the research articles focused on modular product design. Fifty-three percent of papers refer to modular or integral design. The computing industry was one of the first industries to introduce modular design. During the 1980s, companies such as IBM (Langlois and Robertson, 1992) and SUN Microcomputer (Garud *et al.*, 1993), introduced modular design and upgradeability into their products; although it must be acknowledged that the Ford Automotive Company took a similar approach to automotive product design in the early 1900s. The CEO of SUN Microsystems Scott McNealy, stated that the company ‘changed the fundamentals of the computer business the same way Henry Ford changed the fundamentals of the automotive business’ (Schlender, 1987).

With the advent of the IBM PC in the early 1980s, the computer became a modular system with a relatively fixed (or at least slowly changing) architecture, interfaces and standards. Due to the change in PA and SCA, the personal computing industry experienced a phenomenal increase in value and a reduction in cost. This occurred mainly because of improvements in modules (microprocessor, software, modems, peripherals, etc.), rather than improvements in the way modules are interconnected. Companies such as Intel and Microsoft were quick to develop reference hardware and software platforms, based on the use of standardised components. This allowed OEMs such as IBM, HP, Dell and Apple to outsource manufacturing, on a global scale, resulting in lower production costs. The category of industrial equipment is broad and represents many products. This review has shown that industrial equipment is the second largest product category, followed by computing, in terms of the number of academic papers published, shown below in Figure 2-19.

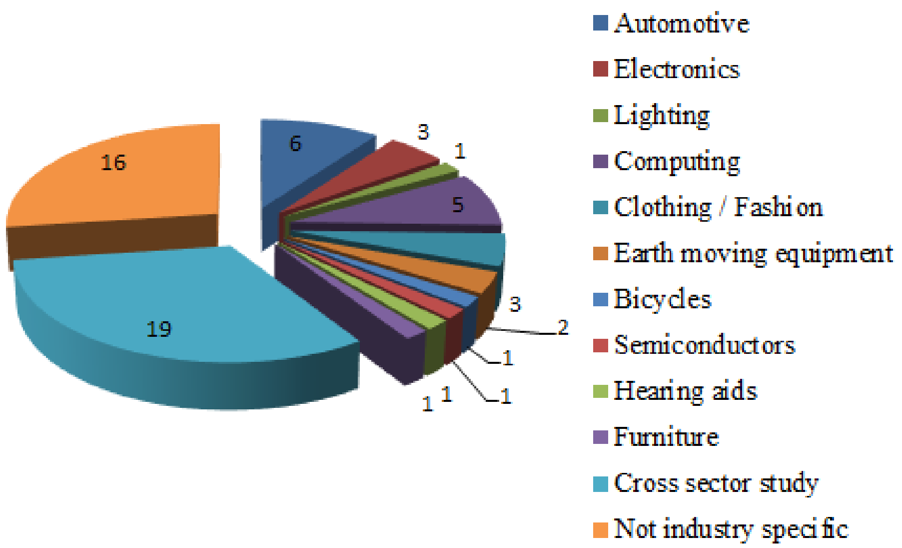


Figure 2-19. Distribution of papers by industry sector

Many of the academic papers included in the review cover multiple industries. Sharifi *et al.* (2006) researched the sports, eye, bath and shower, information kiosk and ultrasonic cleaning product sectors, using four case studies based in the UK. Lau and Yam (2007) researched 251 companies, using a questionnaire research design, across the electronics, plastics and toy sectors in China and Hong Kong, while Marsillac and Roh (2014) researched flooring, IT products, and bedding products.

Novak and Eppinger (2001); Primo and Amundson (2002); Anderson and Joglekar, (2005), and Noori *et al.* (2006) focused on the automotive industry. Other areas of the transport sector, in addition to automotive, have been examined in the literature; these include earth moving equipment (Nepal *et al.*, 2010) and bicycles (Chiu and Kremer, 2014). The electronics industry received the next level of research focus (Carrillo, 2005; McIvor *et al.*, 2006; Pero and Sianesi, 2009; Pero *et al*., 2010), followed by computer products (Lee and Sasser, 1995; Fine, 2000; Graves *et al.*, 2005; Hoetker, 2006; Zhang *et al.*, 2008), and fast fashion clothing (Ghemawat and Nueno, 2006; Khan *et al.*, 2012). Each of the sectors researched exhibit strong competition and increasing industry clockspeed.

At the macro, industry level SC structures oscillate between vertical/integral and horizontal/modular, shown below in Figure 2-20. This double helix model portrays overlapping responsibilities across product, process and SC development. This continuous process highlights the evolving nature of the PA and SCC relationship, and a life cycle view of PA and SCC.

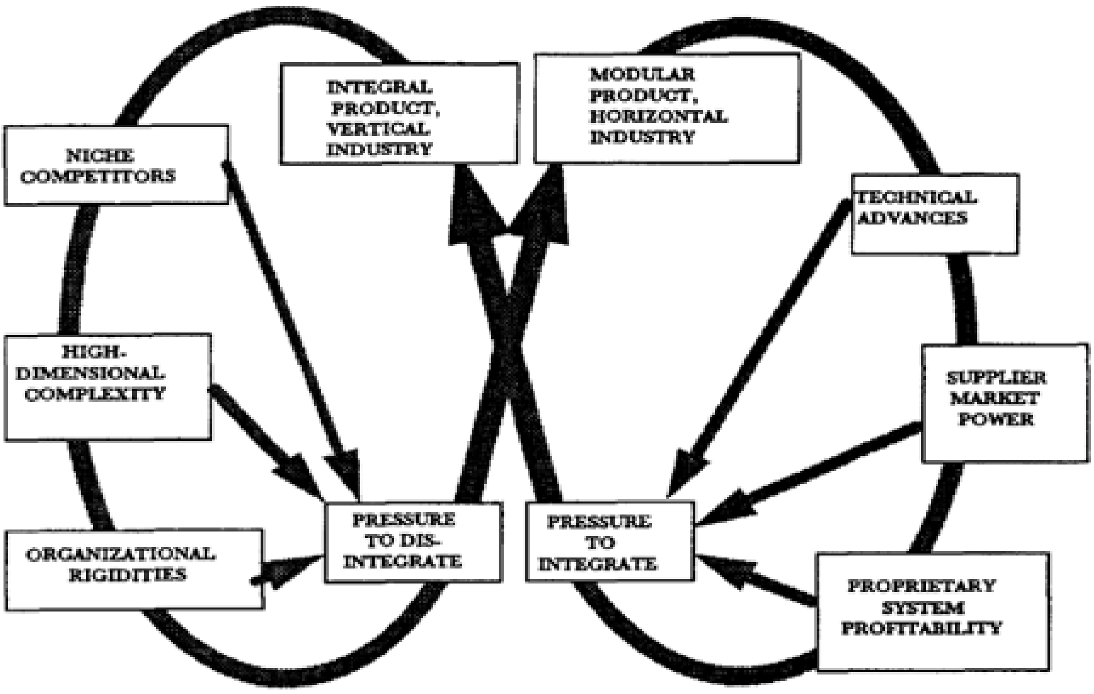


Figure 2-20. vertical / integral and horizontal / modular SCA
Source: Fine (2000, p.216)

The research methods used are shown below in Table 2-26. The research between the NPD, SCC and product planning concepts is mainly confined to case studies and surveys. The singular case study approach is the dominant research method since 2007, with a total of sixteen single case studies identified. Cheung *et al.* (2012) show that the case method is a promising tool for integrating SCC with NPD. In the SLR a total of twenty-eight research papers utilise case studies. These case studies have an average sample size of thirty-two UoA. In this SLR, there were twelve multiple case studies. There are differing opinions on the use of case studies. Eisenhardt and Graebner (2007) advocate the general use of case studies, whilst Timpf (1999, p.131) suggests that they may not necessarily lead to sufficient underpinning for abstraction and generalisation purposes. Whilst one cannot make causal conclusions from case studies, there are methods for improving their reliability. These methods are discussed in project two.

The second dominant research method involves survey-based statistical analysis (Fynes and De Burca, 2005). Whilst these survey-based statistical analyses reveal that certain factors can co-exist, they often do not identify causal relationships. This type of analysis often ignores contingencies. Hoskisson *et al.* (1999, p. 447), note that "quantitative studies are not applicable to all research questions and need to be complemented with inquiries that go into more detail". Hence, the validity of outcomes is limited or insufficiently accounts for contingencies when using the quantitative research approach. One example of this is found in the work of Antonio *et al.* (2007, p. 14), which states that modularity leads to improved reliability of delivery and variant flexibility. It could be that these factors were the main reason that modular design configurations were introduced.

Table 2-26. Research methods

Research Method	No. of papers	%
Case	28	47%
Survey	16	42%
Observation	9	15%
Conceptual	4	7%
Maths model	1	2%
Modelling	1	2%
Total	59	

Whilst product planning is a concept contained within the review question, the SLR highlights that product planning is an integral part of the interface between SCC and NPD, shown below in Figure 2-21. Following the SLR, the boundary of research question one was reduced to incorporate two concepts NPD and SCC. It was determined during project one that product planning is incorporated into the intersection of these two concepts, looking at the whole system and learning about its parts (Anderson, 1999). This change is necessary to avoid sub-optimisation.

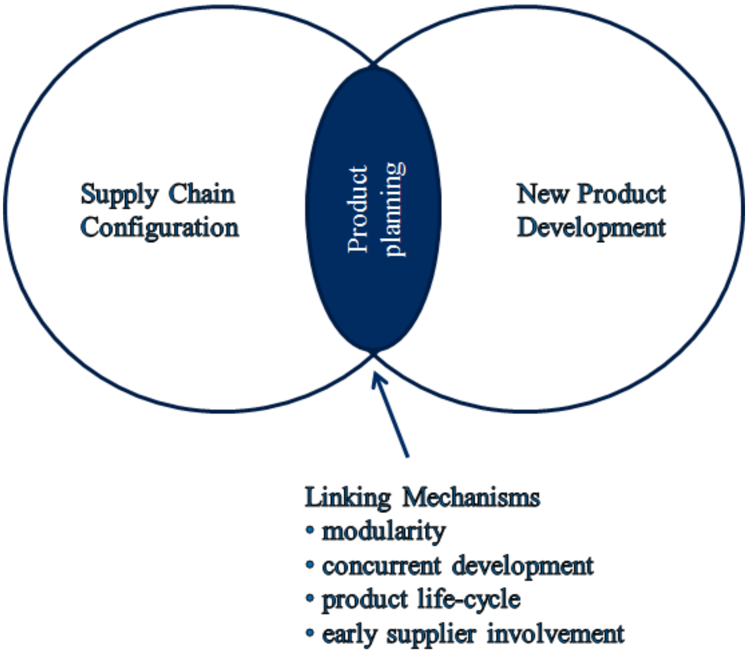


Figure 2-21. Revised research domain

Reflecting on the contextual variables, fast clockspeed industries such as electronics (Fine, 1998); fast fashion (Ghemawat and Nueno, 2006), and toys (Lau and Yam, 2007), receive more attention than slow clockspeed industries. The papers selected focus primarily on early stage product development, prior to product launch. Companies in fast clockspeed industries normally introduce new products initially to existing customers, prior to new customers (Sharifi *et al.*, 2006), shown below in Figure 2-22.

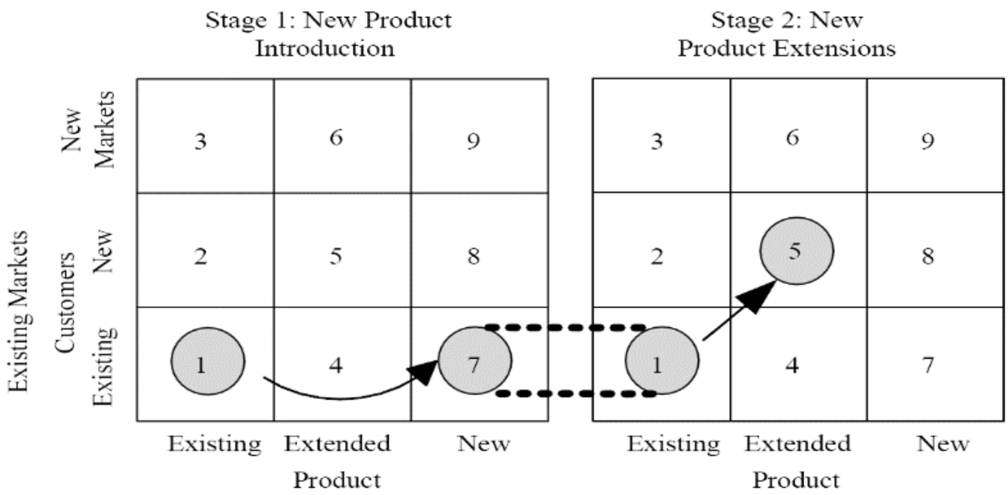


Figure 2-22. Simultaneous design of and design for supply chain
Source: Sharifi et al. (2006)

Moreover, new products are normally introduced using existing process technologies, before introducing products using a new process technology. Fine (2000) highlights this sequence of new product introduction using existing silicon wafer technology, within Intel Corporation. Sharifi *et al.* (2006) illustrate that early product adoption involves the initial introduction of new-to-market products to existing 'knowledgeable' customers, followed by introduction to new markets.

2.4.3. Thematic review

Appendix 2-9, Page 448, illustrates the scope of key research papers. Through a process of extraction, underlying themes emerged, shown below in Table 2-27. No single theme explains the linking mechanisms between NPD and SCC, shown in Appendix 2-8, Page 447.

A limited number of academic studies address the themes linking SCC and NPD, at the product design stage, for 'new-to-market' products. Five linking themes emerged: 1) integral design; 2) modular design; 3) concurrent or co-development; 4) product and process life cycle, and 5) ESI. Case studies published by Guide and van Wassenhove (2003), and Wikner and Rudberg (2005) combine integrality and modularity, along a modularity continuum, the papers covering the co-development, life cycle and PM – SCCM mirroring are shown in Appendices 2-7, Pages 445-447.

Table 2-27. Research themes

	Linking themes	Number of papers	%
1	Modularity	31	53%
2	Early supplier involvement	14	24%
3	Concurrent development	11	19%
4	Life cycle	2	3%
5	Theory Development	1	2%
	Total	**59**	

The four inter-connected themes link to the fifth generation in Rothwell's classification of product development processes (Rothwell, 1977), the key aspects of this generation of processes are integration, flexibility, networking, and parallel (real time) information processing. PA connects the customer and the company. This research presupposes that the market need has been determined. An investigation of six successful innovations at GE Labs show a close link with market needs as the key to product market success (Roberts and Burke, 1974).

2.4.3.1. Integral architecture

Integral design for new-to-market products concerns the search for an integral view of SCC and NPD. Integral SCs are often represent by Vertically integrated in-house design and manufacture. Vertical integration is described as the overall scope of business activities in a SC brought under the management of a single company (Majumdar and Ramaswamy, 1994). It can be achieved by vertical financial ownership and vertical contracts. A meta-analysis of the drivers of a company's financial performance reveals a positive relationship between vertical integration and financial performance (Capon *et al.*, 1990).

It might be expected that the literature on SCC or NPD would have investigated the relationship between NPD and SCC; however, none of the academic papers address the interface from an integral perspective. The interaction has only been mentioned implicitly (Gan and Grunow, 2013), or concerned with specific issues or cases (Ulrich and Ellison, 2009). Salvador *et al*., 2002; van Hoek and Chapman, 2006, 2007, and Dekkers *et al.*, 2013, illustrate the lack of an integral view of NPD and SCC. Ülkü and Schmidt (2011) state that matching integral PA with integral SC networks is not observed in practice. Accordingly, this review represents the first attempt to systematically address the interaction between SCC and NPD processes and activities, with an emphasis on the management control of the interface, during the concept design stage of 'new-to-market' products.

An integrative view must take into consideration: 1) the interdependence of product design and SCC design, as both processes influence each other in creating value; and 2) organisational differences in product design and SC design to ensure efficient resource utilisation. Both considerations appear crucial in creating an integrative view of NPD and SCC. At the early stage of NPD and SCC design, architectural attributes determine the arrangement and configuration of the product and the SCC (Gan and Grunow, 2013). These attributes include locations or nodes in the SC network. These nodes can be supplier, manufacturing or distribution locations. At the tactical level, detailed design attributes are generally related to the physical aspects of the product, size, weight, material and form, and SCC attributes relate to transportation and inventory replenishment policies. At the operational level, dynamic attributes are typically performance-related NPD functional attributes, such as speed to market and product range, and short-term SCC decisions, include scheduling. This hierarchy of attributes helps to avoid the ‘chicken and egg’ dilemma between product designers and SC architects by highlighting that ‘architectural design can begin concurrently without waiting for detailed designs from the other side’ (Gan and Grunow, 2013).

Product complexity plays a significant role in integral NPD and SCC. In a review of the relationship between product complexity and vertical integration, Novak and Eppinger (2001) investigate the governance structure and information exchange in keiretsu companies, addressing the role of asset specificity in determining the make-or-buy decision, drawing from transactional cost theory. These researchers argue that product complexity and vertical integration are complements, with PA being the linking mechanism. Their research methodology involved a longitudinal case study of eight luxury performance cars, from eight companies, over five overlapping five-year periods between 1980 and 1995. The research supports the view that lower complexity products can be more effectively outsourced. Japanese companies tend to more successfully outsource complex components and assemblies to Keiretsu suppliers, with these Keiretsu suppliers partly owned by their customers. This research raises the idea of using KBT to address the knowledge structure of companies. KBT has attracted an increasing level of interest, with the emergence of enhanced data analytics (Grant, 1996). High levels of product complexity often lead to increased levels of in-house manufacture.

There have been many single-product SC decisions which have triggered momentous structural shifts, from a vertical/integral industry structure to a horizontal/modular; for example, Google’s decision to make the android operating system open to developers and OEMs, or Microsoft and Intel’s open systems architecture (Fine, 2000). Treating integral architecture as low modularity has clear advantages in researching these transitions.

2.4.3.2. Modular architecture

The concept of product modularity emerged from the seminal work of Simon (1962), which illustrated that a product is a hierarchical complex system of many interacting parts, which can be arranged into modules. Systems theory and Alderson's functionalist theory of marketing, relate to this theme. In designing modular products and SCs, companies design product assemblies or steps in the SC process than can be 'unplugged'. This enables components or modules to be replaced by an equivalent component or module, or a step in the SC process to be moved to different locations in the network. Modularity is closely linked with various forms of outsourcing alliances, which can be defined as any independently initiated inter-company link that involves knowledge exchange and co-development (Gulati, 1995). Outsourcing is defined as the transfer of a business activity, including the relevant assets, to a legally separate third party (Welch and Nayak, 1992). The literature on outsourcing, has predominantly focused on the need to protect the companies 'core competencies' (Venkatesan, 1992). Despite being important, this risk has perhaps over-dominated the literature at the expense of the need to focus on asset specificity.

SCC and service modularity stem from manufacturing and information systems, including software engineering, which rank among the most often cited research disciplines in service modularity literature (Tuunanen *et al.*, 2012). Modularity can be defined as a property of a system that has been decomposed into a set of cohesive and loosely coupled modules (Booch, 1998). Modularisation helps manage system complexity, and is closely related to encapsulation and abstraction, since the connections between modules are the assumptions which the modules make about each other (Booch, 1998). The elements of abstraction, encapsulation, modularity and hierarchy each require a different mindset, a different way of thinking about the problem (Booch, 1998, p. 46).

There are two concepts which act as guidelines to modularisation: cohesiveness (the grouping of logically related abstractions) and loose coupling (minimising the dependencies between modules). Modularity can be defined as a property of a system that has been decomposed into a set of cohesive and loosely coupled modules (Booch, 1998).

There is extensive literature dealing with modularity in the SC context (Doran, 2005). The main purpose of product design modularity is to increase product variety and production flexibility, while decreasing product complexity. The textile company Benetton manage over five-hundred contractual relationships in the Veneto region of Italy, where each supplier delivers a limited product range, allowing for greater specialisation and control (Kakabadse and Kakabadse, 2002). Simon (1962) illustrates this concept with a parable involving two watchmakers: Hora and Tempus. Tempus designed his watches in such a way that, if he was interrupted during assembly, the watch would fall to pieces, and would have to be reassembled again using elementary components. In comparison, Hora's design consisted of stable subassemblies, each composed of a few parts. If interrupted during assembly, Hora would only have to reassemble the last unfinished subassembly. Unlike Hora's design, which was highly modular, Tempus's PA did not possess a high degree of modularity. This parable also partially demonstrates that product modularisation decreases NPD lead-time and production lead-time by allowing for the potential of mixing and matching modules (Simon, 1962). Product design modularity is best defined as an approach to product design which relies on the use of generic interchangeable and reusable product modules in a range of finished goods (Ulrich, 1995).

Research indicates that PM combined with SCCM results in cost reduction (Sanchez and Mahoney, 1996; Ernst and Kamrad, 2000), improved SC performance (Fine, 1998) and increased flexibility (Schilling and Steensma, 2001). von Bertalanffy (1969) concludes that, given the interaction between a system's components, a system is often more than the mere sum of its components (Helou and Caddy, 2006). System concepts include open versus closed systems and the idea of a definable boundary that separates a system from its environment.

Dekkers (2005) employs a systems framework to connect NPD and SCC with feedback loops according to the mechanisms of the steady-state model. This internal feedback, in the form of ideas, improvement proposals and corrections, is directed towards product design and SCC process for evaluation. Many SCs are closed-loop; for example, the case of Kodak's single-use cameras illustrates a classic example of a closed-loop SC (Guide and van Waddenhove, 2003), shown below in Figure 2-23.

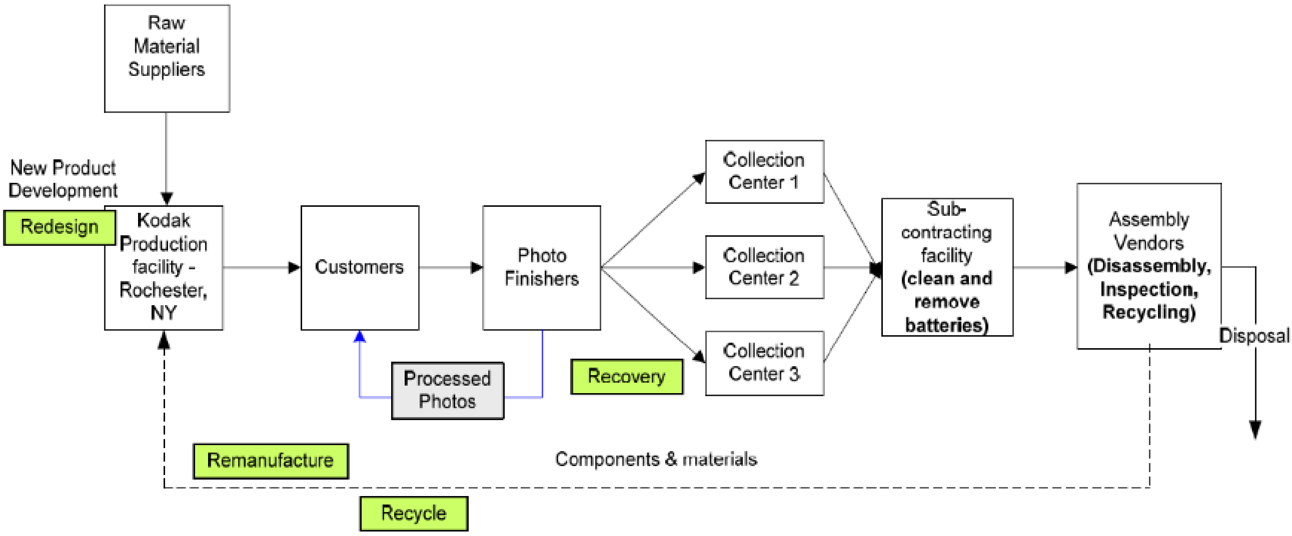


Figure 2-23. Closed-loop supply chain for Kodak single-use camera
Source: Guide and van Waddenhove (2003)

Closely related to the concept of modularity is the concept of postponement. Companies may decide to postpone product design, component or sub-assembly sourcing, manufacture or distribution to the point of customer order receipt. Delayed product differentiation is considered key to SCC (Lee and Sasser, 1995). PRP and PP are key linking mechanisms between SCC and NPD. The concept of postponement benefits greatly from collaboration between R&D and SC partners. Alderson (1957) was the first to coin the term 'postponement' in this context. Alderson's functionalist theory of marketing includes vertical and horizontal dependencies between companies' business activities. 'We must look at the whole system to learn about any of its parts (Alderson, 1950). Systems can be perceived as knowledge-producing (Nonaka and Takeuchi, 1995), value-creating (Grant *et al.*, 1994), total-quality-producing (Mele and Colurcio, 2006) and sustaining (Hakansson and Snehota, 1995).

Closely linked to the modularity theme is the concept of the customer order entry point (COEP), linked to product families (Jiao *et al*., 2000). The concept of COEP was first referred to by Sharman (1984), who studied logistic control, and Wemmerlöv (1984), who proposed the concepts of make-to-stock (MTS), make-to-order (MTO) and assemble-to-order (ATO). The COEP concept is also known as the customer order decoupling point (Yang *et al.*, 2007), order penetration point (Sharman, 1984) and product configuration point (Sabri and Beamon, 2000). The concept of COEP provides a linking mechanism between NPD and SCC. The timing of the COEP depends on whether the SC design is ETO, MTO, ATO or MTS. Modular design is referred to as either a starting point (Mikkola and Gassmann, 2003) or a consequence of the COEP (Mikkola and Skjøtt-Larsen, 2006. If it is an ETO SC, depending on the order fulfilment lead-time, there may be a requirement for modular PA, with provision for the supply of postponement, and configure-to-order capabilities. Gosling and Naim (2009) refer to COEP from an SC perspective and highlight that research has neglected the engineer-to-order SC option, where the product design, or part of it, is customer order-driven, where (MTO) is not. To date, most modular design literature (Stone and Wood, 2000; Sanchez and Mahoney, 2000; Simpson *et al.*, 2001) has not involved manufacturing strategy or logistics as the driver for the configuration of products.

Although COEP and modular design have been accepted, they are rarely deployed as a principle for integral management. Their use in production management and logistics has been described extensively (Rudberg and Wikner, 2004; Pero *et al*., 2010). The separation in academic literature, between the emphasis on manufacturing and logistics management for the COEP and the focus on the design aspects of modular design, supports the validity of Riedel and Pawar’s (1998) assertion that product design, engineering and manufacturing strategy are insufficiently linked in the literature. A closer examination of the integral and modular themes leads to the conclusion that integrality is equivalent to a low level of modularity. For this reason, the integral theme is combined with the modularity theme following project one.

In any future research on modular design, it is important to consider Ulrich and Eppinger's (2008) hypothesis that modularity is a relative property of PA, with products rarely modular or integral. This is true of software-defined products, where much product functionality is delivered following product delivery to the consumer. This point is relevant, since the context of this research relates to the development of new-to-market products. Many new-to-market mobile phones in the early 2000s had poor market and quality acceptance at product launch, due to problems with early software releases. By being able to de-couple the operating and application software layers within the product, companies have been able to simultaneously launch products within a shorter development time, and resolve technical problems without directly impacting on customer experience. The concept of COEP has become of interest as products become increasingly digitised and service-oriented.

The impact of PM on SC design has been observed by Fine (1998); van Hoek and Weken (1998), and Lau and Yam (2005). Fine (1998) indicates that PA and SCA tend to be aligned along the integrality-modularity spectrum, with integral products developed by integrated SCs, and modular products developed by modular SCs. Ulrich (1995) outlines that the selection of the architectural approach, modular versus integral, is a key consideration during product concept development; in addition to selecting the technological working principles, setting performance targets and defining the desired product features and variety required. Modular architecture requires emphasis during the concept development phase.

2.4.3.3. PA and SCC co-development

The forces of globalisation, technology and consumerism are driving the convergence of disciplines intra- and inter-company. During the period 1995-2010, SC research focused on SC efficiency with frameworks such as design-for-X (Dowlatshahi, 1999; Appleyard, 2003; Hult and Swan, 2003); co-development (Griffin, 1993; Swink *et al*., 1998; Lau and Yam, 2007; Wikner and Rudberg, 2005); 3DCE (Fine, 1998, 2005; Ellram *et al*., 2008) and SC fit (Fisher, 1997; Vonderembse *et al.,* 2006; Lo and Power, 2010; Pero *et al.,* 2010; Khan *et al.,* 2012). This research led to more divergence rather than convergence in SC disciplines. “While the concept of an explicit PA is prevalent in large electronic systems design and in software engineering, to my knowledge relatively few manufacturers of mechanical and electromechanical products explicitly consider the architecture of the product and its impact on the overall manufacturing system” (Ulrich, 1995, p. 439).

The literature has investigated approaches to multi-project management (De Maio *et al.,* 1994). All studies clearly indicate the necessity for cross-functional collaboration between NPD and SCC design. Many companies have adopted a team structure in which the traditional functional divisions are less pronounced (Ettlie, 1998). Co-development is an interdisciplinary theory that can investigate phenomena employing a holistic approach (Capra, 1997). Co-development is a clear theme of early NPD and SCC (Swink, 1998; McDermott and Handfield, 2000; Fine *et al*., 2005; Wikner and Rudberg, 2005; ElMaraghy and Mahmoudi, 2009; Gan and Grunow, 2013). CE addresses NPD and SCC mirroring, decreasing NPD cycle time and increasing quality through incremental innovations (Handfield, 1994; Dröge *et al*., 2000; McDermott and Handfield, 2000). Although many companies successfully implemented CE in the 1990s, the 3DCE model, though still in its infancy, integrates product, process and SC design, and is viewed as having a promising future in the field of operational research (Ellram *et al.*, 2008). Similar attempts have been made by Pero *et al.* (2010) to address the mirroring between product development and SCC. Further research on 3DCE is ongoing, such as the goal-programming approach to model the trade-offs (Fine *et al.*, 2005); information requirements (Shahroki *et al.*, 2011), and quality function deployment (Tchidi and He, 2010).

Shahroki *et al.* (2011) used Fuzzy set theory to apply uncertain parameters in solving the multi-objective problem and selecting optimised process and supplier configuration.

Communication between product design, engineering and manufacturing is crucial to the performance of companies (Griffin and Hauser, 1992, p. 361). Meyer and Utterback (1993); Koufteros *et al.* (2001), and Fixson (2005) describe configuring products and product families as a core capability for product innovation. Taken together, these studies reveal a gap in knowledge regarding the effective implementation of NPD and SCC co-development. Research on the interactions relevant to the interface between product design, engineering management and manufacturing strategy is limited, with only Dekkers (2006) and Wikner and Rudberg (2005) conducting research in this area

The SLR located four papers that address concurrent product and SC design (Lee and Sasser, 1995; ElMaraghy and Mahmoudi, 2009; Gokhan *et al*., 2010; Nepal *et al.*, 2012). These papers consider the costs of integrating new suppliers (Gokhan *et al.*, 2010), labour, capacity and transportation constraints (ElMaraghy and Mahmoudi, 2009), and alterative SCC (Lee and Sasser, 1995; Nepal *et al.*, 2012). Lee and Sasser (1995) explain the positive impacts of incorporating all related divisions of the company, key suppliers and key customers into the SCC decision-making process.

2.4.3.4. Early supplier involvement

A participative approach to NPD has been advanced in the literature (Takeuchi and Nonaka, 1986; Novak and Eppinger, 2001. Supplier access at the concept stage depends on NPD competence and modular links with the OEM, for transfer of codified knowledge and level of risk and innovation sharing (Koufteros *et al.*, 2007). The interface between SCC and NPD must be the starting point for integral management approaches (Gunasekaran and Yusuf, 2002).

ESI results in lower product cost (Nepal *et al.*, 2012); increased quality (Primo and Amundson, 2002), and increased levels of sustainability (Mena *et al.* 2013). ESI drives product and SCC co-development, and improves knowledge sharing (Dowlatshahi, 1996). Bonaccorsi and Lipparini (1994), and Ragatz *et al.* (1997) advocate the benefits of ESI in NPD. Rossetti and Choi (2005) conversely highlight the downside of strategic sourcing under certain circumstances, leading to high switching costs, the loss of flexibility and the dispersion of IP. Supplier integration in product development is about knowledge sharing and co-development of the product and its SCC.

A survey of eighty-three US companies conducted by Ragatz *et al.* (1997) indicates that the integration of suppliers in the NPD process is of increasing importance and the early involvement of suppliers in the design process, if applied and managed properly, usually leads to significant improvement in overall NPD performance. The same study revealed that the ability to share intellectual assets (such as technological know-how, product-related knowledge and customer requirements) with suppliers is the foremost determinant of success in joint NPD. Accordingly, knowledge dissemination becomes a vital requirement for integrating suppliers into the design process.

Given the growing complexity of products in many fields and the growing acceptance of time as a factor in competition (Stalk, 1988), companies must use the capabilities of their suppliers more effectively during product development to remain competitive. By identifying compatible suppliers early in the product concept development phase, these suppliers can be integrated into product design and development at an earlier stage, providing opportunities for improving the product and lowering its cost (Nepal and Monplaisir, 2009). Wheelwright and Clark (1992) note that unless the company can impact sourcing early in product development it has almost no impact on the resulting design of the SC. Work in this area has been conducted by Petersen *et al.* (1978), focusing on the resource-dependency stream of organisational theory. They propose that supplier integration into NPD is a social process and, as such, is affected by a variety of behavioural factors (Bensaou and Venkatraman, 1995; Eisenhardt and Tabrizi, 1995; Dyer and Singh, 1998). They conclude that social problems often occur because of a lack of coordinating mechanisms. The governance structure of the relationship between companies and their supplier’s deals with uncertainty, and is consistent with the theoretical arguments in the resource-dependency stream of organisational theory (Pfeffer and Salancik, 1978) and transaction cost economics (TCE), Williamson (1985). Transaction cost theory and the property rights approach indicate that product complexity and vertical integration are complementary (Novak and Eppinger, 2001). Williamson (1985) identifies asset specificity, site specificity, physical specificity and human asset specificity, as related to TCE. In Bensaou's research (1992 p.7), the "auto assembler's asset specificity represents investments highly specific to the relationship", referring to investments of considerably less value outside the focal relationship, through which the supplier may hold the buyer hostage. These supplier investments, make it costlier and more difficult for the buyer to switch to another supplier, and encourage cooperation.

The movement of activities earlier in the product development process requires further examination of the total supply network (McIvor *et al.*, 2006). The SC literature has traditionally examined procurement and value-adding activities, without explicitly defining product development as part of these activities. The literature on ESI in the design process typically focuses on the outputs (Kamath and Liker, 1994; Brown and Eisenhardt, 1995). Such research tends to exclude the dynamics and factors influencing the process of supplier integration, such as the timing of supplier involvement, supplier design responsibility and buyer/supplier communication (Hartley *et al.*, 1997). Research by Hartley *et al.* (1997) indicates that shifting component design responsibility to technically capable suppliers can reduce costs if suppliers have lower wage and overhead costs, than their customers. ESI and frequent communication may increase goodwill, improve the nature of the buyer-supplier relationship and lead to mutual long-term benefits.

Supplier involvement in the NPD process varies greatly depending on the supplier's capability and willingness to collaborate. Wynstra and Pierick (2000) introduced a Supplier Involvement Portfolio to distinguish four types of supplier involvement in development projects: strategic development, critical development, arm's length development and routine development. For new-to-market products, strategic or critical development is required, due to the challenges of introducing these products. Strategic development is usually confined to arrangements such as keiretsu supplier relationships or joint ownership agreements. Arm's length and routine development are confined to non-strategic procurement decisions.

McCutcheon *et al.* (1997) found that the process used to link suppliers with buyers during the component development task was more important than the actual technical (content) outcome, at least in terms of shaping the opinions of the product designers. Whether the respondent was prepared to use a supplier in any future collaborative projects was more strongly related to the cooperativeness of the supplier than to its contribution to technical success. Moreover, in the eyes of the respondents of this study, much of the contribution to technical success could be attributed to the supplier's cooperativeness, through a more complete understanding of the problems facing the product developers, the supplier's quick response and its willingness to mesh smoothly with the agenda of the product developer.

The selection of suppliers during product design and engineering has a tremendous effect on the performance and success of NPD processes and manufacturing, with limited research available on the subject. Available methods have been developed which rely on multi-criteria decision analysis, qualitative (Akarte *et al.*, 2001) and quantitative (Choi and Hartley, 1996; Ghodsypour and O'Brien, 1998), however these methods account for less than the typical characteristics of design and engineering: iterative cycles of decision-making, the uncertainty of technological information and the gradual refinement of technological information (Shishank and Dekkers, 2013). This is confirmed by the case of Boeing, as it is known to have taken the sourcing and supplier involvement strategy to a new level by performing the plane's functional design process in-house (Norris and Wagner, 2009) and contracting sixty percent of the detail design and production of subsystems to at least fifty 'risk-sharing' global suppliers, in a 'build-to-performance' approach. The project contained risk, as the 'Dreamliner' airplane contained many novel, unproven features (Kotha *et al.*, 2005). Boeing was eventually forced to announce six delivery delays in sequence, over a period of two and a half years. The first delivery of the 787 Dreamliner, to Nippon Airways, took place in September 2011. Some of the causes for these delays included the lack of production progress of one supplier, causing Boeing to 'in-source' this operation, and the inability of Alcoa to supply nuts and bolts, due to its reduced production capacity after the 2008-2009 recession. As noted by Mauboussin

(2009, p. 89), this turned out to be a major mistake for Boeing, in terms of outsourcing the design and production of novel products without "fully recognising the circumstances under which it would work". This is a case of early involvement going wrong, because of the novel nature of the components and the risk of outsourcing design for novel products.

One critical element that is likely to be overlooked in the development of novel products is in-depth technical knowledge, both in-house and by way of access to external competencies, on the part of the selected suppliers in solving new problems, which are normally anticipated in the development of novel products. A study conducted by Hilletofth *et al*. (2010) appears to support this hypothesis, while Primo and Amundson (2002) mention the adverse effects of supplier involvement on the performance of product development. Boeing has since reduced the levels of in-house design and production work (Wallace, 2007). This example, along with Hartley *et al.* (1997) findings, underpins the notion that decisions on supplier selection during design and engineering will have a tremendous, and possibly adverse, effect on the performance of product development, and consequently production. This topic is mostly disregarded in the academic literature.

The literature has offered insight and methods for this crucial step in sourcing; for example, Handfield *et al.* (1999) view where technological competence and risk drive the outsourcing decision. The technological competence of suppliers is also stressed by Petersen *et al.* (2003, 2005). Moses and Ahlström (2008) emphasise strategic mirroring between disciplines and the involvement of all disciplines to ensure the adequate selection of suppliers. In addition to adequate processes for supplier selection, another factor which is important for product design, and engineering management and production management, is ESI and adequate knowledge sharing, as previously highlighted in the Boeing case. Hartley *et al.* (1997) declare that the selection of technologically capable suppliers is much more dominant than knowledge sharing during NPD. This study, together with those of Petersen *et al*. (2003, 2005), highlights the importance of ESI and knowledge sharing. Ragatz *et al.* (1997) assert that the benefits of early involvement are compelling. This view is also expressed in the work of Wynstra *et al.* (2010), who found that a supplier's strategic focus on innovation has a stronger impact on product development than its SC position. In this respect McIvor *et al.* (2006), emphasis the necessity of a collaborative attitude across all disciplines. Hicks *et al.* (2000) point out that, in engineer-to-order environments, an adversarial rather than a collaborative attitude prevails, due to high uncertainty and a low number of transactions. It is possible that the difficulties in collaboration with suppliers could also be attributed to absorptive capacity, which originated from the work of Cohen and Levinthal (1990). Absorptive capacity is defined as a company's ability to recognise the value of new information, assimilate it and apply it to commercial ends.

Most studies on this subject concentrate on uncovering determinants (Lane and Lubatkin, 1998; Tsai, 2009) rather than understanding their mechanisms. Based on a case study of Rolls-Royce, Prencipe (1997, p. 1274) advises that companies should "maintain an in-house thorough understanding of contracted out technologies to be able to integrate these technologies and control their evolution over time", a position reiterated by Brusoni *et al.* (2001). This notion of absorptive capacity is obvious; however, of more importance is the fact that, when companies engage in outsourcing design, engineering, manufacturing and SC functions, they can encounter dynamics of inter-organisational learning, a concept which has attracted limited research, except for that of Hoetker (2005) and Dekkers (2005). This raises the research question of whether the model of distributed production, as practiced by Boeing, is suited to producing new products when SC members are required to continuously innovate. In the context of project one, further research is required to investigate the interface between NPD and SCC, supporting Riedel and Pawar's (1998) claim that product design, engineering and manufacturing strategy are insufficiently linked in the available literature. Extending architecture to include the development process necessitates the early involvement of suppliers (Petersen *et al.*, 2005).

2.4.3.5. Life cycle planning

Fandel and Stammen (2004, p. 294) suggest that the adoption of sustainability practices in the design of SCs is now widely accepted. The consideration of SCC during product design is not restricted to modular design, ESI and co-development, it also appears in product and SCC life cycle planning. The theoretical rationale behind the PLC concept is derived from the theory of diffusion and adoption of innovation, Rogers (1962, p. 220). The seminal work on the life cycle theory of technological innovation was proposed by Abernathy and Utterback (1978). Built on a closely integrated interface between product design and SCM, product life cycle management (PLM) enables the planning and implementation of the PLC, from ideation, design and manufacturing to service and disposal (Grieves, 2005). PLM derives its potential value from integrating several otherwise disconnected activities. This integration is normally achieved through computer-based tools such as ERP, CAD, CAM and process automation. Much of this integration is now achieved using cloud-based platforms.

PLM is a KM system which aims to streamline the flow of information about the product and related processes throughout the product's life cycle so that the right information in the right context at the right time can be made available. PLM aims at reintegrating the SC organisation by closing all the knowledge loops and positioning the product at the focal point of the organisation. "The IT infrastructure of PLM is the enabler of KM through supporting systematic knowledge creation and transformation. Attempts to implement state of the art PLM technology will fail unless PLM is embraced as a business vision and strategic approach. Many organisations have realised that PLM strategy is rapidly moving from a competitive advantage to a competitive necessity" *(*Ameri and Dutta, 2005, p. 590). Many companies in the automotive, aerospace and machinery industries have applied vendor-supplied PLM software. The future market for PLM products is expected to grow steadily (Abramovici, 2007). Companies employ PLM to promote innovation in NPD, minimise costs, improve product quality (Grieves, 2010), reduce time-to-market (Shinno, 2009), preserve critical design information (Bermell-Garcia and Fan, 2008; Grieves and

Tanniru, 2008), leverage KM capabilities to drive intelligent business decisions (Lin and Ming, 2010), increase customer satisfaction (Schulte, 2009), and enhance collaboration with suppliers and partners (Wang *et al.*, 2010).

The literature addresses the known shortcomings of PLM, and highlights that not all its users achieve the success they had anticipated. The first weakness of PLM concerns network connectivity (Rouibah and Caskey, 2003). This, in turn, leads to Rouibah and Caskey's claim (2003, p. 19), that "most ECM between companies are paper-based". A second weakness of the PLM concept is the prevailing separation between workflow management and content. Mesihovic *et al.* (2004, p. 402) note that PLM has not been fully integrated with the stage-gate® approach. This notion is supported by the study of Hameri and Nihtilä (1998), which indicates that concentrating on workflows rather than PLM may lead to insufficient connection between disciplines. Taking this into account, Weber *et al*. (2003) propose the integration of these workflows, based on a new approach to design and engineering. A third weakness of PLM is that it requires a structured approach to working. This is bolstered by the growing trend among companies of taking on responsibilities for the total life cycle of individual products, which might include maintenance and overhaul. KM is of critical importance to PLM for this integration to occur. Grant and Baden-Fuller (2004) argue that companies may be characterised as product domains and knowledge domains. Efficient knowledge utilisation requires congruence between the knowledge domain of the company and its product domain. As highlighted by Grant and Baden-Fuller (1995), the loss of tacit and explicit knowledge remains a major obstacle to the successful implementation of PLM. A weakness of the PLM approach is that many companies operate paper-based systems, which are not efficient (Rouibah and Caskey, 2003, p. 19). Co-development, or coordinated product and SC design, is key to improving SC performance. Recent trends in globalisation and many companies' outsourcing of design activities have caused SCs to become much more complex networks. This has created a need for more coordination and integration of SC partners into the NPD process. However, despite the early attention drawn to the topic (Lee and Sasser, 1995, and

Joglekar and Rosenthal, 2003), very little has been published on how to pursue coordinated product and SC design.

2.5. DISCUSSION

The SLR identified the shortcomings of systems theory, in assessing relationships between NPD and SCC and the mirroring of these relationships. KBT is proposed as the means of addressing the SCC and NPD mirroring relationship, in answering research question three. Systems theory and KBT are incorporated in to the conceptual framework, shown in Appendix 2-1, Page 431; using three intervening control mechanisms, CD, FC and FAC to strengthen the mirroring process. Case study research is proposed for project two, to operationalise the SCCM construct.

Supply chains are considered as systems (Helou and Caddy, 2006), similarly the NPD process is considered as a system, which links organisational units or departments with relevant internal and external participants (Henderson and Clark, 1990). NPD and SCC systems are defined by the systems theory framework (Dekkers, 2005). A theoretical underpinning of complexity theory is proposed by Fowler (1999, p. 183): “developments in complexity theory, during recent years, have helped rekindle interest in systems concepts, with particular reference to the effect of non-linearity and its effect on the dynamics of networked systems”. von Bertalanffy (1950) employed systems control thinking to understand the interaction between system inputs and outputs, and the use of system controls. FC and FAC systems provide the mechanism to vary inputs to achieve the desired outputs (Koontz and Bradspies, 1972). FAC focuses on the regulation of inputs (human, material and financial resources that flow into the organisation) to ensure that they meet the standards necessary for the transformation process. FAC is desirable as it encourages management to anticipate problems. These controls require timely and accurate information that is often difficult to develop. This type of control is designed to detect deviation from some reference standard or goal, allowing for corrections to be made, before a sequence of actions is completed.

NPD performance directly influences organisational performance as it often allows the organisation to meet or exceed customer expectations (Ng and Anuar, 2011; Ng and Jee, 2011). The NPD literature emphasises that inter-functional coordination helps to ensure a clear and unified vision by aligning different technical competencies to ensure compliance with common goals (Cooper and Kleinschmidt, 1994; Brown and Eisenhardt, 1995).

Srai and Gregory (2008, p. 393) proposed a framework for capturing and aggregating configuration attributes into "related clusters which resulted in four categories of information; the strategic network level capturing tier structure and network performance, the flow of material and information through the main manufacturing unit operations, the interactions and relationships of the focal company internally and with its network partners, and the product structure in terms of modularity, variety and life cycle". PM allows for a more agile form of supply, in addition to the division of design, sourcing, manufacturing, distribution and after-market services.

2.5.1. Linking mechanisms

Where the NPD and SCC literature domains link, published peer-reviewed research has studied;

1. The NPD stage-gate® process
2. Integral PA and SCA design
3. Modular PA and SCA design
4. Co-development of PA and SCA
5. Mirroring of product and SC life cycles
6. ESI during PA and SCC design
7. Closed loop systems control using FC
8. Open loop systems control using FAC

The findings are shown in Figure 1-9, see Page 26. The literature highlights that there are several theoretical explanations when analysing NPD and SCC, depending on the context. One theory can become dominant, complementing one or several of the other theoretical perspectives. This perspective is supported by research (Halldorsson *et al.*, 2007).

The themes which have received the most attention in the academic literature are modular product and SC design, and ESI during PA and SCA design, see Table 2-28. Integral design is closely aligned with the COEP, product complexity and asset specificity concepts. Modular design, meanwhile, is closely connected to the COEP and product postponement concepts; and modularity is closely linked with the extent to which NPD is customer-driven, and postponement is closely connected to the COEP and the level of product customisation. Modular SCCs tend to have lower asset specificity, lower switching costs and lower risk of IP infringement, Novak and Eppinger (2001).

The linking mechanisms shown below in Figure 2-24, are derived from the object model (Booch, 1998). This model "seeks to simplify and explain complex systems" and uses systems theory to "derive a more specific model of inter-company PM" (Schilling, 2000, p. 331). Schilling (2000, p. 332), goes on to highlight that "all systems may be modular at some level, meaning that any empirical test of the model must attempt to measure change in the degree of modularity and should be designed to capture temporal effect".

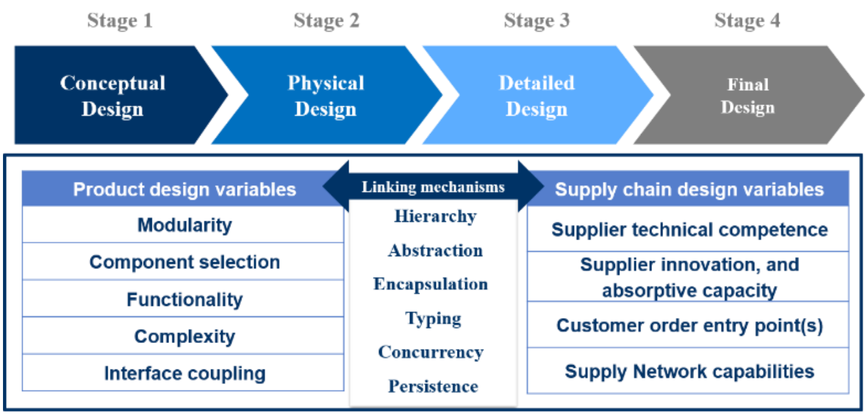


Figure 2-24. Description of linking mechanisms between NPD and SCC
Source: (adapted from Booch, 1998)

Modular product interfaces may be mirrored with SCC interfaces through the SCT and PRP, SCCM attributes shown below in Figure 2-25. Low FS within the PA may be closely mirrored with SCCM by the ability of processes to postpone the final product configuration. Optional attributes or measures may or may not be present in the mirroring relationship between PM and SCCM.

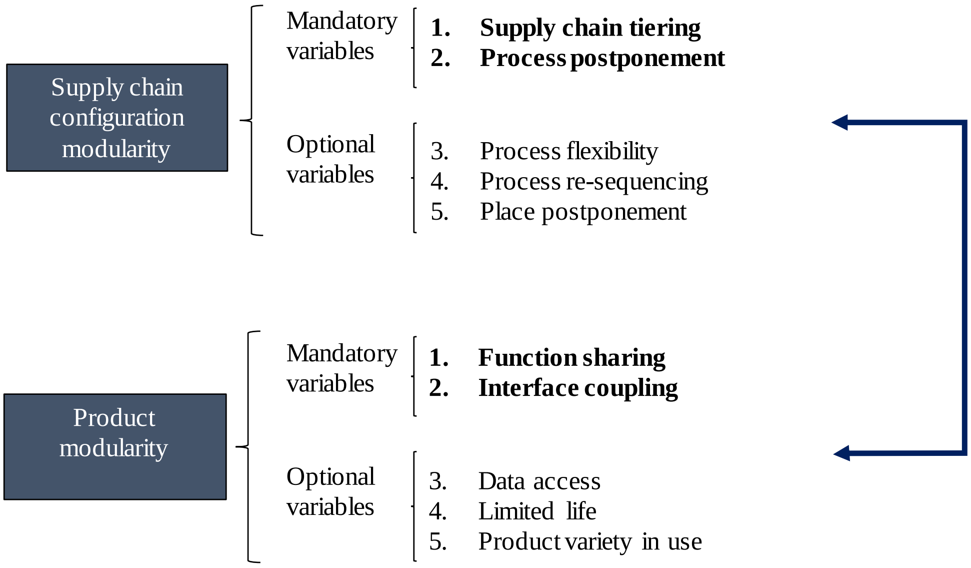


Figure 2-25. Mandatory and optional PM and SCCM attributes

2.5.2. Mirroring concept

Complex product development is driving companies to adopt new and innovative product design and development processes (Rycroft and Kash, 1999). Many companies have embedded concurrent design thinking in their SCC processes (Khan *et al.*, 2012), but prior research primarily considers SCC during the detailed product design phase, after the PA has been defined. Opportunities for NPD process improvement exist, in the earlier concept phase of product and SCC design. The purpose of this research is to improve the effectiveness of the NPD process, incorporating SCC at the earlier product concept design stage.

The notion of 'fit' in OM literature has evolved following the adoption of the contingency approach in an endeavor to achieve greater organisational effectiveness (Sabri *et al.,* 2000). Project two uses the scientific mirroring concept which takes a reductionist approach (Cabigiosu, *et al.,* 2013; Colfer and Baldwin, 2010), adopting the belief that every process in nature can be broken down into its constituent parts and described scientifically. Sabri *et al.* (2000) investigate the possible approaches to achieving a state of fit between SCC settings and performance indicators, while considering contextual factors related to different industry sectors and geographical dispersion levels. Sabri *et al.* (2000) address performance trade-offs faced by SCs to achieve a higher service level and customer satisfaction (effectiveness) on the one hand, while being cost-efficient on the other (efficiency). Sabri *et al.* (2000) suggest adopting guiding principles to achieve a competitive SC, rather than replicating a predefined set of best practices. This concept predicts that there will, or should be, a correspondence between the dependencies in the technical architecture of a complex product and organisational ties between the system's designers.

The mirroring hypothesis proposes that, while modular products (high PM) trigger the adoption of modular organisations (high OM), integral products (low PM) trigger integral organisations (low OM). The first explicit recognition of the PM's positive effect on OM dates to research by Sanchez and Mahoney (1996). 'Since then, scholars had not reached a consensus on whether the mirroring hypothesis can adequately explain the relationship between product and organisation architectures' (Sorkun and Furlan, 2016). This mirroring hypothesis is based on two postulates of PM. First, the standardised interfaces of modular products embed all the information needed to support the coordination of development and production activities (Sanchez and Mahoney, 1996). Second, modules are devised to encapsulate interdependent components within the same technical boundaries (Gershenson *et al.,* 1999), which minimise the interdependencies across modules (Sorkun and Furlan, 2016).

Research reveals that mirroring PM with SCCM results in product cost reduction, improved SC performance, and increased flexibility (Brusoni and Prencipe, 2011; Zirpoli and Becker, 2008; Whitford and Zirpoli, 2014). There are situations where corresponding levels of modularity in PM and SCCM are not observed (Hoetker, 2006; Danese and Filippini, 2010). Ülkü and Schmidt (2011) express that matching PM and SCCM is not normally observed in practice, and van Hoek and Chapman (2006, 2007) detect the lack of an integral view of NPD and SCC.

Colfer and Baldwin (2010), formally define the mirroring hypothesis and review 102 empirical studies spanning three levels of organisation: within a single company, across companies, and in open community-based development projects. Of the sixty-two across-organisation studies reported by Colfer and Baldwin (2010), forty-seven percent fully supported PM and OM and the mirroring of these constructs; twenty-three percent offered partial support; and five percent provided mixed support. These longitudinal studies in turn told two stories. In the first story, the focal industry initially consisted of vertically integrated organisations developing technically integrated products. A modular PA emerged and became the ‘dominant design’ (Abernathy and Utterback, 1978; Tushman and Murmann, 1998; Murmann and Frenken, 2006). The structure of the industry changed to mirror the new PA, with different organisations focused on developing separate modules. The products examined in these studies included stereo systems (Langlois and Robertson, 1992), computers (Langlois and Robertson, 1992; Baldwin and Clark, 2000), bicycles (Galvin and Morkel, 2001), automotive (Ro *et al.*, 2007), and gaming devices (Lecocq and Demil, 2006).

The second story runs in the opposite direction, where the focal industry initially consisted of specialist organisations developing modular components. When a new integral ‘dominant design’ emerged, the structure of the industry subsequently changed to mirror the integral PA (low PM), with individual organisations developing integrated products. Organisations lacking the capacity to integrate are often forced to exit the industry. The products examined in these studies included bicycle drivetrains (Fixson and Park, 2008) and building facilities (Cacciatori and Jacobides, 2005).

PM and SCCM are also studied by Fine, at an industry level. The double helix model, illustrates how industry and product structures reciprocate from vertical/integral to horizontal/modular (Fine, 1995, p. 63.), shown below in Figure 2-20, Page 116. Fine and Whitney (1996) analysed OM at four levels ‘intra-company’; ‘inter-company’; ‘supply network’; and ‘industry’, in the context of making make-buy decisions. They study PA along the modular-integral spectrum, viewing integral SCC as vertically-integrated with a single company owning the SC and modular SCC as horizontal and ‘dis-integrated’. They view SCC as continuously integrating and disintegrating.

In support of Fine’s double helix model at the industry level, Fujimoto (2014) studied PM and SCCM along the industry modularity spectrum, within the Automotive and Computer sectors. Fujimoto viewed low PM as closed and high PM as open (Fujimoto, 2014). This paragraph illustrates the historical evolution of PM to SCCM mirroring in these industries, as shown in Figures 2-6 and 2-8. Empirical results of papers in the personal computer and air-conditioning industries (Hoetker, 2006; Cabigiosu and Camuffo, 2012) verify that higher PM lowers the coordination needs, thus enabling greater OM. Several studies have empirically supported the mirroring effect between OM and PM at different levels of analyses and in different industries (Schilling and Steensma, 2001; Sturgeon, 2002; Fixson and Park, 2008; Cabigiosu and Camuffo, 2012).

PM and SCCM in craft industries was high in the 1890s, when products were often designed to customer requirements. As the automobile industry matured, dominant designs such as Ford’s Model T product platform emerged in 1908, leading to mass customisation. While Ford focused on cost, Alfred Sloan focused on producing a greater variety of better quality cars, allowing GM to overtake Ford in sales in 1927, after which the Model T was discontinued (Gartman, 2006). Since the 1930s, automobiles have moved to higher levels of SCCM. However, Formula one cars for example continued to have low levels of PM and SCCM. From the 1930s to the 2000s SCCM became increasingly modular, with PM remaining at a low level. Since the early 2000s PM levels are increasing, shown below in Figure 2-26. This reflects a further example of the double helix model in the automotive industry.

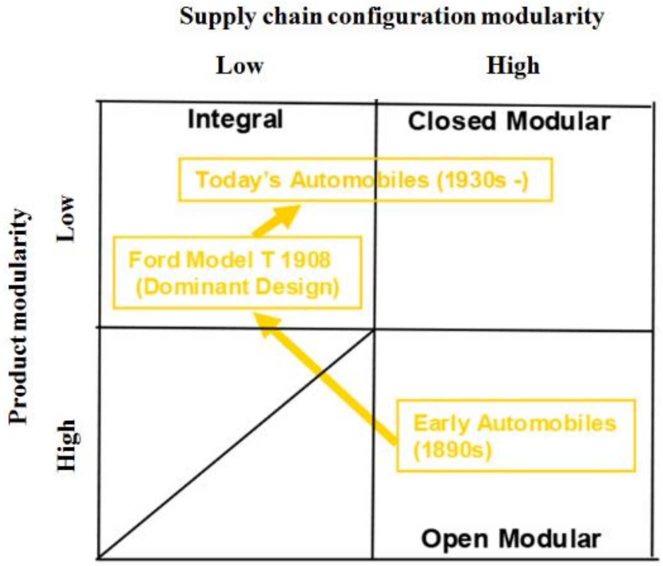


Figure 2-26. Modularity shifts in the automobile industry
Source: Fujimoto (2014)

Fujimoto (2014) illustrate on a time-series graph, the rates of innovation in the automotive sector, see Figure 2-27. During the 1890s PM and SCCM were high, and mirrored each other, as shown below in Figure 2-27. This was a period of high product innovation. With the arrival of the Model T Ford in 1908, PM and SCCM moved to a low level of modularity. This coincided with an increase in process innovation at Ford, a decline in product variety offered to customers, and a decline in product innovation.

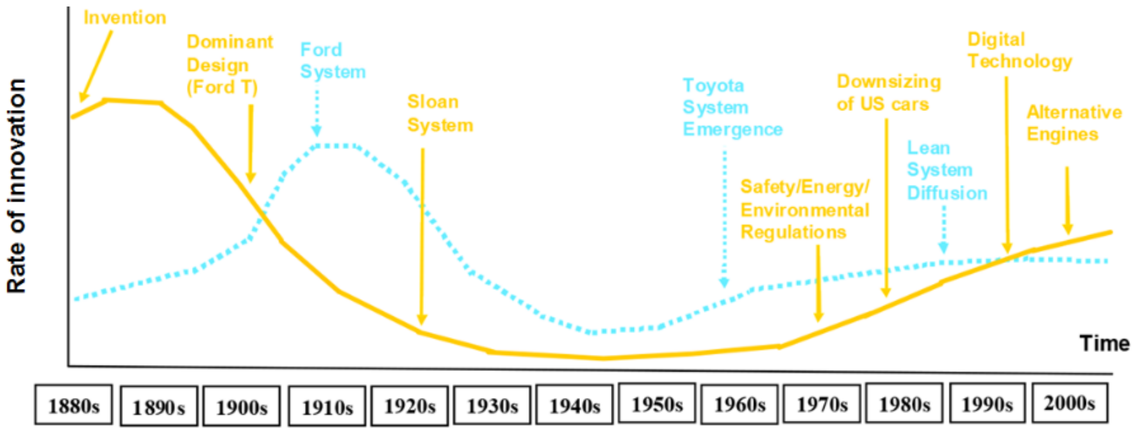


Figure 2-27. Rates of innovation in the automotive industry
Source: Fujimoto (2014) after Abernathy and Utterback (1978)

In the case of computer products, the architectural sequence is different, shown below in Figure 2-28. The first-generation ENIAC computer had low PM, with model-specific circuits (low SCCM). IBM's System/360, dominant design in the 1960s had a high level of SCCM, with the system using industry standard components, together with IBM's proprietary operating system (Freeman, 1982; Baldwin and Clark, 1997). The advent of personal computers (high PM, and high SCCM), with industry standard components and an industry-standard OS and CPU, followed on from IBM's experience in the mainframe sector.

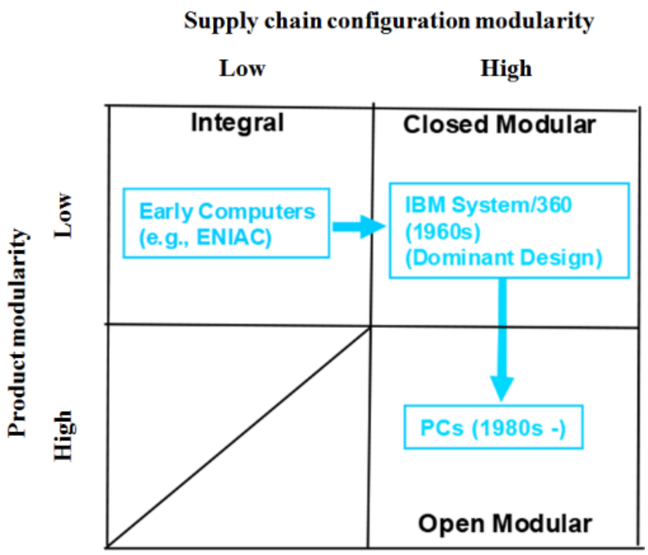


Figure 2-28. Modularity shifts in the computer industry
Source: Fujimoto (2014)

There are also arguments where mirroring may not occur. Wolter and Veloso (2008) point out that obsolescence risk and the need to preserve outside options creates forces causing product fragmentation. Organisations and industries experiencing modular innovations may have a propensity to break apart. Helfat and Campo-Rebado (2009) show that vertically integrated organisations may choose to stay integrated, even when the underlying technical system is modular, if they anticipate that the designs will become reintegrated later.

2.5.3. Knowledge based theory

Informed theory-building and theory testing are necessary if organisational study is to fulfil its potential for generating work that has originality, utility, and prescience (Corley and Gioia, 2011). “Management thinking over the past decade is based on process theory, the idea of management as a process” (Easterby-Smith *et al.*, 20012 p. 4). Process theory emphasises learning processes, the creation and management of organisational knowledge (Nonaka and Takeuchi, 1995), and the importance of power and politics underlying knowledge legitimation. At the wider level there are links to strategic perspectives including the idea of strategy as practice (Jarzabkowski *et al.*, 2007*).* The long-term challenge of designing SCs is also ill-matched with managerial culture, where rapid career moves are combined with successive management fads and fashions (Pascale, 1990; Scarborough and Swan, 2001). The knowledge-based view of the firm stresses that effective communication requires overcoming obstacles such as tacitness and social embeddedness (Ulrich, 1995). It is important to develop a conceptual framework for SCC design, which takes a knowledge-based view of the firm.

KBT recognises that individual knowledge is a key resource of most organisations. KBT considers knowledge as the most strategically significant resource of an organisation (Grant, 1996). KBT was selected as an appropriate framework for studying the inter-relationships of PA and SCC, given the requirement for concurrent product and process design, at the product concept stage. Co-development of PM and SCCM is the first consistent theme of this empirical research. Mirroring of knowledge across epistemic communities involves ‘perspective taking’, a process ‘in which the perspective of another community is considered as part of a community’s way of knowing’ (Grant, 1996). Mirroring is often difficult or impossible to achieve unless requisite ‘integrating devices’ are in place (Lawrence and Lorsch, 1967; Grant, 1996). Coding of PM and SCCM attributes, together with the design and definition of interfaces between these constructs is important to ensure knowledge transmission and exchange, shown below in Table 2-28.

Table 2-28. Typology of knowledge transmission and exchange
Source: Hakansson (2010)

	Degree of codification: Low	Degree of codification: High
***within* epistemic communities**	*Apprenticeship / personal interaction*	*Information exchange*
***between* epistemic communities**	*Integration / combination*	*Design and definition of interfaces*

The literature that pertains to the mirroring hypothesis commonly draws on two distinct sources for its motivation, the literature on product design and products as complex systems (Simon, 1962; Ulrich, 1995), and the literature on organisation design and organisations as complex systems (Thompson, 1967; Galbraith, 1974; Weick, 1976). Recent contributions to cross-company academic literature do not challenge the mirroring hypothesis, but rather add new concerns to prior theoretical arguments. KBT supports the five arguments, presented in this chapter, as to why PM and SCCM mirroring is desirable.

The first argument for KBT supports information hiding as a means of controlling complexity and is a fundamental principle underlying the mirroring hypothesis. With information hiding, each module is informationally isolated from other modules within a framework of system design rules. This means that independent individuals, teams, or companies can work separately on different modules, yet the modules will work together as a whole (Baldwin and Clark, 2000). Parnas encourages product developers to avoid sharing assumptions and data. Specifically, he contends that every developer’s product module, or task assignment, should be “characterised by its knowledge of a design decision that it hides from all others” (Parnas, 1972: p. 1056).

The second argument relates to IP protection, and the notion that PM and SCCM knowledge can be protected by breaking it up. Knowledge is inherently mobile, since it resides in the heads of individuals (Grant, 1996). With the mirroring of PM and SCCM, it is more feasible to isolate the knowledge that is required to be exchanged from that knowledge specific to the product or process module or modules. The alternative is that the OEM must vertically integrate and implement that function or generate that input independently, or provide the product design capabilities in-house. Patents, copyrights, and trade secrets all have their limitations. These protections are extremely limited or non-existent for knowledge that is only partially original, or is tacit, or is long lived. "Integration of knowledge and other types of coordinated action between members of different epistemic communities do not require that each acquire the knowledge of every other" (Hakansson, 2010, p. 1813).

Patents yield organisational effects at the micro level by lowering the costs of contracting intellectual resources, which in turn yields innovation effects by allocating SC functions to the cost-minimising combination of internal and external providers. Patents, copyrights and trade secrets are not the only means of protecting property rights. Depending on the type of market and product field, secrecy, lead-time or the complexity of product and process design may be used to protect innovations, particularly by smaller companies. Modular-based processes are an important consideration in isolating knowledge and protecting IP. 'Companies can protect knowledge from expropriation or imitation more effectively than market contracting' (Liebeskind, 1996). With modular-based systems, it is understood that there does not exist any technological constraint that would bar segregation of design and production functions. This assumption will be most clearly satisfied in markets that have developed standardised interfaces that enable companies to work independently on modular components of a 'system architecture' or to work on the design of a component without being involved in its production (Carliss *et al.*, 1997).

The third argument supports the opportunity to use multi-tier, or outsourced SCs for producing modular products because the levels of knowledge that need to be shared are lower at product module interface level than for an integrated product where functions are shared across components and interfaces are tightly coupled. This argument for mirroring relates to supplier co-ordination and the importance of knowledge sharing between the OEM, system integrators and suppliers. Knowledge can be transferred more efficiently through reduced form. Thus, ‘direction’ involves specialists in one area of knowledge issuing rules, directives, and operating procedures to guide the behaviour of non-specialists and specialists in other fields. The implication for modular products is that where the design and or manufacture of modules is outsourced, knowledge transfer is far less than in the situation where outsourcing is used for an integrated product.

The fourth argument recognises that an increasing portion of product and SCC design is provided by external companies. This argument for mirroring relates to supplier innovation, and sharing of knowledge between suppliers and OEMs. OEMs benefit from access to specialised supplier knowledge. In the SLR, one of the linking mechanisms between PA and SCC was ESI. On the supply side, suppliers must be encouraged to generate new product and SCC ideas. It is in the interest of all parties that strong property rights exist. This knowledge exchange is often referred to as the disclosure paradox; without disclosing information on the module to be supplied it may be difficult to incorporate the component or module in the final product. By modularising product and SCC designs it becomes more feasible to enforce these property rights. Expropriation risk may block efficient sourcing transactions, which in turn may inflate commercialisation costs and discourage R&D investment. Strong IP rights enable companies to disaggregate SCs to the extent necessary to extract specialisation gains with respect to each SC function. Across otherwise disparate markets and periods, a secure background set of property rights supports entry by specialised suppliers offering technological inputs, which in turn set off disaggregation processes that allocate SC functions among a pool of external and internal partners. SCCM can reinforce task disaggregation, where “valuable knowledge-production or knowledge-use processes can be located far away from the other activities of a company” (Liebeskind, 1996, p. 100). The gap in research is due primarily to the lack of empirical research in SCCM, including its integration in the new product concept process. In line with Grant (1996) the activities of companies require the mobilisation and coordination of specialised and diverse expertise. Organisations such as Toyota, Boeing, Microsoft, and Dell have successfully developed a dynamic learning capability, enabled through a knowledge sharing network (Dyer and Hatch, 2004) using a variety of means, including supplier associations, consulting groups and learning teams. Interestingly, these companies appear to be able to protect their knowledge from expropriation or imitation effectively, using modularity, where more traditional SCs have relied on a centralised model of value creation and exchange, managed through contracts. 'Because property rights in knowledge are weak, and costly to write and enforce, companies can use an array of organisational arrangements that are not available in markets to protect the value of knowledge' (Liebeskind, 1996).

The fifth argument stresses the importance of knowledge integration and combination of knowledge which is of interest to PM mirroring with SCCM (Hakansson, 2010, p. 1812). In line with Schumpeter's (1934) definition of innovation, Grant (1996) and Nickerson and Zenger (2004) discussed the relative advantages of companies in the generation of new capabilities through new combinations of specialised knowledge. Product and SC R&D leads many academics to emphasise KM as an important means of R&D innovation (Parikh, 2001, cited in Suh *et al.*, 2004, p.5). Strong implementation of KM methods has a positive effect on NPD performance (Liu *et al.*, 2004).

2.5.4. Conceptual framework

This deductive research takes a positivist approach; it reviews existing literature, identifies weaknesses and limitations of this research and identifies the gaps in the literature. Project one, reviews theoretical perspectives, prior to the development of a conceptual framework to support the direction of further empirical research. Through the SLR, GST emerged as a framework for synthesising the sometimes-complex relationships between NPD, SCC, and product planning, focusing on behaviour and relationships between these constructs. An identified weakness of GST is that it does not take knowledge generation and management in to consideration. Because of this weakness, KBT which focuses on integration, is used as a means of investigating the mirroring of SCC and NPD, post product launch. Hult (2007) highlights the positive effect of KM on SC performance.

A review of the underlying codes, shown in Appendices 2-4, Pages 439-420 and themes, shown in Appendix 2-6, Page 445, identified modular architecture (Fine and Whitney, 1996) and ESI in the product development process (Dowlatshahi, 1998), both of which benefit from improved FC and FAC, as shown below in Figure 2-29.

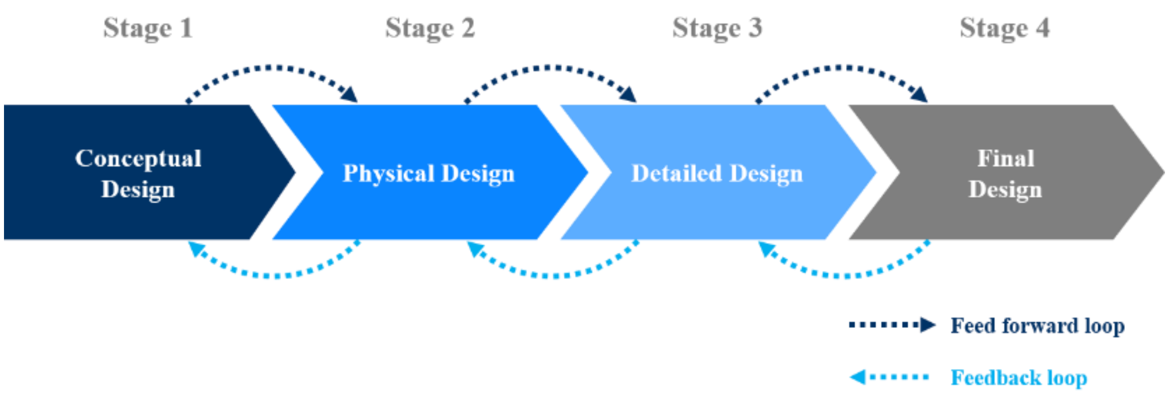


Figure 2-29. Feedforward and feedback knowledge loops
Source: adapted and modified from Gokhan (2007)

Using a system approach, factors can be reviewed within the organisation (or group of organisations) and external to organisations (Balachandra and Friar, 1997). The focus of FAC is to increase the levels of coordination, addressing the concern of Ülkü and Schmidt (2011), who state that a lack of coordination between the product and its SCC results in less successful product launches. The reduced life cycle of many products, together with the requirement for fast launch, necessitates an increasing focus on FAC, which is defined as 'anticipatory' in that it acts preventatively to avoid differences in planned and actual performance, and this is important in an increasingly dynamic environment (Koontz and Bradspies, 1972; Ishikawa and Smith, 1972). It can also assist in managing uncertainty. It is argued that control should be aimed at the relationship between, and the formalised integration between, the planning system and the control function (Ishikawa and Smith, 1972). In other words, FAC should be aimed at the relationship between SCC, and the NPD control function. In answering the research question, it was determined that product planning is an antecedent to product design. FAC focuses on the regulation of inputs (human, material and financial resources that flow into the organisation) to ensure that they meet the standards necessary for the transformation process. These controls require timely and accurate information that is often difficult to develop. This type of control is designed to detect deviation from some standard or goal to allow correction to be made before a sequence of actions is completed. Both areas are related to modularity in product and SC design. FAC takes place while NPD and SCC activity are in progress; it involves the regulation of ongoing activities that are part of the transformation process to ensure that they conform to organisational standards.

The findings and development of the COEP concept in the management of the interface between NPD and SCC have also been discussed. COEP allows companies to manage product complexity and offer their customers variety. FC and FAC should address the COEP. To provide flexibility, SCs must be configured to accept orders at different points in the SC process, separating activities performed on customer orders from those performed on speculation (Wilkner and Rudberg, 2005).

2.5.5. Reliability

Research design must address the issue of quality assurance together with bias. The quality of research is normally evaluated using the criteria of reliability and validity. There must be practical standards to evaluate the quality of conclusions. Those standards address the question of whether the research and findings are good (Miles and Huberman, 1999).

There is a question of trustworthiness in qualitative research. Johnson and Harris (2002) suggest that there are two ways to generate trustworthiness for qualitative research. The first confirmability is effectively concerned with transparency of data interpretation. Miles and Huberman (1999) indicate questions concerning confirmability include:

- Are the study's general methods and procedures described explicitly and in detail?
- Can we follow the actual sequence of how data was collected, processed and transformed?
- Has the researcher been explicit and as self-aware as possible about personal assumptions, values and biases?
- Is there a record of the study's methods and procedures providing an audit trail?

The confirmability quality factor is one of transparency in all aspects of the research project. This study has addressed the challenge of confirmability in the following ways:

- The study's methods and procedures are described explicitly and in detail.
- A sequence of how the data was collected, analysed and transformed through the process of coding and interpretation is provided.
- An explicit discussion of researcher assumptions and bias is addressed.
- Data in the form of a data extraction sheet, is shown in Appendices 2-5, Pages 442-445, and coded transcripts are available for inspection

- The descriptions described previously provide an 'audit trail' of the study's findings and conclusions.

The second way to generate trustworthiness is authenticity of the interpretations, of the data. Miles and Huberman (1999) suggest questions addressing authenticity include:

- Are the descriptions gained 'thick' enough? Are they contextually rich?
- Does the account ring true, seem convincing, plausible?
- Have the rules for interpretation been made specific?
- Have rival's explanations been considered or has only one explanation been considered from the start?

Authenticity is about the trustworthiness of the researcher's interpretation of the data and subsequent conclusions. A social constructionist position using qualitative research methods presents a challenge for the traditional concepts of reliability and validity.

An authentic interpretation of the data is presented in this research using direct quotes from the participants that tell a true account of the data. Alternative explanations have been provided where required. Trustworthiness is a critical factor in evaluating the findings and conclusions of a research study. This study has been explicit in describing the factors critical to building credibility and trust in the findings and conclusions. The findings and conclusions of the research are confirmable and authentic.

2.6. SYNTHESIS

This synthesis addresses gaps in the literature; mechanisms linking the key constructs; limitations of this review; contributions to literature and practice, and literature guidance for empirical studies in NPD, leading to the research hypotheses for project two and project three. Table 2-29 illustrates the benefits of SCC mirroring with NPD, however the academic literature indicates a lack of SCC consideration at the concept stage. Riedel and

Pawar (1998) highlight that product design, engineering and manufacturing strategy are insufficiently linked in academic literature. I have not found a specific theoretical or empirical study undertaken that understands how SCC is used to influence NPD management teams to improve NPD performance.

From this analysis I have concluded a valuable research question for empirical study: *"What is the relationship between new product development, product planning and supply chain configuration prior to product launch?"*. Answers to this question can provide contribution to KM controls and a contribution to practice, in NPD.

A systems perspective is deduced from the literature as the foundation for conducting the empirical research in project two and project three, supported by KBT. During project two field research is undertaken to understand what happens in practice, and investigate the mirroring hypothesis. During project three, further field research is conducted to confirm research hypotheses two, three and four, which deduce from the SLR that the application of CD, FC and FAC at the product concept development stage, lead to improved NPD.

Table 2-29. Impacts of SCC Mirroring with NPD

	Positive impacts of SCC mirroring with NPD	Authors
1	Time to market	Wynstra *et al.* (2001)
2	Supply chain performance	Wynstra *et al* . (2001)
3	Company performance	Wynstra *et al* . (2001)
4	Revenue growth	van Hoek and Chapman (2006)
5	Stock-outs at the retailer level in a pull-based supply chain	Pero, Rossi, Noe, Sianesi (2010)
6	Cost reduction	Narasimhan and Das (2001)
7	Delivery reliability	Shin *et al* . (2000); Narasimhan and Das (2001)
8	Quality improvement, conformance to specfication	Shin *et al.* (2000); Tan (2002)
9	Ability to implement lean practices	Alam *et al* . (2014)
10	Reduced inventory	Alam *et al* . (2014)
11	Enhanced flexibility and responsiveness	Alam *et al.* (2014)
12	Improved operational performance	Cagliano *et al.* (2006)

	Aspects of SCC and NPD performance impacted on by lack of SCC mirroring with NPD	Authors
1	Traditional performance measures, such as quality, flexibility, costs, delivery, reliability and speed	Arnheiter and Harren (2005)
2	Inter-organisational collaboration	Panayidesa and Lun (2009)
3	Early Supplier involvement	Chen and Paulraj (2004)
4	New product development time	Blackhurst *et al.* (2005); Danese and Filippini (2013)
5	Product innovation	Worren *et al.*(2002); Pil and Cohen (2006); Ethiray *et al.* (2008)
6	Delivering product variety	Chung *et al* . (2012)
7	Manufacturing agility	Jacobs *et al.* (2011)
8	Integration and coordination mechanisms	Jacobs *et al.* (2007)

For linking mechanisms to form part of a theoretical contribution, there is a requirement to exhibit a high degree of generalisation and a high degree of certainty, A review of the linking mechanisms revealed that studies have been conducted on product characteristics (Hill, 1985); value chains (Porter, 1985); supply networks (Harland, 2013); product and SC dynamics (Fine, 1998), and 3DCE and PA (Fixson, 2005), fulfilling the requirements of generalisation and certainty, shown below in Table 2-30. NPD requires ESI, and SCC requires ESI. Rossetti and Choi (2005) caution how this involvement is governed. In this area of much research has failed to go beyond the study of product characteristics (Hill, 1985); hence, there is an opportunity to extend this research.

Table 2-30. Theoretical contribution

Degree of Certainty (Low → High)

Degree of Generalisation (High → Low)

Degree of Generalisation	Low	High	
High	Alderson (1957) Williamson (1979) Ancona & Caldwell (1980) Hauser & Clausing (1988) Lee & Sasser (1995) Fisher (1997) Verona (1999) Halldorsson et al (2007) Fleischmann (2000) Christopher & Towill (2000) Krishnan & Ulrich (2001) Vickery et al. (2003) Mentzer (2004) Kainuma & Tawara (2006)	Hill (1985) Porter (1980) Harland (1996) Fine (1998) Fixson (1995)	Links product to market and SC Value chains Supply networks Product and supply chain dynamics 3DCE and product architecture
Low		Saaty (1980) Graves & Willems (2005) Chiu et al. (2011)	Analytical hierachical process Multi-objective modeling Centralised v decentralised supply chain decisions

The co-development theme is closely linked with ESI in the NPD process. This research identifies the requirement for early SCC involvement in product development, and a joint approach to the involvement of SC partners, this observation was also highlighted by Hoek and Chapman (2007), shown below in Figure 2-30. Only two papers focus on PLC.

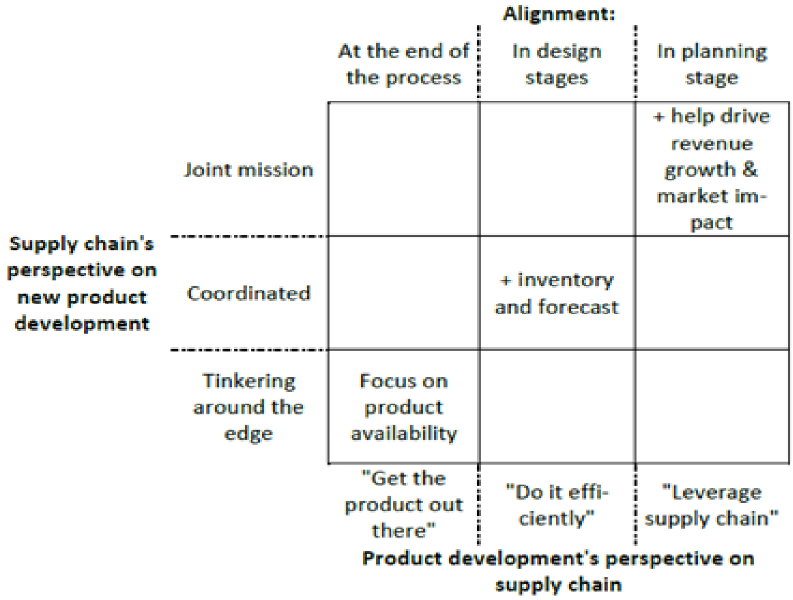


Figure 2-30. Supply Chain perspectives on NPD
Source: van Hoek and Chapman (2007)

2.6.1. Gaps in the Literature

SCC has attracted much attention in scientific literature (Chandra and Grabis, 2016, p. 41). There are many existing surveys on the SCC problem, covering facility location (Melo *et al.*, 2009), global aspects of SCC (Goetschalckx *et al.*, 2002; Meixell and Gargeya, 2005); the location-inventory problem (Graves and Willems, 2005); supplier selection (De Boer *et al.*, 2010), and environmental aspects of SCC (Ramezani *et al.*, 2014), however no research exists on defining and differentiating the main SCC sub-processes, comparing module and interface types associated with each step in the SCC to further understand critical path issues during product concept design.

A review of NPD and SCC co-development is covered primarily by research on 3DCE. Whilst 3DCE held promise in the late 1990s as a framework for concurrent product, process and SC design, there are few examples of its successful implementation. Could it be that 3DCE research did not adequately define the linking mechanisms between the three domains of product, process and SC? The six theoretical frameworks examined in the scoping study fail to address the linking mechanisms between SCC and NPD, at the concept stage. Academic papers on ESI in NPD (Dowlatshahi, 1999; Mikkola and Gassmann., 2003; Zsidin *et al.*, 2005), have addressed the benefits of ESI, but have generally failed to take an in-depth view of the linking mechanisms, except for research into teamwork and team effectiveness (Caron and Fiore, 1995). Early studies by Holt (1970) and Ramsey (1981) have indicated the need for a more structured approach to NPD. Cooper (1988) presented the stage-gate® process as a structured approach to managing NPD. Although stage gates are strongly promoted, they are under-researched (Schmidt and Calantone, 2002). Smith and Reinertsen (1991), in addition to other researchers addressing innovative approaches to product development, claim that phase reviews slow down product development. They assert that gates should be eliminated, with a focus placed on the NPD 'critical path'. Griffin (1997) reports that sixty percent of US companies use a disciplined cross-functional process for NPD. There is limited literature on a critical path approach to NPD.

There is limited empirical evidence showing how SC integration influences NPD performance (Feng and Wang, 2012) and a lack of research literature on the mirroring of NPD and SCC. Fixson (2005) developed a PA framework as a mechanism to coordinate decisions across product, process and SC design. The framework, however, is limited to considering PA only, with no consideration to SCC.

Chiu and Okudan (2011) presented a graph theory-based optimisation method by which to integrate product and SCC decisions at the product design stage. They evaluated the impact of the supplier selection process on manufacturing and external enterprise performance. They incorporated these sub-performance measures into the SC performance and applied their model for a bicycle case study; however, they did not consider all the issues related to SC partners in their model. Fleischmann *et al.* (2000) investigated the design of the reverse logistics networks that recover used products. They identified the basic characteristics of product recovery networks and classified the product recovery networks into three types: recycling, remanufacturing and reuse networks. The definition of sustainability has been evolving over the past years; while some companies consider sustainability to be the extension of a product's useful life, for others, sustainability primarily means environmental stewardship (Srivastava, 2007).

A limitation of current SCC models is the narrow focus on cost minimisation (Lebreton and Tuma, 2006). Many SCC and NPD studies use multi-objective optimisation models. These models can be divided into two types: the stochastic-service model and the guaranteed-service model. Graves and Willems (2003) demonstrate that the total SC cost for a guaranteed service-time model is always lower than that of the stochastic service-time model. Inventory theory is concerned with providing methods for managing and controlling inventories under different policy constraints and environmental conditions (Clark and Wheelwright, 1995). Graves and Willems (2003) introduce the SCC problem of determining the configuration of an SC, including what suppliers, parts, processes and transportation options (modes) to select at each stage in the SC. It arises after the product concept design has been determined. Clark and Scarf (1962) are credited with conducting the earliest research on multi-echelon inventory problems. The multi-echelon inventory management model, which is a variant of the guaranteed-service model, optimises the safety stock placement at each node in the supply network if each stage already has an option (Graves and Willems, 2005). The aim is to establish the lowest unit manufacturing cost (UMC) for each SCC prior to product design completion. The UMC is the linking mechanism between NPD and SCC.

A further limitation of the research is that most of the models in the SLR only consider a single time-period. Of the fifty-nine papers selected for the SLR, only two (Novak and Eppinger, 2001; Aitken *et al.*, 2003) conducted longitudinal studies. To observe the true benefits of pursuing a closed-loop flow, there is a need to run SC models over multi-time periods to capture the performance over multiple product life cycles.

2.6.2. Intervening mechanisms

The SLR presents an argument for adopting a systems perspective during project two and project three. 'The fundamental transformational model, which underpins many keys texts on OM, is intrinsically systems oriented' (Bates and Slack, 1998). This SLR has identified two areas for future research, in project two. The first area covers the conceptualisation of PM and SCCM. This requires the development of the SCCM construct and research question two: *"how can SCCM be conceptualised considering modularity principles and contemporary supply chains?"* The second area proposes that PA and SCC gravitate towards the mirroring of PM and SCCM. This hypothesis is answered by research question three: *"how is mirroring of PM and SCCM manifested?"*.

Project three assesses research question four: *"how do co-development, feedback control and feedforward control systems affect the mirroring of modular product design and modular supply chain configuration after product launch?"*.

2.6.3. Limitations of the SLR

Section 2.6.1. identifies significant gaps in the literature on mirroring of NPD with SCC. Most of the academic papers are from the US, restricting the search criteria to the English language which may exclude relevant academic papers. Nine papers including conference proceedings were from non-ranked publications and four were from 2* Journals. These were however high quality papers, and fulfilled the search criteria.

The limitations of this review are four-fold. Firstly, the findings and arguments are based on fifty-nine academic papers. The search strings are key in identifying related research, although a thorough review was conducted of related literature in the *a priori* development of the search strings, this process is not exhaustive. Whilst a rigorous and extensive approach to the literature search was applied, it is not plausible to claim that all existing and relevant information on SCC and NPD is represented. It is possible that my inclusion and exclusion criteria, though reasonable and justified, have caused the omission of studies that could be relevant to the research question. Moreover, the small number of studies reviewed places limitations on the extent of generalisation that can be made. Hence the findings are tentative; further research is required before any strong conclusions can be drawn.

The second limitation relates to the difficulty in discerning causality in the SCC relationship with NPD. Causal ambiguity makes it cumbersome to determine whether well performing companies engage in SCC planning or whether careful SCC leads to superior NPD process performance. It could be that successful companies with slack resources and better capabilities engage in SCC optimisation. Consequently, my claim of a positive impact of SCC on performance is moderate, tentative and based on extant literature.

The third limitation acknowledges personal bias in the framing of the research question and implementation of the quality criteria. Even though the criteria for assessing quality of the selected studies were determined prior to the review, my personal judgment came into play when I scored each of the studies. I decided what the cut-off score for inclusion should be and this could have made me exclude or miss important pieces of research.

Finally, none of the studies clearly or explicitly state the theoretical mechanisms through which SCC impacts on NPD performance. Most of the studies are not theoretically grounded. Most of the mechanisms were theoretically implied from the arguments made by the authors. Despite all the above-mentioned limitations, this review was conducted objectively.

2.6.4. Contributions

Project one established linking themes between NPD, SCC and product planning. It developed the mirroring concept as a means of linking product and SCC modularity, and identified gaps in the research. These gaps are addressed by hypotheses that were developed during project one, and tested and validated in projects two and three.

The first contribution, is the identification of four linking themes are modular design (Ulrich, 1995, and Baldwin and Clark, 2000); early supplier involvement (Ragatz *et al.*, 2002; Choi and Linton, 2011) product and SCC life cycle (Novak and Eppinger, 2001; Salvador *et al.*, 2002; van Hoek and Chapman, 2006, 2007; Doran *et al.*, 2007; Dekkers *et* *al.*, 2013), and co-development of product and SCC (Griffin, 1993; Swink *et al.*, 1998; Wikner and Rudberg, 2005; Lau and Yam, 2007).

The modularity theory reveals that a positive correlation exists between buyer-supplier integration in NPD at the concept stage. 'Overall interface standardisation better correlates with loosely coupled buyer-supplier relationships in NPD activities and with modular supply networks' (Cabigiosu and Camuffo, 2017).

Amini and Li (2011, p. 313), state that SCC encompasses supplier selection, manufacturing and locations within the supply chain network to hold supply chain inventory. This definition illustrates the multi-objective optimisation requirement in configuring the SC during NPD. SCC consideration at the concept stage can reduce excessive and wasteful NPD (Bisbe and Otley, 2004). Co-development and life cycle focus are aligned with continuous innovation in the NPD process. Modularity is present in over fifty percent of academic papers as the dominant theme, linking PA and SCA.

The second contribution, is the conceptualisation of the mirroring hypothesis which posits that, in the design of a complex system, technical architecture and division of labor and knowledge 'mirror' one another in the sense that the network structure of one corresponds to the structure of the others (Colfer and Baldwin, 2010). Zajac *et al.* (2000) use mirroring to approximate an 'ideal' profile, linking modular systems.

The relationship between PM and organisational modularity (OM) is central to the modularity theory of the firm that aims to explain the positions of the boundaries of companies, and consequently the vertical contracting structure of industries (Sorkun and Furlan, 2016). The relevance of this relationship dates to Simon's (1962) study on the architecture of complexity based on hierarchy and near-decomposability. This research extends OM to the external SC network. Taking configurational research as a foundation, the closer a SC mirrors an ideal constellation, the superior is its performance (Vorhies and Morgan, 2003, 2005). The literature that pertains to the mirroring hypothesis commonly draws on two distinct sources for its motivation: 1) the literature on organisation design and organisations as complex systems and 2) the literature on product development and products as complex systems (Colfer and Baldwin, 2010). Project one, contributes to this literature by expanding the mirroring concept to the SCC, building on the work of Schilling and Steensma (2001) who identified relationships between technology and organisational modularity. Brusoni *et al.* (2001) view SCCM as an inevitable result of increased PM.

The third contribution is the identification of a gap in knowledge. There is limited focus in the literature in understanding the effects of SCC on NPD decisions (Appelqvist *et al.*, 2004). The NPD research literature is generally silent on SCC design, with most research originating on the SCC side. Much of the modularity literature looks at the evolution of the product as the analytical starting point (Langlois and Robertson, 1992; Ulrich, 1995; Baldwin and Clark, 2000), this research proposes a more in-depth analysis of the SCC in support of the new to market product. Whilst PM is covered in the literature, there is gap in the research on SCC modularisation. The complex relationships between IP, SCC, company scope, and market structure have received limited attention in academic research. The SLR has been an effective means of identifying the extant literature on mirroring of NPD and SCC, extracting data and determining what is known about the inclusion of SCC decisions in the NPD process at the concept stage. Project one, identifies a gap in the conceptualisation of the SCCM construct, and lead to research question two: *"how can supply chain configuration modularity be conceptualised considering modularity principles and contemporary supply chains?"*, together with a gap in understanding of the manifestation of mirroring leading to research question three: *"how is the mirroring of product modularity and supply chain configuration modularity manifested?"*.

Existing modelling approaches present a set of method-specific concepts for representing product knowledge required in configuration problem-solving, with research concentrating on constraint satisfaction (Mittal and Falkenheiner, 1990), resource-based configuration (Heinrich and Jungst, 1991) and propose-and-revise approaches (Balkany *et al*., 1993) problem-solving methodologies. There is a clear opportunity in applying GST and KBT to NPD management. The conceptual model provides a starting point for asking questions about the NPD process. The conceptual model provides flexibility in describing the NPD process adopting an open-and-closed systems perspective to product and SCC co-development, where product and SCC can be classified as connection-based (Mittal and Frayman, 1989), resource-based (Heinrich and Jungst, 1991), structure-based (Cunis *et al.*, 1989) or function-structure-based (Najman and Stein, 1992). All four system perspectives are required to adequately represent the knowledge available on products and their SCC (Tiihonen *et al.*, 1996). New model elements can be derived as the empirical analysis occurs.

No explicit causal models exist to explain the process where systems migrate towards increasing or decreasing modularity (Schilling, 2000). No conceptual tool exists to mirror the interdependence of modules, levels of coupling, reconfigurability and imitation in the design of technological and SC systems (Ethiraj *et al.*, 2008). GST was selected to derive a model of inter-company product modularity. The CD, FC and FAC systems mechanisms deduced as key intervening mechanisms in the mirroring of PM and SCCM, in project one, are tested in project three.

FIRST EMPIRICAL STUDY

PROJECT 2

3.1. INTRODUCTION

Project one deduced that modularity represents the strongest link between PM and SCCM. Project one also deduced that mirroring of PA and SCC knowledge at product and SCC module interfaces leads to increased NPIR (Holtta and Salonen, 2003), and can approximate an ''ideal'' profile, or 'strategic type' (Zajac *et al.*, 2000). Systems theory does not adequately take SCC knowledge generation and codification during NPD in to consideration, project one identified the requirement for a knowledge based view, to address this weakness with the GST. Areas of SCC knowledge innovation are shown in Appendix 3-11, Page 458.

Whilst PM and organisation modularity are covered in the literature, there is gap in the research on SCC modularity. Qualitative research conducted in project two develops the SCCM construct and examines the mirroring of PM with SCCM, within-company and across-company. The principle of cyclic progression was deduced from project one. This hypothesis that 'product modular architecture and supply chain configuration migrate towards mirrored modularity', is tested in project two, following the research process shown in Appendix 3-1, Page 449. The implications of project two findings are that modular products are associated with modular SCC, taking in to consideration the contingent relationships outlined between PM and SCCM, see section 3.11.2, Page 293.

3.1.1. Rationale for project two

The business problem driving this research, is the identification of cases which incorporate SCC decision-making early in the NPD process, focusing on a reduction in SCC complexity. Whilst attention has been paid to why it is necessary to expand the scope and depth of SCC activities (Swafford *et al.*, 2006), it is only in the past decade that researchers and practitioners have started to consider the downside of added supply chain complexity, at industry, geographic region and business unit level (Hoole, 2006).

Exploring research question two contributes to the knowledge of management controls in NPD and offers guidance in the management of NPD activities in high-technology sectors, through evidence-based research. Knowledge is defined as a justified belief that increases an entity's capacity for effective action (Huber, 1991; Nonaka, 1994), with knowledge seen as actionable information (Maglitta, 1996). Actionable information is not limited to the improvement of an organisation's products, but also to business and operational processes. Hence, knowledge is a differentiator that can enhance an organisation’s value creation. This position is shared in the academic community where knowledge has been identified as providing competitive advantage (Alavi and Leidner, 2001). KM is emerging as a mechanism to support highly complex NPD environments Roth (2002). It is essential for KM to address knowledge flow within organisations, and knowledge collaboration across organisational boundaries. This is sometimes easier said than done as indicated by previous research (Dayan, 2006).

3.1.2. Purpose of project two

The purpose of project two is to develop the SCCM construct, and explain how PM mirroring with SCCM is manifested, using KBT, linking with project one and project three, shown in Appendix 2-1, Page 431. Two mandatory SCCM attributes; SCT and PRP and three optional SCCM attributes; process flexibility (PF), process re-sequencing (PR) and place postponement (PP) were deduced from the literature, in response to research question two.

Project one highlighted significant use of case research in SCT. SCT was found to play a key role in defining SCC module interfaces. The mandatory SCCM attributes SCT and PRP are mirrored with module FS and IC, with module IC controlled at the SCC module interfaces. Mena, Humphries and Choi (2013) support case study research methodology in multi-tier supply chain’s (MSC), adopting inductive case study research. Organisations operating across multiple tiers should ideally behave as a unified entity with a common purpose (Choi *et al.*, 2001), this common purpose is supported by the GST.

3.1.3. Structure of paper two

This chapter is structured as follows; Section 3.2 discusses the theoretical positioning of the research concepts, and concept attributes deduced from the literature; Section 3.3. outlines the supply chain configuration attributes; Section 3.4 outlines the research methodology; Section 3.5 discusses data analysis; Section 3.6 discusses rigour in the case studies; Section 3.7 discusses results; Section 3.8 discusses within-case data analysis; Section 3.9. provides a cross-case comparison of the results; Section 3.10. discusses the findings and discussion; Section 3.11 presents the conclusions, Section 3.12 presents the research limitations, and Section 3.13 presents implications for further research.

3.2. THEROETICAL POSITIONING

Theory is 'a set of interrelated constructs (concepts), definitions and hypotheses that present a systematic view of phenomena by specifying relationships among variables, with the purpose of explaining and predicting the phenomena' (Kerlinger, 1986). This definition spans two domains. One can be labelled the theoretical domain, and the other the operational domain. Constructs, or concepts, are abstractions in the theoretical domain that express similar characteristics: for example, organisational success and manufacturing effectiveness. These constructs are 'latent' or are not directly observable or measurable (Edwards and Bagozzi, 2000). Therefore, theory attempts to explain observed phenomena by systematically setting out interrelationships between constructs. However, since these constructs are latent, researchers must provide an operational and observable definition of them. In this research it was decided to focus on the discovery of applicable measures which mirror the PM and SCCM constructs. A qualitative assessment of the data from an initial pilot study highlighted the limitations of a quantitative approach to this area of research. SCC is a strategic decision-making problem, not suited to simulation modelling.

The conceptual framework model establishes a formal definition of PM mirroring with SCCM, and provides the structure of research in project two, as shown below in Figure 3-1. This conceptual framework guides the empirical research on PM and SCCM mirroring after product launch, and assesses levels of PM and SCCM mirroring cross-sectorally. Theory-building provides a framework for analysis, and facilitates the efficient development of the field of interest, needed for application to practical real-world problems (Wacker, 1998). For research validity it is important that a clear theoretical framework is developed and used (Gibbert *et al.*, 2008; Francisco *et al.*, 2012; Gan and Grunow, 2013). Theory requires four basic criteria: conceptual definitions, domain limitations, relationship-building, and research hypotheses. A review of theoretical perspectives in project one, identified GST as an explanatory basis for this research (Halldorsson *et al.*, 2007; ElMaraghy and Mahmoudi, 2009), supported by knowledge-based theory (Grant 1996). NPD (Henderson and Clark, 1990; Duray, 2004) and SCC processes (Helou and Caddy, 2006) are considered as systems. Owen (2007) argues that design thinking, in contrast to traditional management approaches, actively avoids making choices for as long as possible to maximise learning as an uncertainty reduction strategy; therefore, learning and KM have long been highlighted as central to the purpose of design activities (Senge, 1990; Beckman and Barry, 2007). Schilling and Steensma (1999) developed a General modular systems framework to guide an understanding of inter-company PM aggregation and disaggregation. The NPD and SCC General systems framework must take account of the circularity of PM and SCCM system relationships, for new-to-market products.

These UoA can introduce complexity internally within manufacturing and externally with downstream and upstream partners. Supply chains are complex systems, often operating across multiple vertical and horizontal tiers. Yates (1978) defines a complex system as one that exhibits one or more of the following attributes; significant interactions; a high number of component parts or interactions; non-linearity; broken symmetry, and non-holonomic constraints. The last three of these characteristics are indicative of higher-order complexity since they make a system's responses hard to predict over time (Flood and Carson, 1988). Complex systems often fail to exhibit one-to-one mapping of inputs to outputs that might exist in a simple system. Non-linearity arises when the response of the system to a given input is non-proportional. Other manifestations arise when portions of the system are in some way not accessible from other portions of the system. This can be due to the asymmetry of the system, or the existence of constraints, which arise when one or more portions of the system are left outside the central control, allowing these portions of the system to "go off and do their own thing" (Flood and Carson, 1988, p.27). An example would be a SCC with multiple downstream demand points that independently place orders on a centralised supply point without regard for supply constraints or the needs of other demand points. In such a case, the same 'input', placing customer order based on pre-established inventory policies can have varying effects, depending on the state of the SCC. These higher-order aspects of complexity make supply chains "qualitatively different from static objects such as computer chips, which are merely complicated" (Waldrop, 1992, pp.11-12). The complex adaptive system (CAS) theory has remained at the conceptual level, precluding its usefulness in this empirical study.

Project two focuses on the right-hand side of the conceptual framework, as shown in Figure 3-1. Since modularity is not a binary measure, different levels of modularity might be appropriate for different applications (Hölttä-Otto and de Weck, 2007). Complex products often require that manufacturers successfully integrate different types of product and SCC modules simultaneously. The degree of modularity of a system will typically have many technical and business consequences (Ulrich, 1995; Sosa *et al.*, 2007). This leads to quantification of modularity along a continuum. Research question three focuses on how mirroring between PM and SCCM, is manifested.

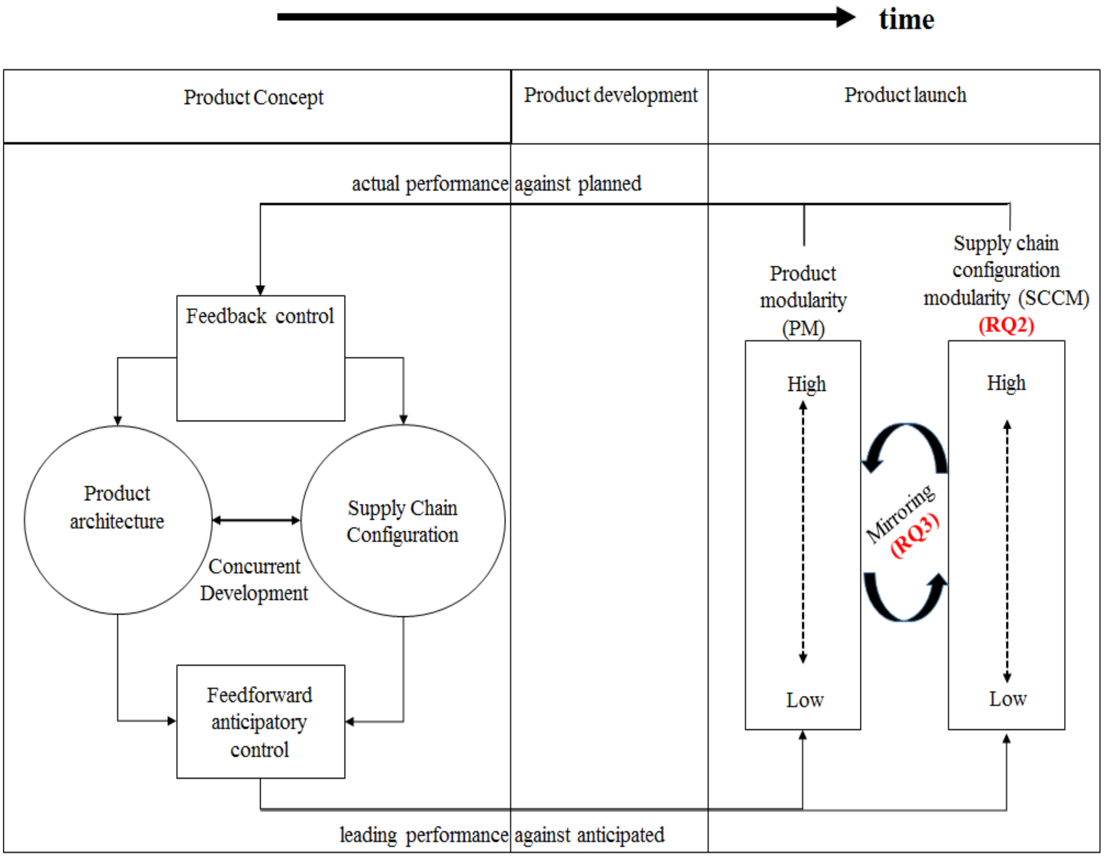


Figure 3-1. Research questions 2 and 3

3.2.1. Key constructs

An organisation which focuses on mirroring PM with SCCM is better equipped to effectively meet customer demand (Aserkar and Kumthekar, 2014). “Modular products, processes and supply chains permit substitution of different versions of functional components, creating SCC variations with different functionalities and performance levels” (Voordijk *et al.*, 2006, p.603). Academic research links PM to SCCM mirroring with improved product development performance (Garud and Kumaraswamy, 1995; Gimenez and Ventura, 2003).

3.2.2. Product modularity

PA is a scheme by which the functional elements of a product are allocated to structurally independent physical components and is the basis of product modularisation (Ulrich, 1995; Sanchez, 2000). Product functionality relates to what the product does, not to a product's physical characteristics. Technical domains such as electro-fluid, mechanical and digital systems, in general formalise product functionality. Technical domain languages are frequently used to create functional diagrams explaining the exchange of signals, materials, forces, and energy between modules (function elements). Functional elements are sometimes called functional requirements or functives and function diagrams are often called function structure, functional description, or schematic description. Ulrich (1995) calls the arrangement of functional elements and their interconnections, a function structure.

A component or module is defined as "a relatively independent chunk of a system that is loosely coupled to the rest of the system" (Hölttä-Otto *et al.*, 2012, p. 791). The degree of component or module modularity depends on the number of functions the component or module perform and the degree of interdependency with other components and modules. Products are generally decomposed at module, building block, subsystem, component and subcomponent level. "Modularity can be a characteristic of each or some of these levels" (Bullinger and Warschat, 1996, p.183). Sanchez and Collins (2001) identified key features of modules: 1) modules are standardised and either re-usable in alternative products, or added-on to the main product; 2) modules offer interchangeable features, changes can be made to key modules without the requirement to redesign others, and 3) modules offer ease of product assembly and disassembly (Henderson and Clark, 1990; Tu *et al.*, 2004; ElMaraghy and Mahmoudi, 2009). Products can be highly modular with respect to some functions for example a car wheel, and less modular with respect to other functions, for example a car's drive transmission (Sanchez and Mahoney, 1996).

PM is the degree of technical interdependency between the constituents of a product (Schilling, 2000), and is grounded on standardisation and specification of component or module interfaces, allowing substitution without required changes to the design of other components or modules (Garud and Kumaraswamy, 1995; Sanchez and Mahoney, 1996; Sanchez and Collins, 2001). PM depends on two design characteristics, similarity between the physical and functional architecture of the design, and minimisation of interactions between physical components of design (Ulrich and Tung, 1991). High PM illustrates a one-to-one mapping from functional elements in the function structure to the physical components of the product. For products with high PM the module interfaces are loosely coupled. Low PM implies a high degree of inter-module functional interaction. Module IC may cover the way that components connect (attachment interface); how power is transferred (transfer interface); how signals are exchanged (control and communication interfaces); the spatial location and dimensions of the component (spatial interface) and the effects that one component may have upon others in the form of heat and magnetic fields (environmental interface), Sanchez (1994). Ulrich (1995) proposes two criteria for measuring the degree of modularity at the finished product level, where: 1) modules are coordinated through standardized interfaces, and 2) each constituent performs only one product function.

Five PM attributes are deduced, from the literature, and shown below in Table 3-1. The mandatory FS and IC attributes (Ulrich, 1995), and three optional attributes: data access, limited life, and product variety in use (Arnheiter and Harren, 2005). The mandatory attributes primarily consider functional design, whilst the optional attributes primarily consider customer-centric design.

Table 3-1. PM construct measures or indicators

Construct		Measures or indicators	Reference
Product modularity (PM)	Mandatory	(1) Function sharing (2) Interface coupling	Ulrich (1995) Baldwin and Clark (2000) Arnheiter and Harren (2005) Sundin *et al.* (2009) Koufteros *et al.* (2001)
	Optional	(3) Data access (4) Limited life (5) Product variety in use	

Figure 3-2, illustrates the inter-dependent relationship between module IC and module FS. Module IC measures include decomposability (Simon, 1962); loose coupling (Weick and Orton, 1990), and similarity and combination (Hölttä-Otto *et al.*, 2012). Module IC is measured on a scale from loose to tight, where loose denotes ease of module de-coupling. A product with high PM normally involves low inter-module dependency and a one-to-many mapping from physical components to functional elements.

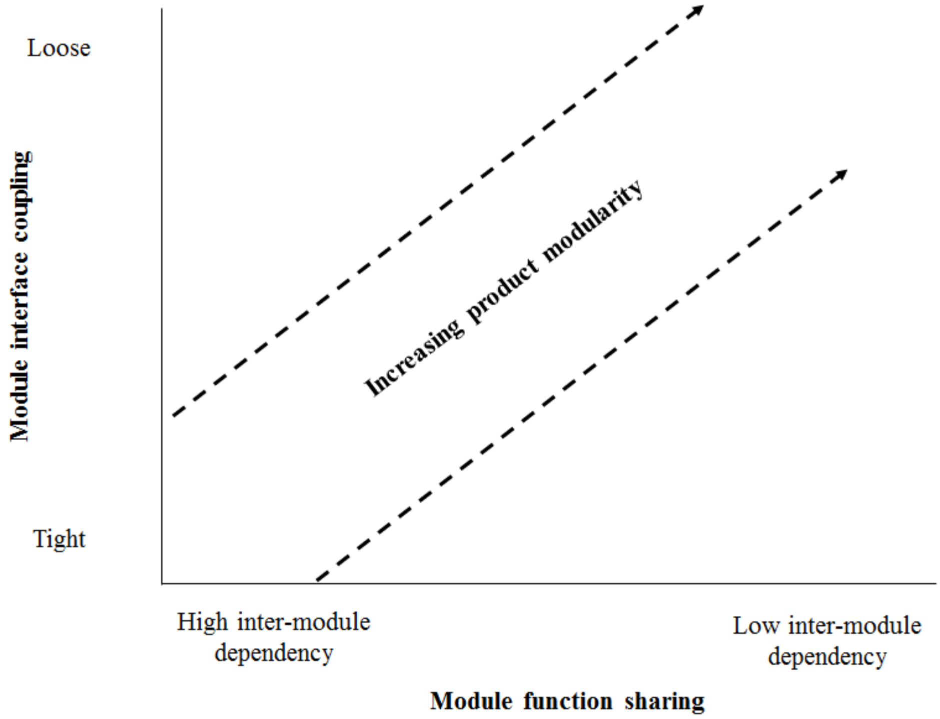


Figure 3-2. Module function sharing and interface coupling

Loose module IC, is also termed combinatorial, slot, or component-swapping modularity (Salvador *et al.*, 2002). Standardized interfaces may differ depending on the combination of families they connect but are independent of the component variant chosen, therefore "all component families can vary while the interface between specific pairs of component families is standardized" (Salvador *et al.*, 2002, p.571). Ulrich (1995) classified interfaces based on the types of coupling they share, distinguishing between slot, sectional and bus modularity. Bus architecture modules are not connected with one another, but rather each is independently connected to a single 'bus' module. A bus could be represented by a control system, a communication channel, a cooling system, or a main structural element such as the main drive shaft in a car (Hölttä-Otto *et al.*, 2012). Development of these modularity typologies, including their characteristics and implications for product design and SCC, has been limited.

O'Grady (1999) distinguishes between hard and soft modules. Many products consist of a mixture of soft and hard modules. Arnheiter and Harren (2005) propose four types of hard modules; 1) manufacturing modules which are covered under the SCCM construct; data access modules; limited life modules, and product variety in use, where: 1) data access modules represented by modules that interconnect with a specialised element, according to a standard (modular-bus), for example a data communications bus; 2) limited life modules represented by modules that interconnect with another module, according to particular interface standards (modular-slot), for example an ink cartridge or a light-bulb, and 3) product variety in use modules represented by modules that interconnect directly, according to a standard (modular-sectional), for example speaker head-phones.

Data access (DA) modularity relates to access to data in the product. High levels of data access refer to continuous data access at the module level. Device to device communications are available using Wi-Fi, Bluetooth, ZigBee, and other data communication technologies. Low levels of data access refer to either no access or intermittent access using removable data access modules such as USB devices. Data access is fast changing from hard modules to a flow-oriented form, including the internet, and cloud-computing platforms (Arnheiter and Harren, 2005). Smart devices are the building block of the internet of things (Borgia, 2014). Whilst there is an increasing focus within high technology product design on the provision of remote data access it is not yet clear to what extent data access is contributing to competitive advantage within supply chains (Grover and Kohli 2012; Fosso-Wamba *et al.,* 2015; Wang *et al.,* 2016). This was a primary decision factor in including DA as an optional PM attribute.

Limited Life (LL) modularity implies the use of disposable modules with distinct characteristics. LL modules require defined interfaces and ease of access, for example a car battery (slot modularity). The form factor and geometry of the LL module are normally restricted such that only worn-out parts require replacement. The axle subassembly built for Toyota by Advics company is an example of a manufacturing module that contains LL modules (Murphy, 2002). As the brakes wear, instead of replacing the entire axle, only the brake pads require replacement. In this case, the brake pads are the LL modules, and sub-parts of the axle module. LL modules are cost sensitive since they are normally replaced multiple times during the product life cycle. The need for frequent module replacement has created many aftermarkets, with competing suppliers seeking to capture the spares and surplus engine parts market (Arnheiter and Harren, 2005). In the context of the proposed typology, 'limited life' implies that the lifespan of the product exceeds that of the module. Indeed, an automobile last's longer than its battery, and a light bulb usually fails before the light fixture. Since a LL module normally has a shorter life expectancy than the product in which it is used, and is designed to be replaced throughout the product life cycle, this was a key factor in the selection of this optional attribute.

Product variety in use (PV) modularity implies the use of modules to facilitate product customisation by the end user. Limited life modules can be product variety in use modules. An example of a limited life and product variety in use module, is the incandescent light bulb. The end customer might decide to replace a low wattage light bulb with a higher wattage or replace an incandescent light bulb with a halogen, or fluorescent type. Other examples of PV modules include computer drives, LAN cards and aftermarket bicycle components (Arnheiter and Harren, 2005). Gilmore and Pine (1997) proposed the term adaptive customisation for this type of PM, without specifically mentioning modularity. Module appearance is often an important design consideration. Standardised modules are normally sold either by the OEM or as aftermarket items. The module supplied with the product is easily removed, stored, and replaced with a different module selected by the user. PV modularity represents a subset of adaptive customisation, and for this reason was selected as an optional PM attribute.

3.2.3. Organisational modularity

Whilst OM is not one of the main research concepts it offers the basis of empirical research on SCCM. Most product design methods generate product models, without adequate consideration of the processes required to deliver these products (Thong *et al.*, 2000; Shehab and Abdalla 2001; Rahimifard and Weston 2007). Organisation modules are interpreted as market-supporting institutions providing technical design rules that standardise the interfaces between different product components or stages of the production process (Sabel and Zeitlin, 2004). Research has examined the disaggregation of many large, integrated, hierarchical organisations into loosely coupled organisational arrangements such as contract manufacturing, alternative work arrangements, and strategic alliances (Ashkenas, *et al.*, 1995; Schilling and Steensma, 1999). While products are usually composed of components and modules an organisation can be partitioned into teams, departments, separate companies, and vertical industrial layers. ‘It is possible to identify products and organisation’s as systems whose constituents have interdependencies to implement their system functions’ (Sorkun and Furlan, 2016). Products comprise of technical, form factor and aesthetic interdependencies among components and subsystems of products, whilst organisation units are comprised of information, governance, and resource interdependencies (Worren, 2012).

OM refers to the level of organisational unit coupling using coordination, geography, culture, and electronic connectivity dimensions (Fine *et al.*, 2005). OM can be analysed at intra-company, inter-company, and industry levels. OM is used to describe three levels of analyses: 1) the intra-company level refers to the degree of decoupling among organisational units within a company; 2) the inter-company level denotes the decoupling between the buyer-supplier dyads, and 3) the industry level which refers to the degree of decoupling of vertical layers within the same industry. OM allows companies link organisational capabilities to support product development. Outsourcing allows companies take advantage of capabilities external to the company's boundaries (Baldwin and Clark, 1997; Fine, 1998). Many OEM's retain the development of critical components or subsystems in-house whilst outsourcing the development of non-core components or modules. These companies enjoy the benefits of NPD outsourcing including access to a larger pool of finance and talent; greater focus on core competency and customer requirements; reduced costs through lower labour and talent costs; global growth through access to critical local information and market, and increased employee flexibility through transferring the responsibility of new employees to suppliers (Rundquist, 2008), with potential profit margin benefits and lead-time reduction, (Calantone and Stanko, 2007). Many OEM's concentrate on the creation, penetration, and defense of markets for end products, while shifting much manufacturing to modular manufacturing partners (Sturgeon, 2002). Sturgeon shows that companies identify specific breaks within the value chain at points where information regarding product specifications and other information exchange between companies can be highly formalised and easily transferred. The evolution towards fragmented vertical and horizontal contracting structures is a characteristic of many industries in manufacturing (Macher and Mowery 2004) and service industries (Jacobides 2005; Jacobides *et al.*, 2006).

Baldwin and Clark (1997) discussed OM as a means of partitioning production, providing economies of scale and scope across product lines. Flexible manufacturing systems (FMS) provide for lower cost customisation using modularity in their design. Manufacturing modularity is akin to PRP, with product completion designed around the use of pre-manufactured subassemblies or modules (Arnheiter and Harren, 2005). There is evidence in the literature that a new model of industrial organisation is emerging in many production systems (Gereffi, 2005; Berger 2006).

3.2.4. Supply chain configuration modularity

Since the seminal work by Starr (1965), research on modularity has not focused on SCC structure and configuration. Starr (1965) compares the behavior of traditional mass production systems with modular or 'combinatorial' production practices, and calls for parts design and manufacturing that utilize interchangeable modules, which can be combined in the maximum number of configurations. Lau *et al.* (2007) argue that the benefits of modularity should be translated into company capabilities; Baldwin and Clark (1997) refer to modularity in production and modularity in use but offers no typology for hard modules; Tu *et al.* (2004) argue that PM impacts a company's SC and the industry structure, while Brusoni and Prencipe (2001) view SCCM as an inevitable result of increased PM.

Drawing on existing PM literature, this research posits that SCCM when mirrored with PM can lead to radical NPD innovation, and speed. SCCM should focus on SC asset selection. Whilst the BOM is part of the product equation, showing '*what*' to make and the ingredients or components required to physically make each modules or product (Vollman *et al.*, 1992), the BOP is part of the SCC process equation, showing '*how*' to source, make, deliver, service, and recycle the product, and the assets required. Modularity in production breaks down the production process into sub-processes that can be performed concurrently or in a different sequential order (Lee, 1998). Key considerations include: 1) the positioning of SC assets; 2) the level of coupling of SCC steps, and 3) the interfaces between processes or elements and the opportunity to mix and match these elements of the SCC system, where SCC encompasses 'the selection of suppliers; manufacturing modes; together with locations in the SC network to place appropriate levels of safety stocks' (Amini and Li, 2011). Since SCCM must consider PM interfaces 'does SCCM only exist as a mirror of PM'? There are arguments to both support and counter this view. The counter-view is representative of process industries where a broad range of products, including petrochemical, inorganic chemicals, plastics, detergents, paints, pigments are outputs of their production processes. A SC network can be broken down in to discrete functions, processes, and process chains. Important considerations of SCC include the ownership structure and operational model for the asset, (Hinterhuber and Hirsch, 1998); who will manage the network, and how will the network remain dynamic and refreshed.

Despite increasing levels of SCC innovation no framework exists for mirroring PM with SCCM. Agyapong-Kodua *et al.* (2012, p. 826) observe that "current best practice design methods offer relevant solutions to industries but at the product concept stage lack the support of appropriate process modelling techniques". The gaps in knowledge include weak development of the SCCM concept, and weak understanding of mirroring PM with SCCM. The SCCM construct and examine its conceptual integrity and robustness are researched during project two. The mandatory SCCM attributes include SCT, (Hieber, 2002; Mena, Humphries and Choi, 2013) and PRP (Zinn and Bowersox, 1988; Tu *et al.*, 2004). The optional SCCM attributes process agility; PF, process re-sequencing and PP (Feitzinger and Lee, 1997; Tu *et al.*, 2004; Amini and Li, 2011), are deduced from the literature, shown below in Table 3-2. It is important to state that the list of optional PM and SCCM attributes is not exhaustive.

Table 3-2. SCCM construct measures or indicators

Construct		Measures or indicators	Reference
Supply chain configuration modularity (SCC)	Mandatory	(1) Supply chain tiering (2) Process postponement	Hieber (2002) Graves and Willems (2005) Fine (1995) Tu, *et al*. (2004) Feitzinger and Lee (1997) Amini and Li (2011)
	Optional	(3) Process flexibility (4) Process re-sequencing (5) Place postponement	

SCCM measures are relative system properties. In the face of dynamic business environments there is a requirement for increased SC agility, provided by PF, PR and PP. Eisenhardt (1989) stresses the importance of creating precise and measurable concepts claiming that such concepts are the foundation of powerful theory. Operationalisation should involve the exhaustive development of observable indicators, for each of the concepts. This principle is followed by defining and operationalising these concepts in a way that ensures construct validity, see Section 3.6. The literature review was continued throughout project two to develop PM and SCCM measurement attributes.

3.3. SCC MODULARITY

This research is focused on mirroring multi-tier supply chains and PRP, with module FS and module IC requirements, at the product concept stage. Pandremenos *et al.* (2009) propose three modularity arenas, modularity in product design; modularity in production, and modularity in use. Modularity in production covers the ability of manufacturing to pre-combine components into modules, assemble these modules off-line and assemble the main product on-line, whilst modularity in use is a consumer driven decomposition of a product focusing on ease of use. The latter arena is connected to the concept of mass customisation. SCCM and PM contain design rules and hidden design parameters, which pertain to 'modularity in design' knowledge. These rules and parameters need to be shared among the NPD and SCC teams, addressing how each part or process interact with each other (Baldwin and Clark, 1997).

Graves and Willems (2005) formulate the SCC problem as an optimisation problem for which the decision variables are the supplier nodes and service times, after product design completion. The optimisation of inventory across the SC is covered in academic literature (Ettl *et al.*, 2000; Graves and Willems, 2000, 2005). These researchers examined the optimisation of safety stock levels for an established SC, with safety stock assessed as a function of the replenishment time. The optimised SCC minimises the sum of the costs of goods sold; safety stock, and pipeline stock cost, as shown below in Figure 3-3. Taking the main assembly there are fewer modules delivered to the main assembly process, as shown below in Figure 3-3.

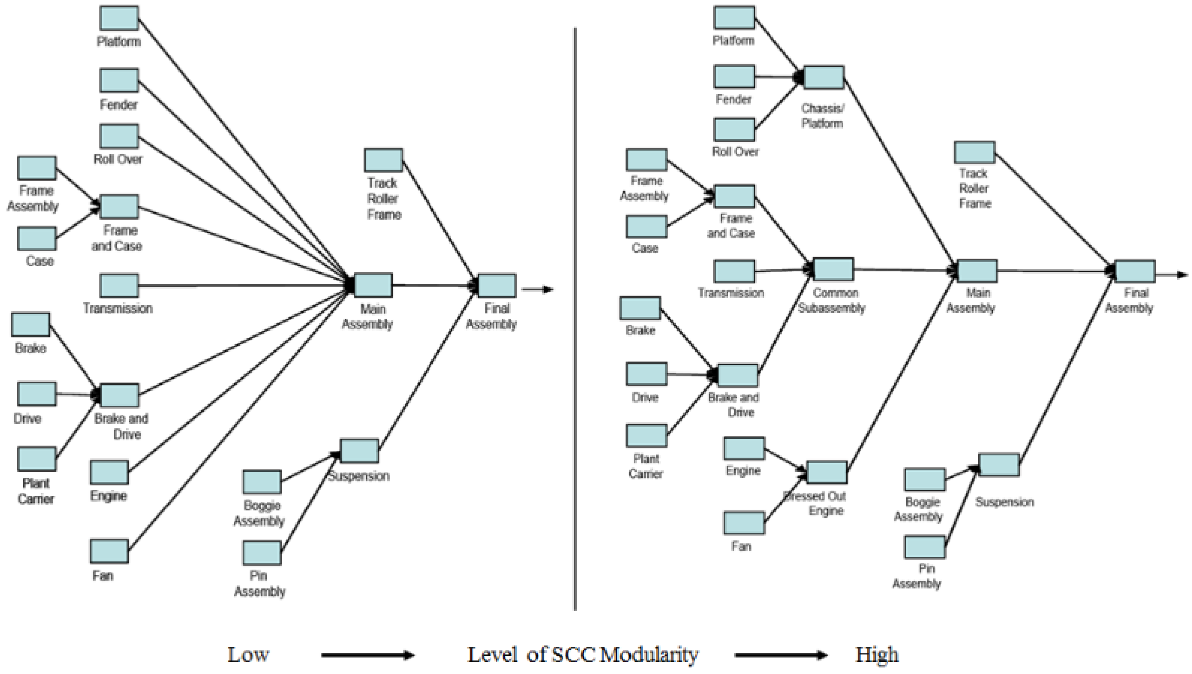


Figure 3-3. SCCM tiers
Source: Graves and Willems (2003)

PA can both determine the SCC, and be dependent on SCC. For most structured product development processes there is a milestone when the materials management organisation (MMO) sources the new product SC. The product's functionality has already been determined at this point. More often PA design and materials sourcing decisions occur within the product concept phase. There are normally several available sourcing options at each stage. Examples include multiple component suppliers, manufacturers and distribution modes. The role of the MMO is to identify and select the options that can satisfy each function. Options differ in terms of direct costs and lead-times. Choices in one SCC process can affect the costs and responsiveness of other SCC processes. The trade-off often involves a higher UMC with a more responsive SCC versus a lower manufacturing cost with a less responsive SCC. This problem integrates and builds upon ideas from literature in the areas of multi-echelon inventory theory and supply network design. A SCC represents the alignment of companies that bring products or services to the market (Lambert *et al.*, 1998) shown below in Figure 3-4. ‘The complexity of MSC’s includes not only the structural issues of networks such as number of links, reverse loops and multi-way exchanges, but also the associated behavioural issues such as nonlinear dynamics, self-organisation, emergence and co-evolution’ (Mena, Humphries, and Choi, 2013). The depth or vertical extent of the SCC as shown below in Figure 3-4, depicts backward integration into materials and components, and forward integration into distribution.

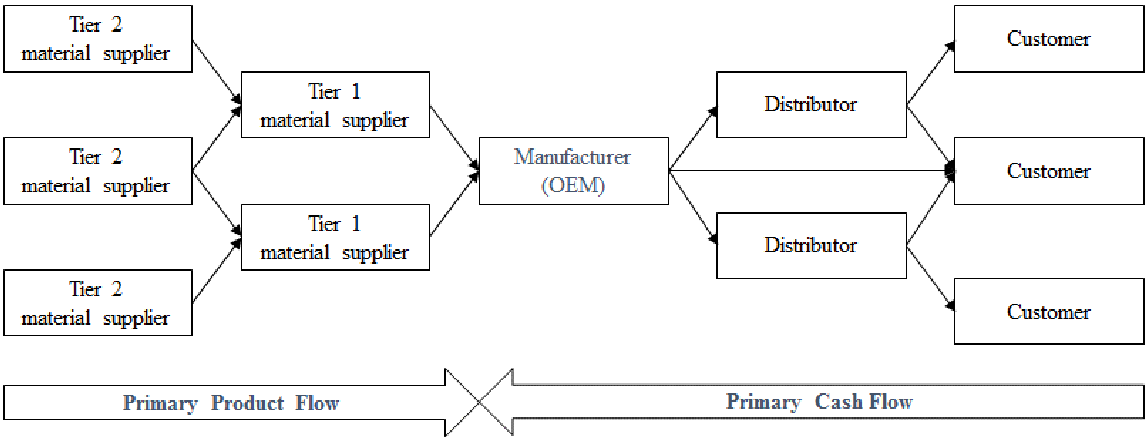


Figure 3-4. Simplified supply chain structure
Source: Lambert et al. (1998)

The evolution towards fragmented vertical and horizontal contracting structures is characteristic of many industries in service (Jacobides 2005; Jacobides *et al.*, 2006) and manufacturing industries (Macher and Mowery 2004). Vertical integration may be managed by a primary supplier, or a primary logistics partner. Horizontal integration across several tiers may be coordinated by a lead supplier, or logistics partner. To address the challenging task of managing an extensive supplier network, a delegated sourcing strategy is often applied (Cousins and Spekman, 2003). This structure has become popular in the aerospace and automotive industries since the mid-1990s. With delegated sourcing selected tier-one or tier-two suppliers are responsible for the delivery of an entire subassembly, instead of an individual part. The outsourcing company delegates authority to these 'system integrators' to manage the manufacturing, and often the tooling, of the associated sub-assemblies. Such a structure can be applied with high PM. In this approach the system integrator, in conjunction often with the OEM designs the sub-systems and develops a hierarchical network of suppliers (Mazaud and Lagasse, 2007).

Such dual responsibility for system integrators is critical in the success of many outsourced programs. Any shortcoming in the qualifications and technical strengths of the systems integrator is potentially transferred to the outsourcing company and can result in negative program impacts. There is an emerging area of research on triadic relationships, and the role of intermediaries (Havila, Johanson, and Thilenius, 2004). Today's multi-tier supply chains, compete at different levels with differing contractual and structural arrangements. 'Competitors want horizontal nodes of production and distribution and vertical hubs of value creation, together propelling themselves diagonally up the ladder of economic complexity' (Tyrangiel, 2012). The scope of each UoA is limited to a maximum of three vertical layers on the SCC.

3.3.1. Organisation proximity

The organisation proximity concept has captured a prominent position in organisation science literature (Meisters and Werker, 2004). When proximity is being discussed, it often relates to physical proximity, however other forms such as institutional (Kirat and Lung, 1999); social (Bradshaw, 2001); technological (Greunz, 2003), and cultural proximity (Gill and Butler, 2003) also exist. Fine (1995) approximates organisation proximity (OP) with geographic, ownership, managerial control, electronic, cultural proximity, interpersonal and inter-team dependencies. Cultural proximity captures "commonality of language, business morals, ethical standards, and laws, among other things" (Fine, 1995, p.176). Due to the growth in international sourcing, contract specificity and procedural rigour in international arrangements, and cultural proximity are less fundamental to the development of the SCCM concept. Companies are today engaged deep in their SCC's, with contractual arrangements governing design, and supply of components and modules. Electronic connectivity can be interpreted as the level of electronic integration between SCC members where demand (orders, forecasts) and supply (inventory availability and inventory level) information is shared between participants. There is an argument that electronic proximity is commonplace given the electronic communication capabilities that exist today. Geographic proximity and economic and legal ownership are deemed to be the two proximity dimensions most relevant to this research. The importance of geographic distance, represented by multi-tier supply chains lies in the fact that small geographical distances facilitate face-to-face interactions and foster knowledge transfer. Today's multi-tier supply chains, compete at different levels with differing contractual and structural arrangements. SCT is the first SCCM attribute selected.

3.3.2. Supply chain tiering

SCT relates to company capabilities (resource based view), after Barney (1991); inter-organisational relationships (transaction cost economic view), after Williamson (1975; 2008); asset ownership (Jensen and Meckling, 1976; Artz and Brush, 2000), and KBT, after Grant (1996). Some scholars have suggested moving beyond a theory of multiple resources and instead focusing on the crucial resource of knowledge. With the rapid development in information technology, and the influence of the dynamic environment, this has led to an emerging KBT framework. Companies however lack many of the formal mechanisms for storing knowledge that is vital in organisations. "The KBT and resource based view (RBV) may be very tightly linked, if not inseparable, in the supply chain context" (Ketchen and Giunipeor, 2004, p.53).

The transaction cost economic (TCE) view relates to governance control and the ability of the focal company to maintain control of the transactions within the network. Low levels of SCT under the economic and legal variables denote a high level of control over business transactions. The economic and legal business involvement is expected to be high when tiering is low and vice versa. Outsourcing is a key strategy across many industries, and is practiced by four of the five case companies whilst the fifth company is a tier-one supplier, to the automotive company. Whilst outsourcing helps drive lower costs, reduce capital assets, and deliver products to market more efficiently, it has its drawbacks which include increased complexity, reduced visibility and control, and often challenges with knowledge sharing, given that key operations now reside outside the focal company. The activities in the supply network require mirroring to deliver new-to-market products on time and at optimal cost, and quality (Lambert *et al.*,1998). The furthest upstream members of the SC typically represent component suppliers, or initial suppliers while at the furthest downstream point the product is used, by end users. The enclosed area, shown below in Figure 3-5 covers the research domain for this research. This research domain is restricted to tier-one, two, and three suppliers.

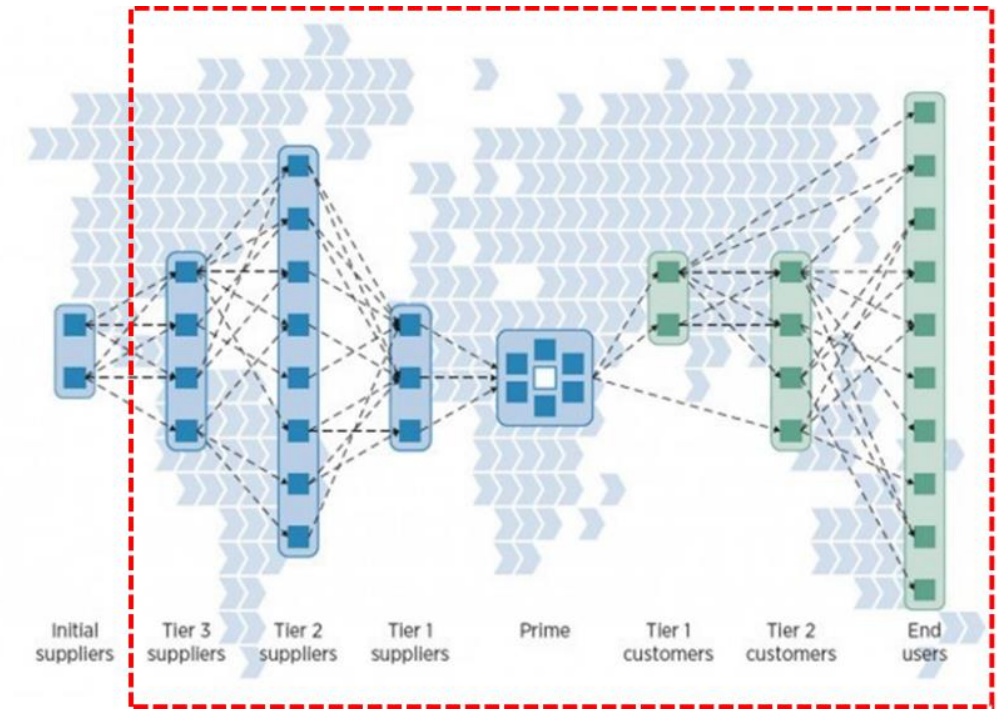


Figure 3-5. SCC depth and breadth of network
Source: Hieber (2002)

Hieber (2002) identified four primary SCT attributes: 1) supply chain depth; 2) supply chain breadth and 3) geographic spread, which cover the span of the network, and 4) economic and legal business involvement by the OEM with of companies within the network. The span of the SCC network dimensions is outlined in Table 3-3. A low span of network level equates to a low level of SCCM whereas a low level of economic and legal business involvement equates to a low level of SCCM, see Table 3-3. SCC depth refers to the number of tiers in the SCC. SCC breadth refers to the number of suppliers represented within each tier. SCC breadth relates to module FS and IC where for a highly modular product you might expect to see a small number of suppliers at the tier where the modules are assembled. Breadth depends on the tier in the SC for modular products. For the concept of SCT economic and legal business involvement is high when tiering is low and vice versa. High SCT and span of supply network are associated with high SCCM, in this instance the involvement with suppliers is expected to be low. With low levels of SCT supplier relationships are simple, and often based on segmentation, whereas with high levels of SCT relationships are more complex Hieber (2002). These higher levels of SCT and complex relationships require high levels of governance, often governed by a modular approach to managing the span of network, shown below in Table 3-3. Knowledge sharing supports the SCCM as a governance model for high SCCM, and high PM, in this case there is a lower requirement for knowledge sharing to protect IP. 'A system-of-systems approach is needed to design complex SC networks' (Chandra and Grabis, 2016).

SCT relates to the span of the network and the level of economic and legal business involvement of the case company with its suppliers. Some OEM's and key suppliers may have an economic or legal interest in the supplier company, re-enforced through contractual and non-contractual supply agreements. OEM's may have contractual supply agreements in place with tier-one suppliers (low level of SCT), non-binding agreements in place with suppliers (medium level of SCT) and arms-length agreements in place with suppliers (high level of SCT).

Table 3-3. Supply chain tiering variables

	SC Variable	SC Dimension	SC Extent		Source	Supply chain tiering (SCT) modularity		
						Low	**Medium**	**High**
1	Number of value adding tiers in the supply network	Depth	Horizontal	Span of network	after Hieber (2002)	1 - 2 value adding tiers	3 - 4 value adding tiers	4+ value adding tiers
2	Number of suppliers of same or equivalent modules or components	Breadth	Vertical			1 - 2 suppliers	3 - 4 suppliers	4+ suppliers
3	Geographical spread of the network partners	Spread	Geographic			Local (within 200 km distance of OEM co)	National (within same country, as OEM)	Regional and Global (within same continent or globally distant from OEM)
4	Economic and legal business involvement of the OEM	Autonomy	Freedom of control			High level relationship by the OEM, e.g. share ownership, credit finance, evergreen contracts.	Medium level of alliance by the OEM, e.g. medium terms agreements, price guarantee, extended credit.	Lower level of dependency by the OEM, e.g. managed by system integrator. This situation is changing as OEM's seek to gain increasing innovation from materials/component suppliers.
	Governance type				after Gereffi, Humphrey, and Sturgeon (2005)	Captive	Relational	Modular

On SCT important questions relate to: 1) what activities are bundled in each node of the network or split among various nodes; 2) how is knowledge, information, and material passed from one node to the next; and 3) where are the nodes located? The 'GVC governance' framework discussed in the linking document helps to explain why some value chain activities are firmly rooted in place and some are more easily relocated (Gereffi, Humphrey, and Sturgeon, 2005). Specifically, modular GVC linkages raise the potential for tight coordination of distant activities, even when complexity is high, while relational linkages typically require co-location to support the exchange of tacit information, driving agglomeration, and industrial clustering. Sturgeon (2008) found that GVC's linkage patterns can be associated with predictable combinations of three distinct variables: the *complexity* of information exchanged between value chain tasks; the *codifiability* of that information; and the *capabilities* resident in the supply base. They found that changes in one or more of these three variables altered value chain governance patterns in predictable ways. For example, if a new technology rendered an established codification scheme obsolete, or was overwhelmed by increasing complexity, modular value chains became more relational. If competent suppliers could not be found, then captive networks and even vertical integration became more prevalent. Increasingly, OEM's are building relationships with lower tier 'system integrators', which increases the requirement for multi-tier SC research. OEM's are owning not only critical modules and components in the PM, but also critical functions, relationships, and asset specificity at lower SCC tiers (Choi and Linton, 2011), as shown below in Figure 3-6.

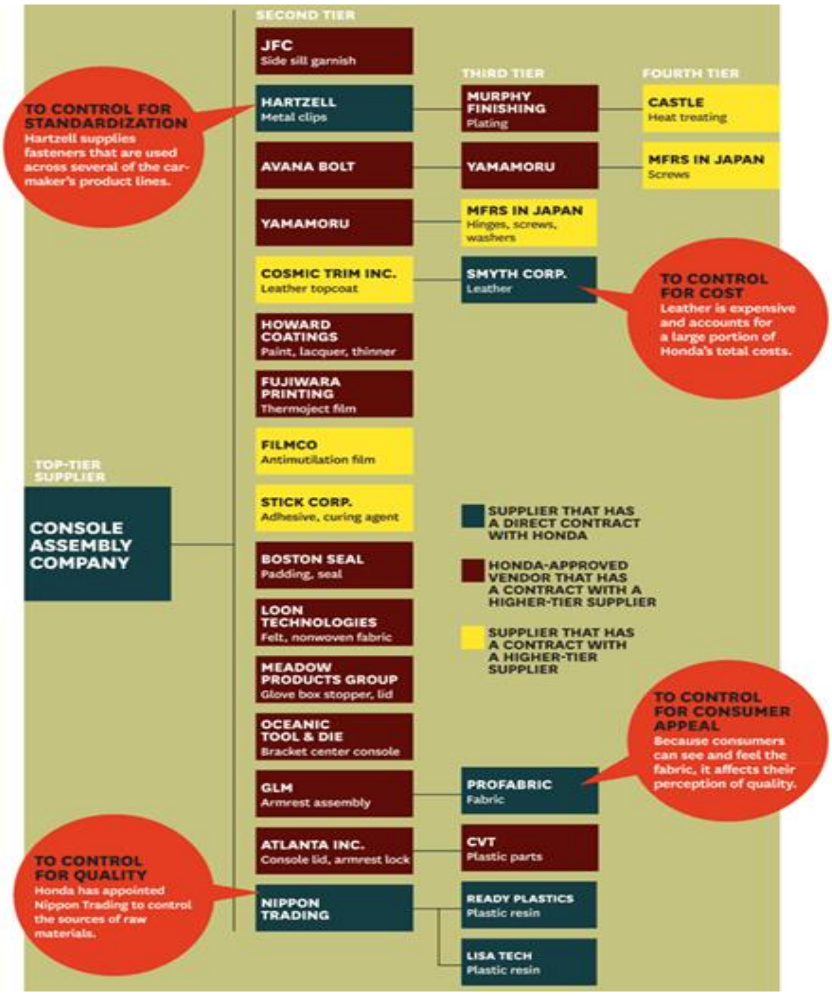


Figure 3-6. Honda Accord Center console supply chain map
Source: Choi and Linton (2011)

3.3.3. Process postponement

The PRP attribute is deduced from Tu *et al.'s* work (2004). Feitzinger and Lee (1997) indicate that SCCM is based on process agility dimensions include PRP, process resequencing and process standardisation (PS), leading to their selection as measures of SCCM. PS breaks the process into standard sub-processes that produce standard base units and customisation sub-processes that further customize the base units. PR re-orders the sub-processes such that standard sub-processes may occur prior to customisation sub-processes. The extent of PRP is defined by the location of the COEP in the process. This is the point where the product is linked to the customer order. In the case of high levels of PRP, the final product assembly is postponed until receipt of a customer order, or on receipt of more accurate order demand information. Figure 3-7 illustrates how higher levels of PRP combined with higher levels of SCT lead to increased levels of SCCM. Loose product module IC is a pre-requisite for SCC PRP. Schuh *et al.* (1998) and Mason-Jones *et al.* (2000), emphasize the strategic flexibility offered by connecting PM to the COEP. In some instances, standardised modules are produced, with late stage postponement taking place at the COEP (Tu *et al.*, 2004, p.151). PRP levels are low where COEP is located after final product assembly.

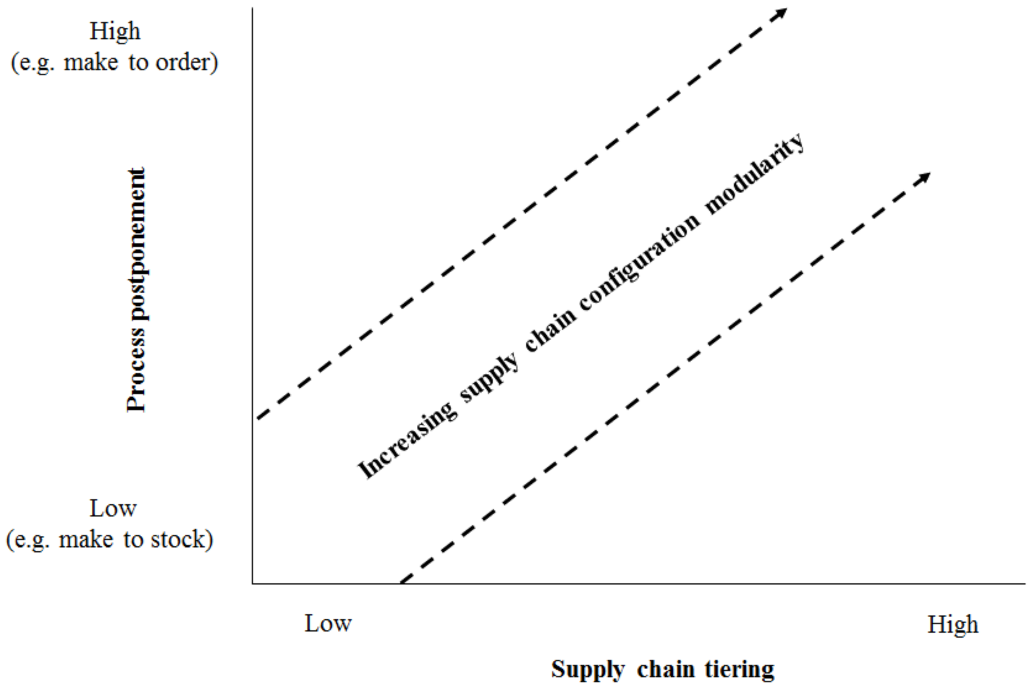


Figure 3-7. SCT and process postponement

3.3.4. Process flexibility

PF reflects SCC ability to cope with changing circumstances or environment instability (Meyer and Utterback 1993; Arnheiter and Harren, 2005). Sanchez (2000) echoed similar thoughts on late-point differentiation of products using modular architecture. High PF is reflective of a processes ability to be reconfigured. For example, Dell's SCC like its products, comprises of a series of interchangeable process units. Dell's suppliers can be co-located or distributed geographically, as the product design requires limited direct coordination or interaction. This SCCM attribute is measured on a scale of high to low, with high flexibility being a SCC processes ability to be reconfigurable and extensible with respect to PA. Low PF denotes constrained SCC tasks.

3.3.5. Process re-sequencing

PR is the re-ordering of sub-processes with standard sub-processes occurring prior to customisation sub-processes (Tu *et al.*, 2004). This attribute is closely linked to PRP and PF. SCC encompasses material and supplier selection; standardization and sequencing of manufacturing and distribution processes; including the configuration of the SC (Amini and Li, 2011). The process re-sequencing attribute is either high or low. High PR represents the ability to re-sequence or re-order standard sub-processes to occur first followed by any required customisation sub-processes. Low PR represent hard tooled processes, with predefined process sequences.

3.3.6. Place postponement

PP refers to postponed customisation or high variety processes at a location close to the COEP, to achieve maximum time flexibility. This attribute typically requires strategic inventory positioning (Dekkers, 2006), since orders require immediate fulfillment. High levels of PP reflect multiple COEP locations. Low levels of PP represent a situation where COEP occurs in a central location, for example via an ecommerce platform. Many design-driven companies use their products' visual imagery as a means of differentiation (Talke *et al.*, 2009). PP affords companies the ability to configure the product based on receipt of the actual customer order, on a relatively short lead-time, in many cases this involves personalisation or customisation of the product. Customisation sub-processes occur relatively close to the market, for instance in a retail store or local distribution center, to achieve maximum flexibility. In many instances supply chains must be reconfigured before determining final product design (Colfer, 2007). The three optional SCCM attributes may or may not be present, in all situations.

3.4. METHODOLOGY

This Section begins with an overview of what is covered in the methodology discussion. Project one, highlighted a lack of development of the SCCM construct, together with a gap in knowledge of PM mirroring with SCCM. Limited prior research on PA and SCA mirroring means that themes and patterns need to be developed (Eisenhardt, 1989). This Section explains and provides justification for the methodological approach used in project two.

3.4.1. Overview

The methodology Section discusses the research design, including the guidance implications derived from the SLR, research questions two and three. It discusses case and UoA selection, followed by data collection and data analysis.

3.4.2. Research design

‘To cope with the growing frequency and magnitude of changes in technology and managerial methods, OM researchers have been calling for greater employment of field-based research methods’ (Lewis, 1998). In-depth case studies were selected as the methodology for this empirical research. Eisenhardt (1989) notes that one advantage of field-based research techniques such as case studies is that operational measures are more likely to be measurable and usable in hypothesis testing because of their grounded nature. This makes case study research valuable in developing, testing and refining operational measures for constructs. This is a necessary precursor to theory testing and particularly important in this research. Case studies are often found when researching complex social phenomena in real-life contexts (Yin, 2014). Case studies allow for a review of formal and informal processes within an organisation and enable researchers to look at a wide array of attributes or variables (Hartley, 1994). The case study method attempts to illuminate a decision, or sets of decisions: why were these decisions taken? how are they implemented? and with what result? The case study method is particularly good for examining '*how*' and '*why*' questions (Yin, 2014) and 'lends itself to early, exploratory investigations where the attributes or variables are still unknown and the phenomenon not at all understood' (Meredith, 1998). The need for more descriptive, empirically based research is argued by various scholars (Mintzberg 1979). This is true for the development of the SCCM construct.

The key strength of the case study approach is its non-isolation of the phenomenon under study, allowing the phenomenon to be studied in relation to its context. This is a consideration that is largely ignored by more variable oriented approaches, such as surveys or modelling, and results in many of the identified weaknesses of these methods. Ragin (1987) states that case-orientated research is based on the application of multiple methods which seek to account for all deviating cases, and therefore creates a rich dialogue between theory and evidence. This is significant for the proposed research concerning the mirroring of PM with SCCM since this body of research is small, especially when considering operational implications. In an area where the theoretical base is weak, field based approaches are the best means of investigating issues, describing problems, discovering solutions and in general 'ground theory in the complex, messy world of real organisation's (McCutcheon and Meredith 1993). Further, Sweeney, Grant and Mangan (2015) state that to generate new SCC theory, research design must expand beyond surveys, to more use of case studies, grounded theory, and action research. Theorizing is not about what the SC is, but rather what the SC does, and how it impacts company performance.

The issue of using operational measures for constructs is one which disqualifies the survey approach for this research. A survey would be an inappropriate approach because many of the concepts, such as SCCM itself and mirroring, are not generally understood and are open to misinterpretation. Further, an administered survey would have proved insufficient because many of the variables are difficult to understand without scrutiny. Importantly the artificial disaggregation of variables into questions, necessary for a survey, denies the dynamic and holistic nature of operations systems. Thus, surveys fail to address the interconnections involved. These problems are compounded by the relative remoteness of the survey researcher who may only pay occasional visits to participating companies, if at all. Concerns have been expressed about the rigour of empirically based descriptive research. Daft and Lewin (1990) highlight one such concern saying it ‘requires comprehensive understanding of a specific situation that is often not generalisable to other settings’. Harrison (2002) states that ‘case study research is of particular value where the theory base is weak and the environment under study is messy’, as is the case in the research of SCCM. Finally, the conditions that Yin (2014) proposes when case study research is appropriate are: 1) the form of the research question; 2) whether the researcher has control of, or access to, the actual behavioral events under study, and 3) the degree of focus on contemporary events. This research is explanatory in nature and SCCM is a phenomenon that the researcher had no control over, but access to since it is a contemporary phenomenon. Research design considerations to address the concerns regarding rigor of case studies are addressed in Section 3.6. Data was collected from multiple sources and multiple viewpoints. Three primary sources of evidence were used, research papers, archived records in the form of reports and press releases, and interviews. These sources are among those outlined by Yin (2014), as primary sources of evidence, in qualitative research

3.4.3. Case selection

Ragin (1987) states that case-oriented research is based on the application of multiple methods which seek to account for all deviating cases, and therefore creates rich dialogue between theory and evidence. In SCC where the theoretical base is weak field based approaches are a suitable method to investigate specific phenomenon, ‘describe problems, discover solutions and generally ground our theory in the complex, messy world of real organisation’s (McCutcheon and Meredith, 1993). SCC contains relationships among elements representing multiple domains within the supply network. This empirical work focuses on the interrelationships between PA and the different domains within the supply network, and seeks to provide a contribution to SCC and NPD process transformation, through a review of PM and SCCM mirroring.

Case companies were selected across medical device, domestic appliance, automotive and aerospace industries. The cases were selected from different tiers within the SC to address different perspectives on SCCM. The case study design incorporates five cases across these four industry sectors. The SLR highlight that the automotive and aerospace sectors accounted for the most academic references, with much of these publications referencing modularity-based SC practices, as a means of managing product complexity (Novak and Eppinger, 2001). The aerospace industry is increasingly adopting modular architecture, Rossetti and Choi (2005). The rapid growth in market share by the airplane OEM during the 1990's, is partly attributed to this OEM's use of modular design. Where the main competitor employed two-hundred and sixteen workers for every airplane produced, the OEM had one-hundred and forty-three workers, a productivity difference of fifty-one (O'Grady, 1999). The automotive and aerospace OEM's, tier-one and tier-two suppliers were selected to assess the effect of vertical SCC. The medical device and domestic appliance sectors were selected, since these are under-going significant technological change.

Miles and Huberman (1994) state that case sampling involves two actions: 1) setting boundaries that define what you can study and connect directly to the research questions, and 2) creating a sample frame to help uncover, confirm, or qualify the basic processes or constructs that underpin the study. Multiple cases improve external validity and help guard against observer bias, but have the disadvantage of possibly less depth in each case (Voss *et al.*, 2002). The case selection focused on innovative companies who are sector leaders in the design of new-to-market products. These companies use PA to offer product variety and maintain market leadership positions, recognising that many product innovations originate within the supply base.

Pettigrew (1990) discusses the process of selecting cases: 'there is an intentional or design component in the process of choosing and gaining access to research sites, but the practicalities of the process are best characterised by the phrase planned opportunism'. Cases were selected where there was access to knowledge experts in product design and SCC design, from each case company, except for the airplane OEM where access was not possible. Case data on the aerospace UoA was provided by a service engineer from an airplane service company, supporting the OEM. The knowledge experts were invited to offer insight in to the research topic. The participants have certain common experiences, in NPD and SCC. Where possible, experts were selected with a mix of NPD and SCC experience, this was the case in the medical device, domestic appliance, drive-line systems, and automotive companies. The knowledge experts were senior product design or SCC design personnel, within their companies. In addition to contributing to the richness and variety of the data, this approach mitigates potential biases from respondents who might engage in convergent retrospective sense-making (Eisenhardt and Graebner, 2007).

Prior to each case study an interview protocol was provided to each knowledge expert. A general list of secondary questions was developed including the research concern, theoretical framework, and goals of the study, and maintained throughout the data collection process, following the recommendations of Auerbach and Silverstein (2003, p.44). Preparatory phone calls were organised to explain the research domain, the central research question, the aim of the case study and a general discussion in advance of each case study. A confidentiality agreement was provided in advance. Some companies elected not to enter in to a confidentiality agreement. Triangulation is achieved within each case such that different data sources and methods corroborate each other, see Section 3.6. The qualitative data is gathered through systematic interviews, publicly available information, and focus group interviews in the case of the medical device and domestic appliance companies. The interviews are approached from a position of flexible and open-ended inquiry. The interviews adopted a curious and facilitative stance, rather than an interrogative approach.

3.4.4. Units of analysis

All UoA are designed in-house, and have a strong architectural design focus. The UoA are all new-to-market products, whilst some products have been in the market for considerable time, they have not been replaced, in the market. Two UoA were selected within each focal company, shown in Table 3-4. One objective was to select one product with a high level of PM and one with a lower level of PM, for comparison purposes. This objective however was not achievable with the automotive, driveline company, and aerospace companies. In the case of the medical device company, a disposal surgical cartridge device (A1), and blood glucose meter (A2) were selected. In the case of the domestic appliance company, an air purifier (B1), and cordless vacuum cleaner (B2), were selected. The UoA associated with the automotive company, include a 4X4 Sports Utility Vehicle (C1), and a Crossover Utility Vehicle (C2). The auto-drivetrain company UoA include a drivetrain (D1) and drive shaft sub-assembly (D2). Finally, the UoA researched from the aerospace companies includes a fixed trailing edge structure for an airplane wing (E1) and a medium to long range wide-body twin-engine airplane (E2). Except for A1, D1, D2 and E1, all UoA represent platform products.

Table 3-4. Units of Analysis

Units of Analysis (UoA)										
Company	Med device co.		Domestic appliance co.		Auto co.		Auto driveline co.		Aerostructure co.	Airplane co.
UoA	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
	Surgical cartridge	Blood glucose meter	Air purifier	Cordless vacuum cleaner	4-Wheel drive SUV	4-Wheel drive CUV	Automotive driveline	Automotive drive shaft	Fixed trailing edge for airplane wing	Wide-bodied airplane
										

Each UoA and their SCC context are shown below in Figure 3-8. A1 and A2 are manufactured by the OEM; B1 and B2 are assembled by tier-one suppliers; C1 and C2 are assembled by the OEM; D2 and D1 are manufacturer by a tier-one supplier to the automotive OEM, and E1 is a sub-module of E2. An airline maintenance company represented the airline OEM, in the case research. Additional product and SCC data is shown in Appendix 3-8, Page 456.

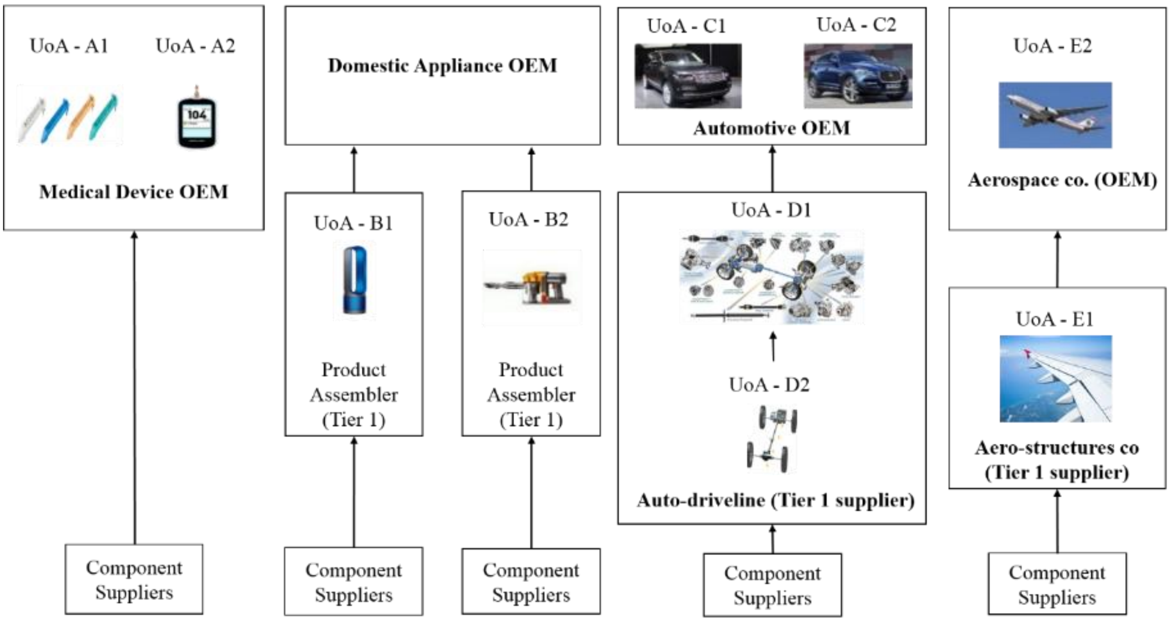


Figure 3-8. UoA nested in their product architecture

The research was conducted at different tiers in the SCC, and at different levels of the BOM. Within-case and cross-case analyses was completed, shown below in Figure 3-9.

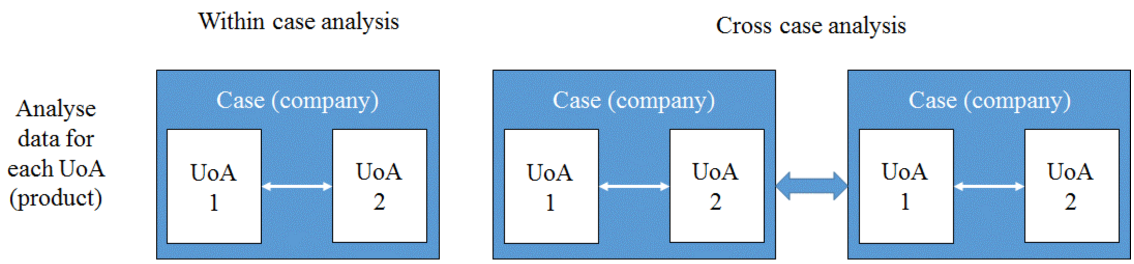
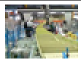


Figure 3-9. Within-case and cross-case analyses

The launch dates for the UoA vary from 1992 to 2016, shown below in Table 3-5. The time-period span varies for each UoA. All UoA have a concept stage time duration of five years or less, and a total concept to launch cycle time of three to six years, except for the aerospace UoA. C2 had a three-year concept to launch, which represents a fifty percent reduction on similar automobiles launched five years prior to this launch.

Table 3-5. UoA descriptive data

	Unit's of Analysis									
Company	A (Med device co.)		B (Domestic appliance co.)		C (Auto co.)		D (Auto driveline co.)		E (Aerospace co.'s)	
Respondent	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
UoA	 Surgical staple cartridge	 Blood glucose meter	 Air purifier	 Cordless vacuum cleaner	 4X4 wheeldrive SUV	 4X4 wheeldrive CUV (Crossover SUV)	 AWD driveline solutions	 Driveshaft, for AWD system	 Fixed trailing wing edge for A350 airplane	 A330 airplane
International Standards	ISO-10993	ISO15197	ISO 8573 (Air quality) ISO 3744 (Decibel level)	ICS 97 BS EN 60312:2008	ISO 43.02 (plus others)	ISO 43.02 (plus others)	ISO 43.02 (plus others)	ISO 43.02 (plus others)	ISO/TC 20 (plus others)	ISO/TC 20 (plus others)
SIC or NAISC Code	339112	339112	26400	26400	29100	29100	29100	29100	33641	33641
Launch date	1995	2013	2015	2009	2012	2016	2004	2004	2013	1992
PM-SCC alignment	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	No
Concept time (years)	2	5	2	2	2	2	5	4	10	10
Concept to launch (years)	5	6	3	3	3	3	6	6	20	20

The UoA were restricted to the top-level-assembly (TLA), sub-assemblies and modules, shown below in Figure 3-10. There is an argument that all products become increasingly modular as they approach component level.

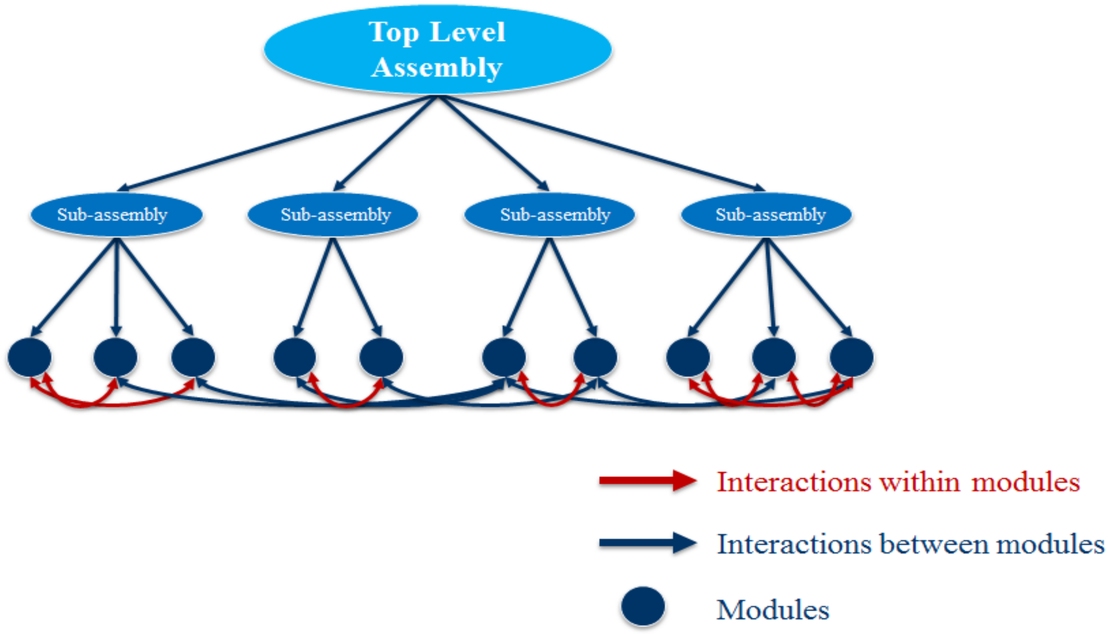


Figure 3-10. Generic bill of material
Source: Nepal (2012)

Products exhibit different levels of PM at different levels of the product BOM, for example automobiles, as shown below in Figure 3-11. With many products that offer product variety in use, modules are often combined to provide the required level of customisation. "*Whether functional elements map to more than one module depends on the level of detail at which components and functional elements are considered*" Director of Products, Programs, and Operations, with the automotive company.

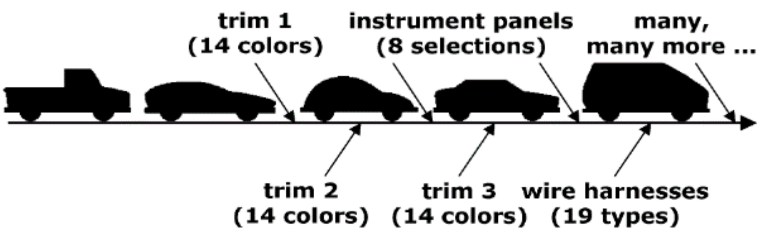


Figure 3-11. Delivery of product variety

Distribution, retail, and end customer configuration, are within the SCCM boundary, as shown below in Figure 3-12. Many products today are delivered Omni-channel, using physical (offline) and digital (online) communication channels. Consumer products such as the domestic appliance UoA can be delivered via retail, online, resale, or direct channels. The medical UoA are delivered via healthcare distributor channels, whilst the automobile UoA are delivered via distributors. The airplane is delivered direct to the airline or leasing company; the driveline solutions, drive shaft and fixed trailing edge module for the airplane wing are delivered up-stream to the module and final assembly plants, as shown below in Figure 12.

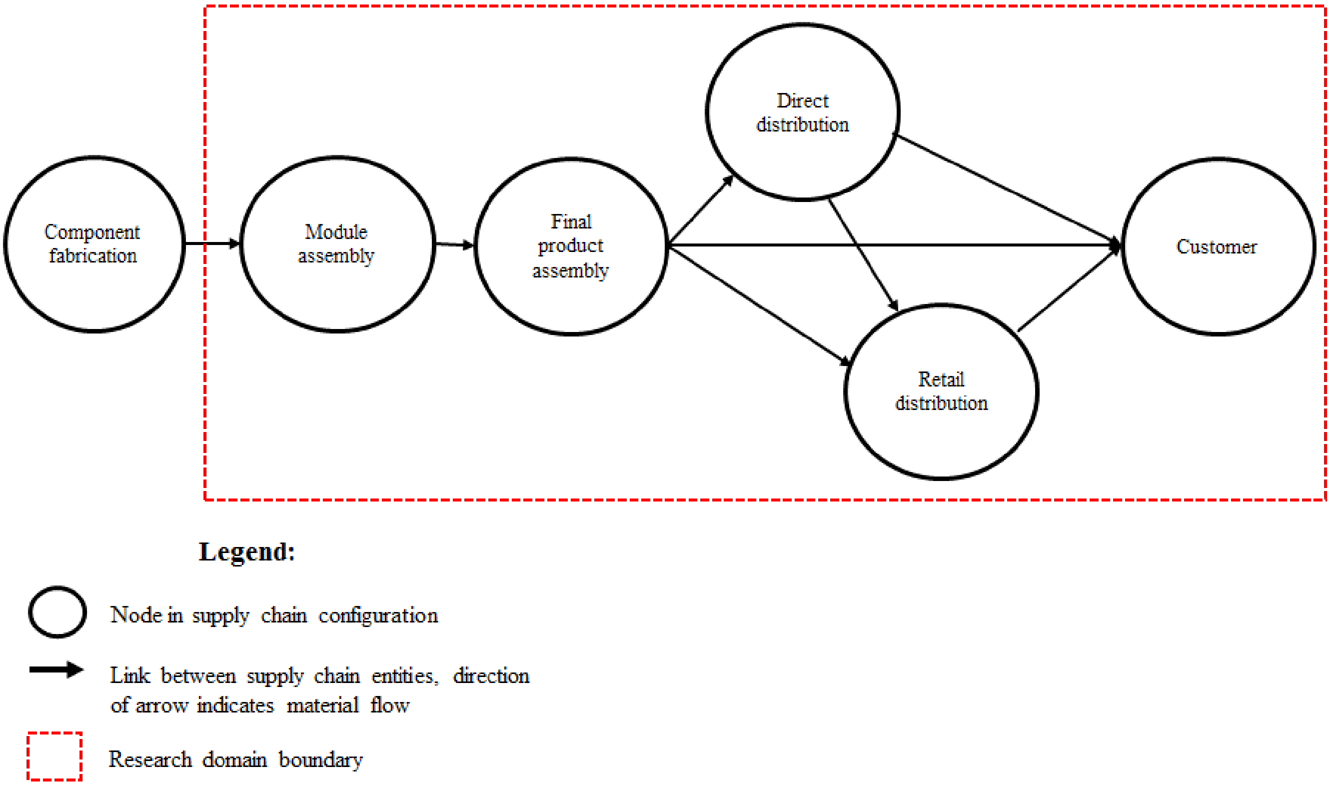


Figure 3-12. Supply chain configuration boundary

Whilst the research boundary is limited to three levels of the BOM, the SCC extends to the point of delivery to the end customer, or industrial customer. The primary distribution channels are identified are shown below in Table 3-6.

Table 3-6. Distribution channels

	Distribution channels for each UoA									
Company	Med device co.		Domestic appliance		Auto co.		Auto driveline co.		Aerospace co.'s	
UoA	Disposable Surgical cartridge	Blood glucose meter	Air purifier	Cordless vacuum cleaner	Standard utility vehicle	Crossover utility vehicle	Driveline solutions	Drive shaft	Fixed wing trailing edge	Aircraft
	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
										
Primary distribution channel	Healthcare distributors	Healthcare distributors	Retail	Retail	Auto Distributors	Auto Distributors	JIT delivery to Auto (Product) assembly	JIT delivery to Auto (Product) assembly	JIT delivery to Wing (module) assembly plant	Direct to Airline operator

3.4.6. Data collection

The empirical data was collected for each of the cases using a selection of methods, including semi-structured interviews, published reports and case company provided data. The data collection commenced with three pilot interviews.

3.4.6.1. Pilot interviews

These three pilot interviews were conducted via telephone to evaluate the key constructs, and sub-themes from the SLR. These pilot interviews provide a means of assessing the interview questions and evaluating the interview process. The three persons interviewed were the Operations Director at LEGO, and a Design and Engineering Manager and VP Design and Engineering at Flex., shown below in Table 3-7.

Table 3-7. Pilot interviews

Phase	Company	Turnover (US Dollars) 2014	Number of employees 2015	Role(s)	Unit of Analysis	Number of interviews	Total duration (minutes)
Pilot	Toy Manufacturer	$4.182B	12,582	Global Operations Manager	Plastic Toys	1	40
	Global Supply chain services	$26.147B	150,000	VP Product Design	Blood Glucose Meter	1	36
				Snr Director Product Design	Industrial controller	1	35

A draft questionnaire was prepared, with primary and secondary questions, for each of the PM and SCCM attributes deduced from the literature. The original plan was to rate the levels of modularity present for each UoA, and rank the relative importance of each attribute. The levels of PM attribute were rated on a seven-point Likert scale (from very high = 7, to very low level =1). The importance of each PM and SCCM attribute were ranked on a five-point Likert scale (from 1 = most important, to 5 = least important). The pilot study targeted senior manufacturing managers, in Flex and LEGO.

There was consensus from the three pilot interviews on the relative importance of the PM and SCCM attributes, shown below in Table 3-8. The multi-functional product configuration measure was subsequently changed to the SCT measure, following these pilot interviews. SCT is also deduced from the literature. Initially, the sub-themes were rated and ranked following a quantitative approach. Following a test of the quantitative approach in the first pilot interview it was decided not to rate and rank the interview responses as this methodology tended to stifle PM and SCCM construct development. Instead questions were posed to elicit and develop PM and SCCM constructs and their attributes, as shown below in Tables 3-1 and 3-2. Prior to commencing the case studies two further interviews were held with the principal global engineer with a medical device company, and the senior aerospace maintenance consultant engineer, to validate the themes and sub-themes, developed during the SLR. After these initial interviews the PM and SCCM attributes were further developed. Quantitative techniques shown in Appendix 3-4, Page 452, were evaluated to assess their level of suitability. Further quantitative analysis was deemed not suitable for this empirical analysis.

Table 3-8. Pilot interview results

Constructs	Variables	Alternative definitions	Primary questions	UoA (rating) Industrial	UoA (rating) Medical	UoA (rating) Toy	UoA (ranking) Industrial	UoA (ranking) Medical	UoA (ranking) Toy
Product modularity	Function sharing	Many functional elements in one module	Does the product prevent function sharing, by mapping single functions to single component or modules? (from very high = 7, to very low level = 1)	7	7	7	1	1	2
	Interface coupling	Interdependence of modules	Are component and module interfaces standardised and clearly specified, allowing ease of component substitution? (from very high = 7, to very low level = 1)	2	6	7	2	2	1
	Data access	Level of data accessibility	Does your product offer component, module and system level performance data access? (from very high = 7, to very low level = 1)	5	5	1	4	4	5
	Limited life	Component swap or upgradeability	Does your product take in to consideration useful (or limited) life of components? (from very high =7, to very low level = 1)	5	7	7	3	3	4
	Product variety in use	Product customisation	Does your product design facilitate user product customization? (from very high = 7, to very low level =1)	3	2	7	5	5	3
Supply chain configuration modularity	Multi-functional product configuration	SCC process standardisation	Does the supply chain configuration provide varying product configuration options? (from very high = 7, to very low level = 1)	3	2	2	2	1	1
	Process flexibility	SCC process resequencing	Can supply chain configuration deliver both standardised and customized modules and systems? (from very high = 7, to very low level = 1)	5	5	6	4	3	4
	Process re-sequencing	SCC process postponment	Can supply chain configuration be re-sequenced so standard subprocesses occur first while customisatoin or differentiation sub-process occur last? (from very high = 7, to very low level = 1)	5	2	1	3	4	3
	Process postponement	DC enabled process postponment	Supply chain processes can be rearranged so that product assembly occurs afteer the COEP? (from very high = 7, to very low level = 1)	2	2	3	1	2	2
	Place postponement	Customer enabled process postponment	Can supply chain configuration provide user late stage form postponement (Fp) at a location close to the COEP? (from very high = 7, to very low level = 1)	1	1	1	5	5	5

Rating of variables (7 = very, to 1 = very low)

Ranking of variables (1 = most important, to 5 = least important)

3.4.6.2. Semi-structure interviews

Following the pilot interviews fifteen semi-structured interviews were conducted in total, with knowledge experts in the case companies, as shown in Appendix 3-4, Page 452, and Table 3-9. Ten primary interviews were followed by five follow-up interviews to validate the information exchanged. Two sample interview transcripts from Project two are shown in Appendix 4-14, Page 486, and Appendix 4-15, Page 49.

Table 3-9. Project two interview schedule

	Project 2 Interviews	Number of interviews
1	Decide UoA which will be part of the analysis. ↓	
2	Pilot interviews. ↓	3
3	Collect and analyse data, and generate report, and fine-tune questionnaires, for semi-structured interviews. ↓	
4	Interview product design and supply chain design experts. ↓	10
5	Follow-up interviews to validate the data collected in initial interviews.	5
	Total Interviews	18

Significant effort was deployed in gaining access to these knowledge experts. All experts have high levels of expertise, and responsibility within their respective companies. The duration of each interview varied from thirty-five minutes to two-hundred and ten minutes, as shown below in Table 3-10.

Table 3-10. Project two interviews

Phase	Company	Turnover (US Dollars) 2014	Number of employees 2015	Position of the interviewee	Unit of Analysis description	UoA	Number of interviews	Total duration (minutes)
Case studies	Medical Devices	$74.331B	126,500	Principle Global Engineer	Surgical cartridge	A1	2	120
				Senior Process design Engineer	Blood Glucose Meter	A2	1	95
	Domestic appliances	$2.005B	4,545	COO and Board member	Air Purifier	B1	2	135
				Director Global Manufacturing	Cordless vacuum cleaner	B2	2	145
	Automotive	$28,169B	27,953	Purchasing Director	Sports utility vehicle	C1	1	120
				Director products, programs and operations	Crossover utility vehicle	C2	2	95
	Automotive driveline products	$10.832B	55,000	Director Group business improvement	Automotive driveline	D1	1	105
				Group Director - Supply chain excellence	Automotive drive shaft	D2	1	65
	Aerospace	$66.311B	55,000	Director Group business improvement	Fixed trailing edge section for wing of airplane	E1	1	35
				Snr. Aerospace maintenance consultant engineer	Wide bodied passenger airplane	E1	2	210
							15	1125

These interviews were conducted in person, except for interviews with the Group Director responsible for SC excellence with the automotive driveline company, and the Director of products, programs, and operations with the automotive company, who were interviewed via telephone. The Director for Group business improvement for automotive driveline products was interviewed for UoA D1 and E1, as the same case company produced D1, D2 and E1. Of the seven persons interviewed face-to-face during project two, five were interviewed a second time, to expand on topics, and clarify initial interview responses. Sample interview extracts are included in Appendices 4-14, Page 488 to Appendix 4-17, Page 511.

The research uses triangulation methods (Yin, 2014). Two persons were interviewed from each company (source triangulation), shown below in Table 3-11. Additional data collection methods were used, including product data sheets, filed accounts, company procedures where available, and bills of materials where available (method triangulation).

All interviews were taped, transcribed and analysed using data reduction techniques to identify emerging themes, concepts, and typologies guided by the primary research questions. The data is disguised, and the names of organisation's and individuals are anonymized to preserve privacy and confidentiality.

3.5. DATA ANALYSIS

Each interview was digitally recorded with the permission of the participant. The participants were informed that their information and identity would remain confidential. The participants acknowledged that the interview was voluntary and that they could refrain from answering any question.

3.5.1. Content analysis

The interviews were transcribed, and the data interrogated for ideas and constructs selected in advance. Each transcript was coded, using *a priori* codes. The content analysis sought causally linked attributes or variables, and clarity in the data. The coding also sought underlying themes, theoretical perspectives and patterns in the relationships within the data. Data coding was completed using the pattern coding technique. Pattern codes are explanatory or inferential, and identify emergent themes, configurations or explanations (Miles and Huberman, 1994).

Coding was performed in two steps: 1) data was analysed and coded into second-level codes, and 2) codes were developed that summarise data into broader patterns, and second-level codes. A comprehensive list of codes and code descriptions are listed in Appendix 3-5, Page 453. Codes start at level-one with an abbreviation identifying each category. Level-one codes were derived from the interview questions. PM for example, is the level-one code for PM. Level-two codes are then assigned to represent various responses, L for 'low', M for 'medium', and H for 'high'. Level-two codes were created to represent unique responses to the interview questions and often represent the respondent’s exact words (*in transcript).* Each low, medium and high level for each construct attribute or variable (Level-two code) was defined *a priori.*

3.5.2. Pattern codes

With the data summarised and coded into descriptive codes the analysis turned to investigating possible patterns between the key constructs. Pattern coding is a means of grouping descriptive codes into smaller sets of inferential pattern codes. Appendix 3-5, Page 453 and Appendix 3-6, Page 454, show a list of pattern codes and pattern descriptions, deduced from the literature. Miles and Huberman (1994) describe pattern codes around themes, causes, explanations, and relationships among constructs.

3.5.3. Themes

Patterns were identified in nine areas. The first area relates PM and SCCM constructs, and the mirroring of the mandatory construct attributes. These patterns relate to mirroring of FS and IC, deduced from the literature in project one. Patterns relating to mirroring SCT and PRP, were deduced from the literature in project one, any deviating pattern is explained, an understanding of these thematic patterns is key to this research. The SCT modularity construct is an aggregate measure of the span of the supply network and the level of economic and legal business involvement by the OEM company, in the business of their suppliers’ business. The depth, breadth and geographic span of the supply network was the strongest combination or pattern, with a low to medium level of economic and legal business involvement by each of the OEM’s. These construct patterns relate to the independence of each product or SCC module, and their ability to be combined, separated, or re-sequenced. This independence closely relates to the IP of each module, and the ability to manage and govern product and process IP. Additional patterns which relate to optional PM and SCCM attributes, deduced from the literature, are explained in Appendix

2-8, Page 447. Additional patterns were deduced from the literature linking PM and SCCM, these are co-development (knowledge sharing), ESI and the life cycle perspective. These themes illustrate either a low, medium of high level of mirroring relationship between PM and SCCM. Finally, two patterns system agility and customer order entry point, were deduced relating to the mirroring of PM and SCCM. All patterns are shown below in Figure 3-13.

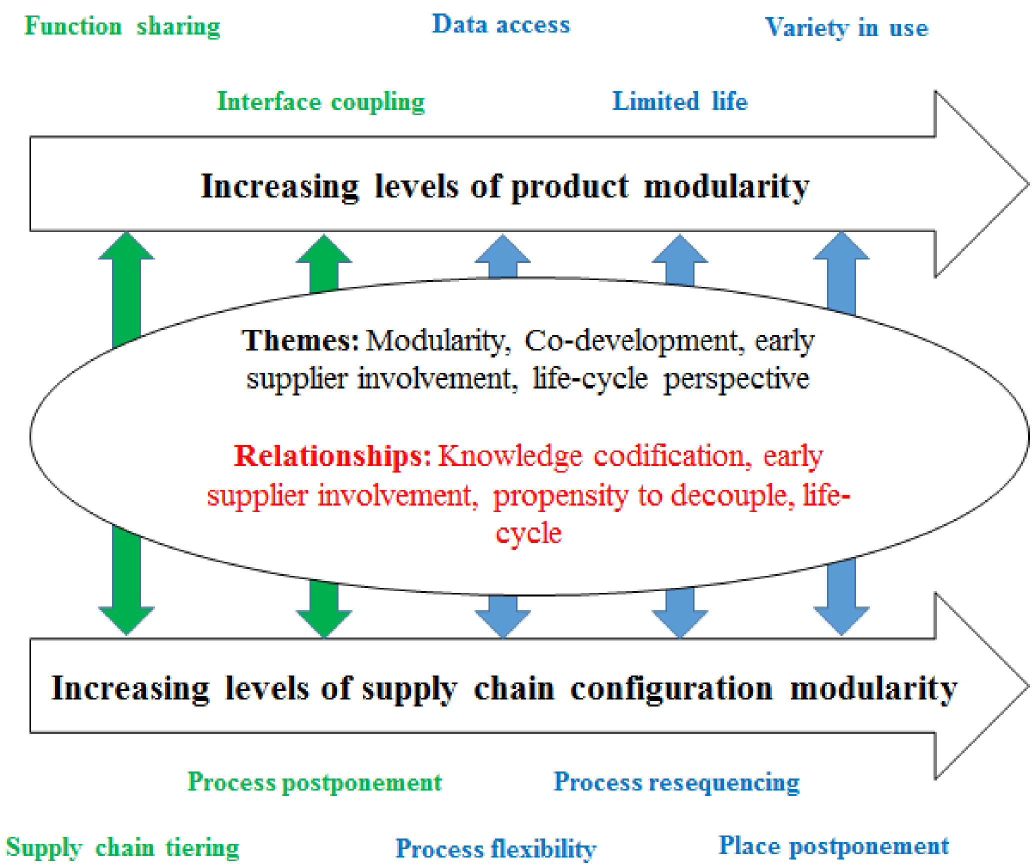


Figure 3-13. Data patterns deduced from the SLR

3.6. RIGOR IN CASE STUDIES

In this Section, it will be explained how rigor was addressed in the case studies using four tests to establish the quality of the empirical research, using construct validity, internal validity, external validity, and reliability (Yin, 2014), as sown below in Table 3-11.

Table 3-11. Quality Criteria

Construct validity	1	Multiple sources of evidence were used (Yin, 2014).
	2	Key informants were in top management positions including Chief Operations Officer, Global Operations Manager, Principle Engineer, VP Product Design, Purchasing Director, Snr Consultant Engineer, Snr Process design engineer, Director Global manufacturing, Senior Director product design, Group Director - Supply chain excellence - with full responsibility for product and supply chain design processes.
	3	Construct operationalization was supported by a systematic literature review.
Internal validity	1	Assured through pattern matching (Yin, 2014).
	2	Two units of analysis selected for each case study.
	3	Where possible units of analysis were selected from high and low modularity level extremes.
	4	In the case of automotive and aerospace a Tier one supplier was included in the case studies.
External validity	1	Achieved through analytic generalization and replication logic (Yin, 2014).
	2	Case studies are taken from five industry sectors, medical devices, domestic appliances, automotive, automotive driveline and aerospace.
	3	Two of the industry sectors are highly involved in modular-based practices automotive and aerospace, this was determined from a systematic literature review.
Reliability	1	Reliability is achieved through transparency of the process (Yin, 2014).
	2	The case study protocol defines the way the data were collected.
	3	In the data collection phase a case study database has been developed.
	4	Draft cases studies prepared and validate by each case company.

3.6.1. Triangulation (construct validity)

Construct validity is ‘the extent to which a concept’s operational measures reflect the concept’s observable effects’ (Nunnally, 1978), and entails establishing operational construct measures. Triangulation represents ‘the combination of methodologies in the study of the same phenomena' (Denzin, 1978). 'Case study enquiry relies on multiple sources of evidence, with data needing to converge in a triangulating fashion' (Yin, 2014), where 'sources of evidence' refer to different methods such as semi-structured interviews and documentary evidence.

Four tactics identified by Yin (2014) were used to strengthen construct validity in this qualitative research; 1) multiple sources of evidence was sought, through eighteen interviews and backup literature research; 2) a chain of evidence was established by interviewing two experts from each company; 3) a draft case study report was reviewed by the persons interviewed, and 4) data triangulation was conducted.

3.6.2. Analytic strategy (internal validity)

The analytic strategy of pattern matching was used to address internal validity. Pattern matching involves the comparison of an empirically based pattern with a predicted one. Two UoA were included in each of the cases studies. Case study research follows Pettigrew's 'meta-level' analytical framework, as shown below in Figure 3-14. This framework enables change to be studied in different environments without theory limitations in comparative case study research. Three primary variables; context, content and outcome are described. The key constructs PM and SCCM and the construct measures shown in tables 3-1 and 3-2 constitute the research domain. These qualitative measures are mapped onto Pettigrew's 'meta-level' analytical framework (Pettigrew, 1990, 1992), shown in Figure 3-14.

CONTEXT: The company and the market in which it resides

CHANGE CONTENT: Development of the PA and SCC

OUTCOME: The PA and the SCC and the level to which they mirror each other

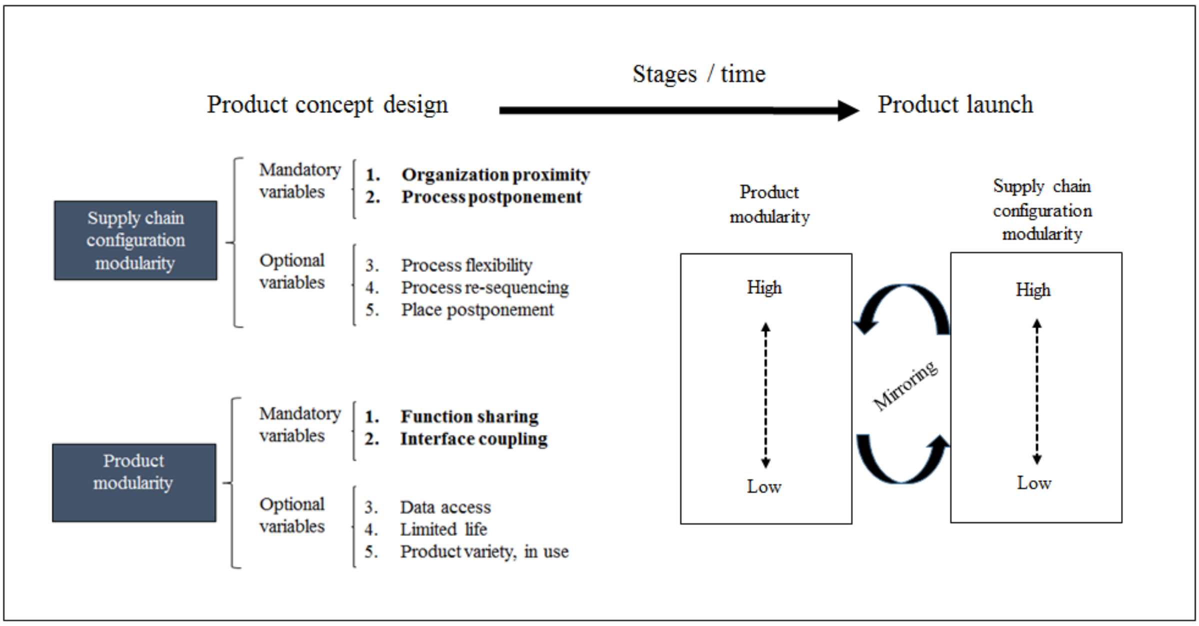


Figure 3-14. Meta-level case study framework
Source: Pettigrew (1990)

3.6.3. Case selection (external validity)

External validity is important in establishing the domain to which a study's findings can be generalized. Case selection using replication was used (Yin, 2014). Theory is fundamental to OM research, and drives the creation of knowledge. Predictions, without the underlying causal logic, as to why something is likely to happen do not constitute theory (Whetten, 1989). Theory explains why something is likely to happen (Sutton and Staw, 1995). From the literature review no explicit causal models were found that mirror the PM and SCCM constructs, explaining PM and SCCM mirroring. In this study the aim is to gain an understanding from cross-case analysis, on the ability to generalise findings of this research across different industry sectors. For example, can the mirroring of PM and SCCM in the automotive sector be used to generalise mirroring in the medical device or domestic appliance sectors? It is this generalisation that determines the theoretical contribution of this work.

Pettigrew (1990) states that with a limited number of studies, it makes sense to choose cases such as extreme situations and polar types. Literal replication logic was used to select the cases because it was expected that similar levels of PM and SCCM would apply. Each case was expected to produce similar results (Yin, 2014). For each of the cases the aim was to select one high PM and one low PM product for the research to extend the generalisability of the findings. This aim was achieved with the medical device, domestic appliance and auto-driveline companies.

Eisenhardt (1989) defines sectors as populations, and maintains the concept of a population is crucial, because the population defines the set of entities from which the research sample is drawn. Selection of an appropriate population controls extraneous variation and helps to define the limits for generalizing the findings. The population comprised of UK and Ireland manufacturing companies. This increases the generalisability of this research. All cases selected are UK or Ireland divisions of multi-national companies. The domestic appliance, automotive, auto-driveline and aerospace supplier are headquartered in the UK, the medical device company is headquartered in the US, and the aerospace company is headquartered in France. The domestic appliance company and medical device company outsource production of their products to contract manufacturers. With the automotive and aerospace company's products were selected at different levels of the product BOM.

3.6.4. Case contexts

'A problem in conducting case research is where to draw the line' (Harrison, 2002). Defining the UoA is not sufficient in determining the research boundaries. Harrison observes that in practice, the case boundary will often define itself reasonably well if the research design has been clarified. This clarification can be provided by the product BOM and the SCC bill of process (BOP). Modular BOM's that describe the sub-assemblies, for example a NAAMS BOM, are used in the automotive industry to list the components on the assembly line. The structure of the NAAMS BOM is comprised of the system, assembly line, tool, unit, and unit detail, including intra- and inter-module connections. A configurable bill of materials (CBOM) is used by industries that offer multiple product options and configurable products, for example telecom systems, data-center hardware and automobile products. BOM's such as planning bills (Stonebraker, 1996); modular bills and kit bills (Oden *et al.*, 1993), and generic bills (Jiao *et al*., 2000) are used in different SCC contexts.

3.6.4.1. Medical device UoA

UoA A1 is a disposable surgical cartridge (DSC), used in invasive surgical procedures to suture internal wounds. The product has more than five-hundred stockable known units (SKU's). A1 is inserted in the body by a manually operated linear cutter designed for consistent staple formation and hemostasis, across a broad range of tissue thickness, shown below in Table 3-12. A1 is assembled at the OEM factory in Mexico, using globally sourced components. The product is supplied directly and indirectly through distribution channels to medical care centers. Launched as a new-to-market product in 1995, this device has not been replaced in the market to date. The knowledge expert who participated in this study is the Engineering Fellow, responsible for this company's global center of automation excellence.

A1 is comprised of approximately two-hundred discrete parts. It does not have a data communications bus. There is an opportunity, with further product enhancement to integrate data feedback in to the product and SCC process. Feedback control (FC) between PM and SCCM is a theme running through this empirical research. This product which is non-configurable post the COEP, has high reliability and a long shelf-life. The core technology is offered as hundreds of SKUs. If there were multiple variants of the same core technology this would compromise the efficacy of delivering this device.

Table 3-12. UoA descriptive data

	Unit of Analysis (UoA)				
Company	Product	Level's of Bill of Material included in research*	Component count	Stockable Known Units (SKUs)	Supply chain configuration
Medical device Co.	Non-invasive surgical disposal cartridge, part of suturing system	3	200	~500	Global supply chain, wire, metal components, and plastic molded components. Semi-automated assembly, takes place at OEM plant in Mexico
	Verio blood glucose meter	3	~90	550	Global supply chain, semi-automated meter manufacturing partner, in China. The test strips are produced by the OEM in Scotland, in a continuous automated process.
Domestic appliance Co.	Air Purifier (AP)	3	~150	108	Global component supply, with tier 2 and 3 partners and tier one prime sub-assembler based in Malaysia
	Cordless vacuum (DC74)	3	258	190	Global component supply, with tier 2 and 3 partners and tier one prime sub-assembler based in Malaysia
Auto Co.	Sports Utility Vehicle (SUV)	3	1000's	100% customisation	The SUV is assembled in the UK. JIT module plants are located close-by. The components supply base is global
	Crossover Utility Vehicle (CUV)	3	1000's	100% customisation	The CUV is assembled in the UK. JIT module plants are located close-by. The components supply base is global
Auto driveline Co.	Driveline systems	3	100's	~ 100 per car	Global supplier base, with forty-six manufacturing plants distributed globally.
	Driveshaft	2	50-60	20-40 SKU's per car	
Aerospace Co.'s	Fixed trailing edge wing frame	2	100's	N/A	One site for the fixed trailing edge wing frame, in France. The product is transported to the OEM's facilities in the UK, for integration in to final wing. The final wing is transported to France for the airplane final assembly.
	Wide bodied aircraft	2	100,000's	N/A	Single production site in France

UoA A2 is a diabetes monitoring system designed to be used by patients and healthcare professionals for measuring the glucose concentration in capillary blood. This blood glucose measurement system is based on amperometric electrochemical biosensor technology using dry reagent test strips. Every test requires a blood volume of 0.4 μL. The system is comprised of an electronic measurement meter, a metallic blood test strip and software algorithm which reads the blood glucose level present in the blood sample. It is over forty years since Anton Clemens at the Ames Research Division, Miles Laboratories, in Elkhart, Indiana, USA, developed the first blood glucose meter (BGM). Advances in blood glucose monitoring technology have resulted in improved accuracy, smaller required blood test volume, and the ability to transfer data between the BGM and insulin delivery devices. There are approximately five-hundred and fifty SKUs of this device. This device uses direct current (DC) battery power.

This medical device sector is highly regulated, which leads to high levels of vertical integration. Core product IP resides in the metallized enzyme strip which uses a glucose oxidase reaction to measure the plasma glucose values present in the blood sample, using software algorithms to measure these glucose values. A2 was approved by the FDA in the US and Canada, in February 2012, five years after product concept commencement. This device is assembled by a tier-one systems integrator in China. The electronic meter uses globally sourced components, and is supplied through retail and distributor channels. The test strips are design and manufactured by the OEM. The knowledge expert who participated in case is a senior process automation engineer.

3.6.4.2. Domestic appliance UoA

UoA B1 is an air purifier designed to filter ultra-fine particles greater than 0.3 microns in diameter, removing 99.97 percent of allergens and pollutant particulates from the surrounding air. This device is powered by a brushless energy efficient DC motor surrounded by a 360-degree HEPA glass filter. The OEM who is headquartered in the UK, designed this product in-house. The electronics use industry standard components. The airflow, and acoustic design requirements lead to a tightly coupled design, minimising noise levels. Launched in 2015, this product took three years from concept commencement to product launch. This product was new-to-market, and is an extension of previous products such as a cyclonic vacuum cleaner. The initial launch of B1 is not customer configurable, except for system controls which allow for adjustment of air speed and oscillation. The power cable is attached to this device, with the system motor being region specific. This device comprises of approximately one-hundred machined parts. The knowledge expert who participated in case is Chief Operating Officer, and product design expert.

UoA B2 is a cordless vacuum cleaner with two tier Radial™ cyclones and machine filtration which capture fine dust particulates and allergens. The product is powered by nickel-cobalt-aluminium batteries, and has two-hundred and sixty-four digital motor patents and patents pending. The proprietary DC motor required one-hundred and fifty engineers and one-hundred and eighty-eight thousand hours of development time to complete. This represents over twenty years of research and development, required to perfect this device's cord-free technology. B2 belongs to a platform of products, with the original product launched in 1992. The product selected is the new-to-market cordless variant, which took three years from concept commencement to market launch. This TLA exhibits a medium level of PM. This medium PM level is driven by the power system which powers the cyclone and the cleaner heads. The PA is defined by the motor, which is offered in five SKU's. Over two-hundred plastic parts are required to ensure a rigid product architecture. The digital motors are designed, manufactured and tested in-house. Given tight system tolerances, glue joints, micron level tolerances between the system parts, operating at 100K RPM, the OEM is required to manage the SCC in detail down to the level of specifying the chemistry of certain parts to be supplied by tier-two suppliers. The hybrid SCC is vertically integrated with final assembly provided by the primary supply assembler. The final assembly process is standardised, with the products assembled on the same production line, regardless of the colour of the outer enclosure. The knowledge expert who participated in case B2 is the senior process and quality engineering manager. In summary both B1 and B2 use a hybrid, vertically integrated SCC.

3.6.4.3. Automotive UoA

UoA C1 is a four-wheel drive standard utility vehicle (SUV). It represents the fourth platform of this automobile platform, with the first platform launched in 1970. This company release three to four SUV models on each platform or cross car line. This company headquartered in the UK have adopted a modular product design process, like the MQB (Modularer Querbaukasten) modular traverse matric toolkit developed by the Volkswagen Audi Group (VAG), as shown in Figure 3-15. The concept stage for these products was reduced to two years, with a further three years from concept to launch. This represents a considerable NPD cycle time reduction on previous products, which took up to ten years from the start of the concept stage to launch. PM is highly adopted in the automotive sector where technical complexity requires the combination of functional sub-units to form an aggregated unit (Sanchez, 2000). PM is an integral philosophy within many mass customisation operations where production efficiencies and customer satisfaction require optimisation. Many automotive companies use similar frame and engine platforms across multiple automotive models. For example, the same Ford B3 subcompact automobile platform is used around the world on models including the Eco Sport, Fiesta, Fusion, Ikon, Ka, Demio and the Mazda2 (Answers, 2008). This approach to design can enhance the utilitarian value and functional differentiation of a product in a cost-effective way, making modularity a powerful design tool.

The MQB modular transversal toolkit is inextricably linked with its counterpart in production, the modular production toolkit (MPB). MQB permits alternative drivetrains to be integrated, using gas, hybrid, or electric drives. Previously, vehicle-specific adaptions were necessary in each case. The MQB has created an extremely flexible PA that permits dimensions determined by the design concept such as the wheelbase, track width, wheel size and seat position to be harmonized company-wide and deployed variably. The MQB architecture reduces the number of engine and transmission variations in VAG by approximately ninety percent. Similar architectural modules can be used across different cross-car lines. The person who participated in this research is the Purchasing Director.

Figure 3-15. Modular transversal toolkit (VAG Group)

UoA C2 is a new-to-market four-wheel drive combination utility vehicle (CUV) with a choice of diesel or gasoline engines. This product offers a 2.0-liter turbocharged diesel engine. The advanced powertrain combines refinement with high performance. The product is equipped with stop/start technology and smart regenerative charging, harvesting kinetic energy from braking to charge the battery for maximum economy, especially during urban driving. Electronic power assisted steering (EPAS) software is tuned for feedback and control. The products chassis and suspension system offer a unique balance between agility and ride comfort. The product has an aluminum architecture, reducing weight whilst enhancing vehicle handling and braking performance. This product was released to market in mid-2016. The PA is highly modular with a common bill of design and common BOP. With this modular design, product delivery scheduling is based on standard product lead-time analysis. The person who participated in this research is the Director of product, processes, programs, and operations.

In the last two decades, the automotive industry has shown a steady increase in the outsourcing of vehicle development and a shift of product development tasks and product-process knowledge from automobile makers to suppliers. This trend has increased the interest in PM as a tool to ease the integration of external sources of innovation, however there is contradictory evidence concerning the benefits of modularity in inter-company coordination in the automotive industry (Cabigiosu *et al.*, 2013). This consideration influenced the selection of the auto-driveline company, for C1 and C2 as a case company, for this research. The empirical evidence derived from the analysis of the research by Cabigiosu *et al.* (2013) shows that, different from what modularity theory claims: the interface definition is neither technologically determined nor a mere result of product architectural choices. The OEMs and the supplier's capabilities, degree of vertical integration, knowledge and strategic focus drive the partitioning of the design and engineering tasks, the interfaces definition process, and the choice of the inter-company coordination mechanisms. Furthermore, while component modularity and design outsourcing are considered as complements in modularity literature, the findings of this research indicate that these may work as substitutes and are rather difficult to combine.

3.6.4.4. Automotive driveline UoA

D1 is a complete drivetrain or driveline for C1 and C2. As in many other sectors, to effectively integrate newly designed modules and components inside the automotive system, auto-makers and their suppliers have developed 'hand-in-glove relationships' (Clark and Fujimoto, 1991) and started sharing a relevant amount of information. The driveline systems company is the world's leading supplier of automotive driveline systems and solutions, and is a tier-one supplier to the C1 and C2 automotive company. This driveline company, is the worldwide supplier of industry leading constant velocity (CV) jointed prop-shafts, all-wheel drive (AWD) couplings and driveline disconnects and is uniquely positioned to develop and manufacture full AWD systems. As a global business serving leading vehicle manufacturers, the company design, build and supply an extensive range of automotive driveline products and systems, from low-cost to the most sophisticated premium vehicle, demanding complex driving dynamics. Headquartered in the UK, this company operate forty-six manufacturing plants in twenty-two countries. D1 is supplied from two plants in the UK, and comprises of a drive-line, comprising of power transfer unit, drive shaft, all-wheel drive couplings, final drive unit and disconnects. The driveline or drivetrain consists of the powertrain excluding the engine and transmission. It is the portion of the vehicle, after transmission that changes depending on whether the vehicle is front, rear, or four-wheel drive. D1 is an all-wheel drive-line, and uses a significant number of standard components, displaying modular PA, and configured within an integral SCC. This product took eleven years from product ideation or commencement of product concept to market launch. The person who participated in this research was the group business improvement director. UoA D2 is the drive shaft section of D1. D2 has an integral PA, built in an integral SCC. The person who participated in this research is the group Supply chain excellence director.

3.6.4.5. Aerospace UoA

UoA E1 is a fixed trailing edge for an airplane wing. To reduce weight and improve costs this is the first time that the fixed trailing edge of an airplane wing is constructed from composite fiber material. This UoA comprises of inner, mid, and outer rear spars, rib posts, root joint fittings, spar vertical stiffeners and spar joints, as shown in Figure 3-16.

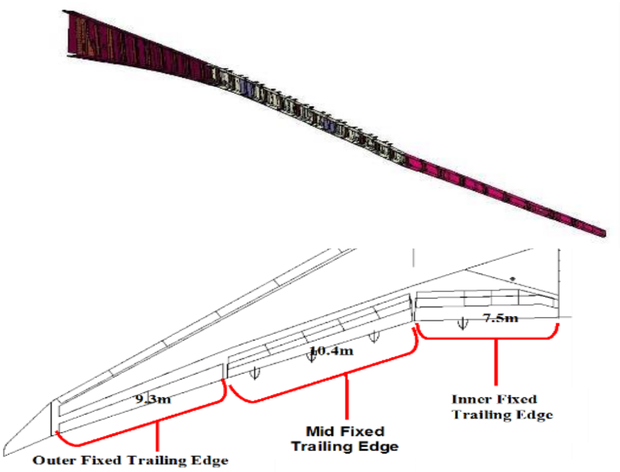


Figure 3-16. Fixed trailing wing edge for wide-bodied airplane

E1 is manufactured in the UK, and delivered to the OEM wing assembly plant in the UK in three sections, the largest section being thirteen meters long. The delivery process was a major undertaking, given this entire structure is twenty-seven meters in length and required innovative manufacturing, assembly and transportation techniques at the design stage. This aerospace company is a separate aero division of the driveline systems company (D2). The research participant is the group business improvement director. The current generation sub-assemblies (aero-structures) use a new composite material, which has been over twenty years in development. E1 was ten years in product concept development and took twenty years from concept to market launch, as shown in Table 3-5, Page 201.

UoA E2 is a medium to long range wide-body twin-engine airplane, launched in 1992. Amongst the many new-to-market features this airplane uses a digital fly-by-wire (FBW) control system, and side-stick control. Advanced automated processes for assembly, spar drilling and fettling, riveting and fastening along with innovative research in close tolerance jointing and determinate assembly allows this product to achieve higher levels of product quality and performance. This company spends approximately one-hundred and fifty million euro's each year on product enhancements and improvements to E2. The newest version of the E2 family has a new engine option building on E2's original economics, versatility and reliability, reducing fuel consumption by a further fourteen percent per seat, and expanding range capability increase up to four-hundred nautical miles. The person interviewed is a senior aerospace maintenance consultant engineer, experienced in servicing the E2 airplane. This expert works for a leading aviation service's company, based in Ireland. The company works with international airlines, private operators, and aviation leasing companies globally, servicing wide and narrow body airplanes.

E2 has been using modularity as part of their operations since they were founded. SCCM modularity is because of the nature of the company structure and supply partnerships involved. This OEM represents a consortium of French, British, Spanish and Germany subsidiaries. The relatively low level of knowledge sharing across SCC tiers is a concern in the aerospace industry and addressed by this OEM. There have been examples of product launch delays, and cost over-runs as an example of this medium level of knowledge sharing. This company experienced a six-billion dollar cost over-run and a three-year delay with a previous product launch due to inconsistent knowledge sharing.

3.7. RESULTS

SCT is an aggregate measure of supply network proximity.

3.7.1. Supply chain tiering

All companies in this research use network of suppliers. The span of the supplier network is an important variable of SCT, and includes depth, breadth and geographic spread dimensions, and economic and legal business involvement (Hieber, 2002). Is should be noted that Hieber (2002) focused primarily on top-level assemblies. SCC depth represents the number of value adding tiers and is a measure of horizontal tiering. SCC breadth represents the number of suppliers at each value adding tier, and is a measure of vertical tiering, as shown in Table 3-13.

This research establishes a low-level of economic and legal business involvement for lower level assemblies; a medium-level of economic and legal business involvement for top-level assemblies where the product is low to medium-level complexity, and a high-level for complex top-level assemblies, shown below in Table 3-13, see also Appendix 3-9, Page 457.

This research highlights the significant role of the systems integrator in managing dispersed supply networks. Tier-one or tier-two system integrators manage the span of the network, for A2, B1 and B2, whilst the OEM performs this role, for the remaining UoA. With case company's A and B, the level of economic and legal involvement with the supplier network is at a medium level. Alliances exist with system integrators and key suppliers based on mutually beneficial performance agreements designed to incentivise suppliers, on delivery, cost and quality performance. Economic and legal business involvement is low-level where supply network suppliers have lower levels of financial autonomy and a low-level of SCCM exists, as with UoA D1, D2 and E1.

There is a growing trend among Western manufacturers to reduce the number of tier-one suppliers and establish longer-term contracts with a select group of key supply partners, C1, C2 and E2 are evidence of this trend. Where products have become increasingly complex and often too difficult for the assembler to handle (Arnheiter and Harren., 2005), this has led to larger chunks of the product including the complete product being modularized, and sourced from strategic suppliers.

Table 3-13. Supply chain tiering (SCT) modularity
Source: Hieber (2002)

Levels of supply chain tiering and modularity											
Company		Med device co.		Domestic appliance co.		Auto co.		Auto driveline co.		Aerospace co.'s	
Respondent		A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
UoA											
Depth of the network	Span of network	Medium	Medium	Medium	Medium	High	High	Low	Low	Low	High
Value add tiers		4	4	3	3	6	6	2	2	2	6+
Breadth of the network		Medium	Low	Medium	Medium	High	High	Low	Low	Low	High
Suppliers per module		3	1	3	4	6+	6+	2	2	2	6+
Geographical spread of the network		High	High	High	High	High	High	Low	Low	Low	High
		Global	Global	Regional	Regional	Global	Global	Local	Local	Local	Global
Economic and legal business involvement		Medium	Medium	Medium	Medium	High (low involvement)	High (low involvement)	Low (high involvement)	Low (high involvement)	Low (high involvement)	High (low involvement)

3.7.2. Within-case PM and SCCM analysis

Mandatory PM and SCCM attributes deduced from the literature are shown in Table 3-14. In assessing levels of PM and SCCM, mandatory attributes are weighted more heavily than optional attributes, which may or may not be present. FS is at a medium-level for six UoA and at a high-level for four UoA, where high FS represents low PM. IC is medium level for five UoA and tight for five UoA, where tight IC represents low PM. In general, there is tight IC where there are high levels of FS, except for E2, which exhibits low PM because of tight module interconnections, associated with the high reliability requirements of this airplane.

With E2, FS is medium-level due to the high levels of circuitry and systems integration in modern airplanes. FS varies from medium-level for top level assemblies except for B1, and lower level assemblies D1, D2, and E1 which are high-level (low PM). IC is at a medium level for A1, A2, B2, C1, and C2 and a low level for the other UoA.

Table 3-14. Levels of PM and SCCM mandatory attributes

	Company	Med device co.		Domestic appliance co.		Auto co.		Auto driveline co.		Aerospace co.'s	
	Respondent	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
	UoA										
PM	Function sharing	Medium	Medium	High (low PM)	Medium	Medium	Medium	High (low PM)	High (low PM)	High (low PM)	Medium
	Interface coupling	Medium	Medium	Tight (low PM)	Medium	Medium	Medium	Tight (low PM)	Tight (low PM)	Tight (low PM)	Tight (low PM)
SCCM	Supply chain tiering	Medium	Medium	Medium	Medium	High	High	Low	Low	Low	High
	Process postponement	Low	Medium	Low	Low	High	High	Low	Low	Low	High

The levels of the mandatory PM and SCCM attributes are shown above in Table 3-14. whilst the corresponding levels of PM and SCCM are shown in Table 3-15. High-levels of SCT illustrate high-levels of SCCM, prevalent with top-level assemblies C1, C2 and E2. a

Medium-level of SCT is present for medical devices and domestic appliances, whilst sub-assemblies D1, D2 and E1 illustrate a lower-level of SCT. PRP is at a high level for final-level assemblies C1, C2 and E2, providing the required levels of product customisation driven by the requirement for product variety at the TLA. PRP is at a medium-level for A2 where it is limited to regulatory product labelling, and PRP is at a low-level for A1, B1, B2, D1, D2, and E1.

There are low levels of PM associated with low-level assemblers, except for B1 which illustrates a low-level of PM, and E2 which illustrates tight IC. There are medium levels of PM associated with A1, A2, B2, C1, and C2 that are decomposable. A1 is a surgical cartridge which releases staples, A2 contains a replacement battery and single use test strips, and B2, C1 and C2 have many detachable and serviceable components. A2 is a closed loop system, with a high-level of FS. With A2, IC is at a medium level due to the removable test strip. With E2, FS is at a medium-level and IC is at a low-level, since certain systems in a top-level airplane assembly are not inter-connected.

Table 3-15. Levels of PM and SCCM

	Company	Med device co.		Domestic appliance co.		Auto co.		Auto driveline co.		Aerospace co.'s	
	Respondent	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
	UoA										
PM	Function sharing	Medium	Medium	Low (low PM)	Medium	Medium	Medium	Low (low PM)	Low (low PM)	Low (low PM)	Medium
	Interface coupling	Medium	Medium	Tight (low PM)	Medium	Medium	Medium	Tight (low PM)	Tight (low PM)	Tight (low PM)	Tight (low PM)
SCCM	Supply chain tiering	Medium	Medium	Medium	Medium	High	High	Low	Low	Low	High
	Process postponement	Low	Medium	Low	Low	High	High	Low	Low	Low	High

In this Section all PM and SCCM attributes are assessed, using the levels shown in Tables 3-4 and 3-7. An aggregate level of PM and SCCM is assigned to each UoA. A within-case comparison is conducted, to understand the modularity measures, and generate knowledge on the modularity specific to each case.

3.7.2.1. Medical device company

A1 is comprised of an independent cutting blade and staples, providing independent functions and sharing a common enclosure. A1 exhibits a medium-level of FS and a medium-level of IC. SCT is at a medium-level with the OEM responsible for all levels of the SCC, and there is no PRP present, shown below in Table 3-16. A strong partnership between the SC partners, with a high degree of trust and collaboration, has been developed over twenty years, since product launch. A1 is assembled using a multi-tier, fragmented SC network with many components single-sourced. Injection molded parts are sourced globally; precision metal components are sourced from Switzerland, and final assembly takes place at the OEM's Mexico facility. Tier-one suppliers deliver sub-assemblies and are classified as module integrators (Sako and Murray, 1999). The product is built to forecast, with the COEP post manufacturing.

Whilst A1 does not have a communications bus, it has a rigid mechanical structure. These products have a high-level of reliability, with a focus on patient safety. There is an opportunity with further product enhancement, to integrate product performance feedback. The product has a long shelf-life and is not reconfigurable. There are no opportunities for the surgeon to configure the final module. This results in approximately five-hundred available SKUs and high inventory levels with. The complex product structure and varying material thicknesses place the assembly processes at the limits of control. The final product assembly process is semi-automated, with automated wire insertion. The process has a low level of PF and low PR opportunities.

Aggregated PM and SCCM are at medium levels. Optional PM and SCCM attributes all exhibit low levels of modularity. FS is key to the overall levels of PM and SCCM. A1 is designed as a single use device, the enclosure is disposed post the operating procedure. Due to cost pressures the components and sub-assemblies are outsourced; however, final assembly is in-house, leading to a medium-level of SCCM. Final assembly is semi-automated and located in a low labour cost region, due to the requirement for repeatable quality and low assembly costs. The module interfaces align with the SCC tiers and supplier interfaces. The SCC is optimised to deliver the appropriate modules to the final assembly operation. The optional PM and SCCM play a limited role in the mirroring of PM and SCCM.

Table 3-16. Comparison of PM and SCCM for A1 and A2

	Medical device co.											
	Surgical cartridge A1 						**Blood Glucose meter** A2 					
	Product modularity levels			Supply chain configuration modularity levels			Product modularity levels			Supply chain configuration modularity levels		
Mandatory variables	Function sharing (FS)	The cutting blade and staples are supported by the metal and plastic cartridge. There is a medium level of function sharing between the cutting and stapling components. The metal and plastic frame provides a level of bus modularity. FS is at a medium level.	Medium	Supply chain tiering (SCT)	There are three SC tiers, in this globally dispersed supply network; some tiers have more than two suppliers. The OEM is the system integrator, and final system assembler, managing the network, therefore SCT is at a medium level.	Medium	Function sharing (FS)	This is a closed loop system. A blood sample is placed on the test strip; this is absorbed by the biologics layer. A measurement of the blood glucose level is analysed using the pre-programmed algorithms in the meter. FS is at a medium level.	Medium	Supply chain tiering (SCT)	Critical components such as the melanex material for the test strip are dual sourced.There are three levels in the supply network. The supply network is globally dispersed; the tier one EMS company operates as the system integrator.	Medium
	Interface coupling (IC)	Components have a medium level of coupling. The staples are discharged from the cartridge during the operating procedure.	Medium	Process postponement (PRP)	The COEP is after the manufacturing process, product is built to stock, therefore PP is at a low level.	Low	Interface coupling (IC)	Interface coupling is medium level between the mechanical and electrical components and modules. There is loose coupling of the metallised test strips.	Medium	Process postponement (PRP)	Final product packout is postponed until after the COEP. PRP is at a medium level.	Medium
Optional variables	Data access (DA)	There is no data access to the surgical cartridge, therfore the level of DA is low. Remote cameras are used to assist the operating procedure; these are not connected to the surgical cartridge.	Low	Process flexibility (PF)	There is limited process flexibility. Products are built to finished stock, therefore PF is at a low level.	Low	Data access (DA)	Whilst data are readable using a digital display, and can be converted to local language, there was no remote data access available with A2. DA level is low.	Low	Process flexibility (PF)	There is a low level of process flexibility.The circuit boards are built to forecast and the meters completed to a purchase order schedule.	Low
	Limited life (LL)	The device is a sterile, metal product, which will oxidise and become brittle, after approximately three years.	Medium	Process re-sequencing (PS)	There is no opportunity to re-sequence the assembly process flow. Products are distributed through standard medical distribution channels.	Low	Limited life (LL)	There is a medium level of shelf-life with the test strips. For measurement accuracy these should be stored in their moisture proof dessicator.	Medium	Process re-sequencing (PS)	There is a low level of opportunity to re-sequence the assembly process flow. Products are distributed through standard medical distribution channels.	Low
	Product variety in use (PV)	There is no opportunity to configure these at the point of the operating procedure, therefore PV is at a low level. There are approximately 500 final SKUs.	Low	Place postponement (PP)	The COEP is in a central location. Product orders are directly fulfilled, through distribution channels.	Low	Product variety in use (PV)	The meter can be configured with country specific language. The overall level of PV is low however.	Low	Place postponement (PP)	There is the ability to provide place postponement; this is confined to customer labelling. PP levels are high.	Medium
	Level of PM	The medium level of PM is due to the inability to re-configure, or de-couple the components in the device.		Level of SCCM	Medium SCCM due process inflexibility in providing modular product configuration and distribution.		Level of PM	The medium level of PM is due to the inability to re-configure, or de-couple the components in the device.		Level of SCCM	The medium level of SCCM is due to a medium level of SKU flexibility, including flexible module assembly, packout and distribution.	

A2 represents a closed-loop design; the electrical circuit is closed by inserting the test strip in the port connector. All functions of the meter are controlled by this circuit, using algorithms to measure the level of glucose on the enzyme enriched test strip. The level of

IC is medium, with the test strips being replaceable, and FS is at a medium-level, shown above in Table 3-16. There are a small number of variants of the test strip, port connector and test software algorithms. The meter is comprised of standard off-the-shelf components with a customised enclosure. A2 does not have direct data access (DA). Since the meter is battery operated, the device has a medium-level of limited life (LL). The meter is pre-calibrated prior to leaving the factory. There are no options for end user configuration driven by the requirement for regulatory validation of any product changes. Product changes require Federal Drugs Administration (FDA) submission, to the FDA. A2 exhibits a medium-level of PM influenced by medium levels of FS and medium levels of IC (medium PM).

There are a limited number of suppliers of key components, and a medium span of the SCT network, SCT is at a medium-level for A2. A2 has three levels of SCC, with the final assembly managed by a tier-one supplier. A2 is designed as a re-usable metering device, with the test strip being disposable. Due to cost pressures components, sub-assemblies and final assembly are outsourced to China, with the test strips manufactured in-house, by the OEM, leading to a medium-level of SCCM. The module interfaces align with the SC tiers and supplier interfaces. The SCC is optimised to deliver the appropriate modules to the final assembly operation, and pack labelling is postponed to after the COEP. This supplier has been producing these products for twenty years, and has an established partnership with the OEM. Over ninety percent of the components are sourced in Asia; this strengthens the requirement for a tier-one integrator located in Asia. The balance of the components is sourced in Europe, with final assembly in China. The tier-one supplier is also providing joint product design to the OEM. The OEM manufactures the test strip. There is limited PR, within the standardised strip manufacturing process. This standard process required five to six years to complete validation. A medium-level of PRP exists for A2 to allow for end customer labelling, which can vary by language, payer and distribution channel. SCCM operates at a medium-level, influenced by the medium levels of SCT and customer product pack-out taking place post the COEP.

Module FS is a key determinant of the overall levels of PM mirroring with SCCM. The small form factor and tight tolerances of the connections within A1 and A2 require precision assembly and testing of these devices. A1 and A2 illustrate a medium-level of PM and SCCM at the aggregate level.

3.7.2.2. Domestic appliance company

B1 is designed as an integrated air purification system, operating at a low acoustics level. The low acoustics specification poses a challenge, given the high number of plastic parts and system interface tolerances. This challenge drives a requirement for tight mechanical bus PA. With B1, FS is at a high-level (low PM) and IC is tight (low PM).

There is an internal control system which stops the motor if the temperature or RPM exceed predefined thresholds. There is limited DA with this UoA confined to measuring machine run-time. Follow-on variants of this product have planned DA, offering remote operator control. The original market requirement focuses on removing formaldehyde pollutants from the air; follow-on designs will offer alternative filters for removal of additional pollutants, including pollen and smog, using air quality measurement sensors. The digital motor is designed in-house and built by an external supplier to the OEM's specification. DA is at a low-level, LL is at a medium-level and PV exhibits a low level. B1 exhibits a low-level of PM, driven by the tight IC, shown in Table 3-17.

With B1, SCT is at a medium-level, due to the span of the supply network, whilst PRP levels are low, see Table 3-22. COEP occurs after the manufacturing process, with final product assembly scheduled around country level demand forecasts. B1 was initially launched in China, as it is rolled out across other regions, the company are discussing the provision of regional PP, allowing COEP prior to final product configuration. Mature OEM to tier-one and tier-two relationships has allowed the development of these suppliers. Over ninety percent of the components are sourced in Asia; this strengthens the requirement for tier-one integrators located in Asia. These primary suppliers are responsible for tooling, module assembly and final assembly. The COEP occurs after the manufacturing process, with the products assembled to stock. Finished products are shipped direct to markets globally. The product is built to a country level forecast. The manufacturing and distribution processes are standardised with limited flexibility, medium-level of LL and low levels of PP. This is an area of future focus, which will involve the evaluation of a cost efficient universal power supply. There is some multi-language packaging, however there is an opportunity to increase the level of PP. B1 exhibits a medium-level of SCCM, due to the important role of the primary suppliers in managing a regional and global supply base.

Table 3-17. Comparison of PM and SCCM for B1 and B2

	Domestic appliance co.											
	Air purifier B1 						Cordless vacuum cleaner B2 					
	Product modularity levels			Supply chain configuration modularity levels			Product modularity levels			Supply chain configuration modularity levels		
Mandatory variables	Function sharing (FS)	The UoA has a high level of function sharing (low PM). The market requirement for low noise and vibration is a challenge, given the high number of plastic components and component interfaces.	Low	Supply chain tiering (SCT)	Tier one primary systems assembler plays a key role in integrating the supply chain, which is concentrated in Malaysia, but with a global supply network. There are three primary tiers within the supplier network. SCT modularity level is medium.	Medium	Function sharing (FS)	The digital motor shares functionality with the cyclone and the power cleaner heads. There are many functional elements to a small number of modules. FS is at a medium level.	Medium	Supply chain tiering (SCT)	Tier one primary systems assembler plays a key role in integrating the supply chain, which is concentrated in Malaysia, but with a global supply network. There are three primary tiers within the supplier network. SCT modularity level is medium.	Medium
	Interface coupling (IC)	Interface coupling is tight (low PM). Industry standard parts are used. The high number of components and product performance specfication requires tight interface coupling.	Low	Process postponement (PRP)	The COEP occurs after manufacturing. Product is built to a country level forecast. The PP modularity level is low.	Low	Interface coupling (IC)	Interface coupling is medium level (medium PM). There are tight system tolerances, with a large number of glue joints. There are also detachable accessories.	Medium	Process postponement (PRP)	The COEP occurs after manufacturing. Product is build to a country level forecast. The PP modularity level is low.	Low
Optional variables	Data access (DA)	This UoA had no remote data accessibility, and exhibits a low level of DA modularity. (Follow-on variants automatically monitor and control this appliance using Wi-Fi link).	Low	Process flexibility (PF)	There is limited process flexibility (low level of PM). Products are built to stock.	Low	Data access (DA)	The UoA had no remote data accessibility (low level of DA modularity).	Low	Process flexibility (PF)	There is limited process flexibility (low level of PM). Products are built to stock.	Low
	Limited life (LL)	The high-efficiency particulate arrestance (HEPA) filter has a medium shelf life (Medium PM), and needs to be replaced periodically.	Medium	Process re-sequencing (PS)	There is no opportunity to re-sequence the assembly process flow (low level of PS modularity). Products are distributed through standard channels. The PS modularity level is low.	Low	Limited life (LL)	The UoA has a high MTBF (low level of LL modularity). The battery is rechargeable.	Low	Process re-sequencing (PS)	There is no opportunity to re-sequence the assembly process flow (low level of PS modularity). Products are distributed through standard channels. The PS modularity level is low.	Low
	Product variety in use (PV)	Filters are interchangeable. Ten years is the recommended life, depending on operating conditions. The product has a low level of PV modularity.	Low	Place postponement (PP)	There is no opportunity to reconfigure the product close to the point of use. COEP occurs in a central location (low level of PP modularity).	Low	Product variety in use (PV)	There are limited options to adjust the cleaner heads and add new accessories.	Low	Place postponement (PP)	There is minimum opportunity to reconfigure the product at the point of use (low level of PP modularity).	Low
	Level of PM	Low level of PM		Level of SCCM	Medium level of SCCM due to the role of the primary integrator, and low level of process postponement		Level of PM	Medium PM due to minimal reconfigurability of the product.		Level of SCCM	Medium level of SCCM due to the role of the primary supplier / integrator, and the low level of process postponement.	

B2 is designed as an integrated cordless vacuum cleaner, and uses a digital motor. Both FS and IC are at a medium-level. Many fittings are detachable and adjustable by the end user. The power system is a key driver to how components are selected for this design, with a medium-level of FS along the power bus. The cleaner brushes are electrically powered. The module interfaces have a significant focus on product reliability. The battery is rechargeable, whilst the product has a high reliability level, depending on the user operating conditions. The OEM is moving to re-usable parts and modular design. The medium-level of FS leads to the product exhibiting a medium-level of PM. Module FS is key to the overall levels of PM and SCCM.

SCT is at medium-level for B2, due to the span of network, whilst PRP is low. Due to cost pressures components, sub-assemblies and final assembly are outsourced to Malaysia, with the digital motor designed and manufactured by the OEM, leading to a medium-level of SCCM. The medium-level of SCT is driven by the focus on the Asia-based manufacturing network. COEP occurs post the manufacturing process, with manufacturing scheduled around country level demand forecasts. The primary suppliers manage tooling, molding and final assembly. Four variants of the digital motor are produced by the OEM in-house. The COEP occurs prior to the manufacturing process, with B2 manufactured to country-level forecasts. There is limited opportunity for end user customisation of the motor and cleaner heads. There are country options with this UoA, as it does not plug in to an electrical socket, except for recharging purposes. Cleaner heads do not have to be added until the end of the process. B2 exhibits a medium-level of SCCM, due to the strong role of the primary sub-assembly suppliers in managing a regional supply base.

B1 demonstrates a low-level of PM and medium-level of SCCM at the aggregate level, whilst B2 demonstrates medium levels of PM and SCCM. Optional modularity attributes play a minor role in defining the levels of PM and SCCM for these UoA; except for LL considerations on the filter for the air purifier, there is evidence of a low-level of modularity for all other optional attributes. B1 is designed as an integral air purification system, whilst B2 is designed as an integrated cordless vacuum cleaner. The module interfaces are slightly misaligned with the SC tiers and supplier interfaces. There is a medium-level of process PR available, yet this is not utilised to provide PRP. PP is also not utilised; for example, the filter is pre-loaded in the factory. A universal power supply would allow for increased levels of PP. With B1, aggregated PM is at a low-level whilst aggregated SCCM are at medium-level. FS is high (low PM) for B1, and IC is tight (low PM), illustrating a match between these attributes. FS is key to the overall levels of PM and SCCM.

3.7.2.3. Automotive company

The top three levels of the product BOM for cars include the chassis, trim, internal fittings and instrument panels. Fixson (2003) reviews existing PM literature in the automotive industry and offers a list of vehicle sub-systems that literature has classified as modular. These systems are located at the first level of the vehicle PA and their development is based on the involvement of several suppliers facing challenging coordination problems. Fixson (2003) ranks the air control system, the automotive console, the drivetrain, the instrument panel, the brake system, and climate control as the most modular sub-systems. MacDuffie (2013) maintains that the definition of modules in the automotive industry is different from those in other industries since the modules in an automobile are seldom developed to perform single product functions. 'Many modules with automobiles are 'visible' and have interdependencies with other system modules' (Staudenmayer *et al.*, 2005). For the automotive case analysis, it was decided to include a tier-one supplier to offer more depth of analysis in to the PA and SCC. Doran *et al.* (2007) and Ro *et al.* (2007) agree that modularisation in the automotive industry guides the 're-definition' of the role of tier-one suppliers. The auto-driveline company, was on this basis selected as an ideal case company, for our analysis.

C1 is the fourth generation of this sport utility vehicle (SUV), with the original SUV launched in 1970. C1, a full-sized SUV is a platform product, shown below in Table 3-18. Two types of module exist in the automotive industry: assembly or architectural modules, for example the cockpit, doors, front-end and rear-end modules which are usually built some distance from the final assembly line, and design (cross-car line) modules, for example wheel trims, seating, infotainment systems or sun roofs which are delivered post the COEP, and optimised at the final assembly level by independent suppliers. These cross-car line modules are delivered late in the assembly process. For C1 and C2, FS is at a medium-level; this is partly explained by the fact that these UoA represent the top three levels of the top-level BOM assembly. The top three levels of these product BOMs include the chassis and trim, internal fittings and instrument panels; the levels of FS between these modules is at a medium-level. At the top levels of the BOM, the focus is on delivering product variety. C1 contains a data bus, including wireless Bluetooth technology, with DA to the engine software (high PM). LL modules such as brake pads, wipers and engine components are easily accessible, and replaceable (medium PM). The OEM has an off-line facility for end-user customisation, and there are specialist companies who provide customised fittings and finishings for the SUV (high PM).

In automotive, production concerns drive the formation of modules rather than product design features. Automotive modules can be defined as: 'A group of components, physically close to each other that are tested outside the facilities and can be assembled very simply onto the car' (Sako and Warburton, 1999). There is one facility in the UK producing this SUV.

Approximately sixty percent of automobile PA development costs occurring between the gas accelerator and front wheels, including the engine, and are designed at the concept stage. Architectural modules include the transmission, drivetrain, powertrain, chassis parts, and braking modules. The automotive transmission forms a primary architectural bus. Bus modularity offers the ability to add one or more modules to the existing automotive powertrain. Competitive pressures have led to designs involving higher internal pressures, greater instantaneous forces and increased complexity of design and mechanical operation. Automotive companies aim to establish the lowest UMC for each SCC module prior to product design completion. C1 exhibits a medium-level of FS and IC, and an overall medium-level of PM.

SCT and PRP are high, reflecting a global supply network, and the requirement for product customisation post the COEP. As with many automotive companies, many modules are single-sourced. Tier-three and tier-four parts are sometimes dual sourced. System integrators manage certain module combinations. For example, the suspension and steering module must be designed, assembled, and tested together. This combination modularity requires a matrixed organisation or module team. There are elements of flexibility built into the assembly process. There are limited opportunities for re-sequencing the production line, due to the setup cost; however, offline manual processes can be re-sequenced. Customers can revise their product specification configuration up to twenty days prior to the vehicle production start date. PP is offered by specialist companies who operate at the high end of the market. There is close SCT with tier-one and tier-two suppliers. C1 exhibits a high-level of SCCM.

Table 3-18. Comparison of PM and SCCM for C1 and C2

	Automotive co.											
	Standard utility vehicle C1 						Cross-over utility vehicle C2 					
	Product modularity levels			Supply chain configuration modularity levels			Product modularity levels			Supply chain configuration modularity levels		
Mandatory variables	Function sharing (FS)	Architectural modules have a medium level of function sharing.	Medium	Supply chain tiering (SCT)	Cross car line modules are delivered post the COEP. There is strong cultural, information technology and geographic proximity. Cross car modules are delivered on a Kanban replenishment basis. SCT modularity levels are high.	High	Function sharing (FS)	Modules in this all-wheel drive have a medium level of FS modularity. An example is smart regenerative charging which harvests kinetic energy from braking to charge the battery.	Medium	Supply chain tiering (SCT)	Cross car line modules are delivered post the COEP (high level of SCT modularity). There is strong cultural, information technology and geographic proximity. Cross car modules are delivered on a Kanban replenishment basis.	High
Mandatory variables	Interface coupling (IC)	Loose coupling is an architectural principle and design goal in automotive architectures. Bus modularity offers the ability to add modules to the drivetrain. IC modularity is at a medium level.	Medium	Process postponement (PRP)	Architectural modules are delivered prior to cross car line modules. There is a high level of PRP modularity.	High	Interface coupling (IC)	Electronic power assisted steering, intelligent driveline dynamics, computer-controlled, adaptive engine cooling and all surface progress control, all support medium coupling (medium level of IC modularity).	Medium	Process postponement (PRP)	The model is built on the OEM's modular platform.	High
Optional variables	Data access (DA)	This product has Bluetooth connectivity, and allows remote updates of the system software. Data is secure and accessible remotely. DA modularity as a result is high.	High	Process flexibility (PF)	Company use simlation techniques and virtual reality to cut time and cost of product development. This technology has been applied to reduce physical prototyping, giving the design team greater scope to experiment with design and technology variations and allow manufacturing processes to be adjusted, therefore PF modularity is high.	High	Data access (DA)	This model is 'connected' in the sense that it can exchange information wirelessly with the vehicle OEM. Product has satellite navigation and smartphone connectivity with Wi-Fi Hotspot and some models allow the owner to control the vehicle remotely, pre-heat the interior or unlock the car using a smartphone application. DA exhibits a high level of DA modularity.	High	Process flexibility (PF)	Company uses virtual reality to plan process flexibility. This has been an integral technology behind 'design for X'. The product exhibits a high level of PF modularity.	High
Optional variables	Limited life (LL)	Certain parts are susceptible to routine wear and tear. These are accessible and easily replaceable. There is a medium level of LL modularity.	Medium	Process re-sequencing (PS)	The assembly process is a modular design. The PS modularity is high.	High	Limited life (LL)	Certain parts are susceptible to routine wear and tear. These are accessible and easily replaceable.	Medium	Process re-sequencing (PS)	The all-new aluminium robot body shop, can re-sequence certain stages of assembly. PS modularity levels are high.	High
Optional variables	Product variety in use (PV)	The customer has the option to choose the automobile model, and experiment with interior and exterior design, features, colours and technology, on-line, in the dealer's showroom. PV modularity is high.	High	Place postponement (PP)	Final product specification is configurable in the distributor channel and with specialist third party configuration companies. PP modularity level is high.	High	Product variety in use (PV)	The customer has the option to select the automobile model, and experiment with interior and exterior design features, colours and technology, on-line or in the dealer showroom. The PV modularity level is high.	High	Place postponement (PP)	Final product specification is configurable in the distributor channel and with specialist third party configuration companies, exhibiting a high level of PP modularity.	High
	Level of PM	Medium level of PM with common bill of design. Architectural modules share functionality.		Level of SCCM	High level of SCCM with common bill of process. Cross car line modules are delivered post the COEP.		Level of PM	Medium level of PM with common bill of design. Architectural modules share functionality.		Level of SCCM	High level of SCCM with common bill of process. Cross car line modules are delivered post the COEP.	

C2 is a new platform product, with at least four product variants. The cross-over utility powertrain includes a standard 340, or optional 380 horse-power, supercharged V-6 engine, each with eight-speed automatic and all-wheel drive. The design has an aluminium construction, creates a rigid light-weight structure. Sixty percent of parts are common across the four product variants. 'The platform principle is based on standardised components, which offer a combination of high model variety with comparably low levels of complexity' (Sako and Warburton, 1999). The product was launched in 2016, and provides a high-level of electronic integration designed in at the concept stage. There is a medium-level of module coupling, medium-level of FS and a high level of DA modularity. The challenge is with infrastructure and DA security. Certain data is encrypted to prevent their misuse. There is a high level of product variety provided by the OEM. C2 exhibits a medium-level of PM.

C2 SC tiers are managed across architectural modules. SCT and PRP levels are high, reflecting a regional supply base. The final product is assembled by the OEM in the UK. There is flexibility in the offer of variants of the product. In the US, the product is sold from dealer forecourts, and built to stock, whilst in Europe fifty percent of final products are configured to customer order, after receipt of the COEP. Final configuration is performed using PP after the COEP, with total production lead-time in the region of twenty days. C2 followed the MQB modular design and MPB modular production system introduced by the Volkswagen Audi group (VAG), in 2012. The MQB uses a core matrix of components across a wide variety of platforms, for example using a common engine-mounting core for all drivetrains. C2 exhibits a high-level of SCCM, with the SCC comprising of a modular consortium.

C1 and C2 illustrate a medium-level of PM at the aggregated level; the module IC is medium-level to allow for product customisation post COEP. C1 and C2 illustrate a high-level of SCCM at the aggregate level. Optional modularity attributes play a significant role in defining the levels of PM and SCCM for these UoA. SCT and PRP are driven by the overriding focus on product variety (PV) in use. Process agility, which incorporates PF, PR and PP is high, reflecting the strong focus on product variety, which is a key differentiator for high-end utility vehicles.

3.7.2.4. Auto-driveline company

Where the levels of FS for cars are at a medium-level at the TLA, the levels of FS are low at the mid-levels of the product BOM, where product variety is less of a consideration. With D1 and D2, FS and IC exhibit low modularity levels, see Table 3-19. SCT and PRP are low, reflecting a local supply network, and no requirement for product customisation post the COEP.

The D1 driveline solution is comprised of a family of devices that control the performance of the powertrain, including torque control. The internal sub-assemblies exhibit high levels of FS. The prop-shaft and drive-shaft configurations are modular; however, they tend to be custom built for each application. There is a move towards standard IC, driven by the requirement for increased efficiency, fuel consumption, and reduced vehicle friction. The driveline has a high-level of DA modularity, with numerous sensors interfaced with the main vehicle stability software. The servo technology and software are accessible from the main automobile control system. There is significant investment taking place in this area to assess driver performance. Customers are interested in condition monitoring for warranty purposes. Most problems relate to driver misuse rather than product and manufacturing reliability. The product is designed to the required duty cycles, and in most instances designed for life. Modules are customisable on two levels, depending on the vehicle. In certain products stability controls can be customised by the driver, see Table 3-19. D1 exhibits a low-level of PM, with all PM attributes showing low levels of PM, except for DA.

The manufacturing processes are standardised, with a low level of SCT. The customer order is received prior to the end customer COEP. The processes are standardised with limited flexibility. There are situations where configure to order processes are set up, for specific configurations. Product configurations are tested as they come off the production line. There is no requirement for PP. D1 exhibits a low level of SCCM, with all SCCM attributes showing low levels of SCCM. Process agility is low, indicating a high level of PS.

D2 is comprised of the prop shaft, and front and rear side shafts; these provide for power transfer, electronic torque, differential controls, and electro-magnetic control. Modules are interdependent and demonstrate a high-level of functional sharing, with tight IC. Approximately thirty percent of components are specific to customer applications; no single application is the same; the intent is not to make the modules interchangeable. Components are designed and built to perform over the lifetime of the automobile. There is a data communications bus to allow DA. D2 exhibits a low-level of PM, with all PM attributes, DA, LL and PV showing low levels of PM.

There is a low-level of SCT, due to the localised supply network, and the high level of economic and legal involvement of the OEM. The COEP occurs post the manufacturing process. Modules are built to stock and the production processes are standardised. There is postponement of the final product. D2 exhibits a low level of SCCM with all SCCM attributes showing low levels of SCCM.

D1 and D2 exhibit low levels of PM and SCCM at the aggregated level. Tight IC is the key driver of mirroring between PM and SCCM. Optional modularity attributes play a minor role in defining the levels of PM and SCCM for these UoA. All optional attributes are low-level except for DA for D1, which is accessible by the driver through the vehicle's controls. Process agility is low, reflecting the strong focus on product standardisation, reliability and repeatable execution within the manufacturing process.

Table 3-19. Comparison of PM and SCCM for D1 and D2

	Aerospace co.											
	Fixed trailing wing edge for airplane E1 						**Aeroplane** E2 					
	Product modularity levels			Supply chain configuration modularity levels			Product modularity levels			Supply chain configuration modularity levels		
Mandatory variables	Function sharing (FS)	This UoA represents the first application of composite material in an airplane wing, and the first large scale application of automated fiber placement. This composite wing structure was delivered in late 2014, with first commercial flights in 2015. There is an extremely high level of function sharing. FS modularity is low.	Low	Supply chain tiering (SCT)	The components are manufactured by the tier one sole supplier, in the UK and integrated into the aiplane wing assembly. The span of network is low. SCT demonstrates a low level of modularity.	Low	Function sharing (FS)	The UoA is the complete airplane, launched in 1987. The product is an integral design (low PM), with levels of bus modularity and combinational modularity. There are varying degrees of PM present. The avionics and wings reflect high PM where the fuselage reflects medium PM.	Medium	Supply chain tiering (SCT)	This is a multi-tier SCC. The final aircraft is assembled at the OEM's facility in France; however, sub-asemblies are sourced globally. The Aerospace co.'s experienced weak electronic proximity; this has been strengthened. There is high cultural proximity, with long-term binding supplier agreements in place.	High
	Interface coupling (IC)	The aircraft wing provides multiple functions, including fuel storage. This UoA includes rear spars, rib posts, root joint fittings, vertical stiffeners, spar joints and main landing gear fittings. Interface coupling is extremely tight.	Low	Process postponement (PRP)	The fixed edge wing is built to order. COEP occurs prior to assembly process. Automated fibre placement, is followed by routing, followed by drilling, and assembly of fixed trailing edge components onto the frame. PRP modularity is high.	Low	Interface coupling (IC)	Reliability, safety, pressurisation safety margins, payload distribution, fixing points, service connections all lead to tight signal, energy, force, and material interface coupling. There are strict standards specified by regulatory agencies EASA and FAA. IC modularity is high.	Low	Process postponement (PRP)	The airplane is built to order. The cabin fit-out and external painting are the last postponed processes. COEP occurs prior to product assembly. PRP modularity is high.	High
Optional variables	Data access (DA)	There is no data storage or data access. Embedded sensor technologies are planned for future designs. DA is low level of modularity.	Low	Process flexibility (PF)	The process is standardised. The focus is based on advanced materials processing and utilisation of lean initiatives and concepts such as "Coefficient of Transportation Difficulty" (CTD). PF modularity is high.	High	Data access (DA)	Airplace connectivity (avionics) is often first tested on business jets. This airplane uses advanced avionics, governed by Airinc and IEEE standards. The airplane has satellite communications. DA modularity is high.	High	Process flexibility (PF)	There is an increased role for integrators in managing technology convergence. In-flight entertainment has a high rate of technology innovation. The airlines have developed clear standards for IFE suppliers to follow. PF is high.	High
	Limited life (LL)	Material design duty cycle is critical. There is a low level of LL modularity.	Low	Process re-sequencing (PS)	There is limited opportunity for process re-sequencing.	Low	Limited life (LL)	Material (design for life, duty cycles).	Low	Process re-sequencing (PS)	There is a move to increase SCCM, driven by global production requirements. PS is low.	Low
	Product variety in use (PV)	There is no flexibility in use, low level of PV modularity.	Low	Place postponement (PP)	This is a continuous build process. The product is delivered to a plant in the UK to be integrated into the final wing-frame. There is no opportunity for place postponement, due to design and tooling cost constraints.	Low	Product variety in use (PV)	Upgradeability and improvement programmes are the norm with airplane operators. Fuel efficiency drives technology improvement. Operators have a wide selection of options on cabin design.	Low	Place postponement (PP)	There are opportunities for place postponement at customer (carrier) locations. There is pressure to further modularise the SCC. PP modularity levels are low.	Low
	Level of PM	Low level of PM due to the design of the sub-assembly. This is a fixed trailing edge wing, with tight interface coupling.		Level of SCCM	Low level of SCCM due to standardised auto fibre placement and assembly processes.		Level of PM	Medium level of PM due to medium levels of function sharing and tightly coupled system interfaces.		Level of SCCM	High level of SCCM due to technical and economic considerations.	

3.7.2.5. Aerospace company and aero-structure supplier

E1 is a fixed trailing edge sub-assembly of the wing for the finished airplane and represents a lower level of the final product BOM. E1 is a mechanical structure, with high functional sharing (low PM), and tight IC (low PM). E1 is designed around a strong mechanical bus architecture, shown in Appendix 3-7, Page 455. This innovation is driven by the requirement for weight optimisation; stability and rigidity form a second essential requirement. The focus is on tight component IC. This composite wing structure was delivered in late 2014, with the first commercial flights in 2015. There is no data bus associated with this structure. The product is designed for the duty cycle specified by the customer. E1 exhibits a low-level of PM, driven primarily by the tight IC. All optional attribute levels are low. There is DA to the wing controls, however not to the trailing edge, which is a fixed structure. There is no PV requirement, since all products are standardised. This is the first instance where composite material has been used in an airplane wing, and the first large scale application of the automated fibre placement.

The SCC is vertically integrated, with most parts manufactured in-house in France, by this tier-one supplier. The process is flexible, given the novel design of this technology. The product is sole sourced with this tier-one supplier, and demonstrates a low-level of SCT, with low levels of PRP. SCT and PRP levels are low, reflecting a local supply base and the fact that COEP is post the manufacturing process, E1 built to forecast. Whilst the SCC is not vertically integrated, the OEM controls the tier-one supplier’s location, in what could be described as an ‘industrial condominium’. The OEM has personnel on the supplier’s site ensuring there is close SCT. The assembly is shipped to the OEM, which assembles the airplane wing in the UK, prior to shipment to France for final assembly of the airplane by the OEM. E1 exhibits a low-level of SCCM.

E2 is a wide-bodied airplane, which uses a bus modular construction. Functional sharing is medium-level and interface tolerances are extremely tight (low PM), shown below in Table 3-20. There are high levels of DA, with the airplane controllable from the ground. The performance of the airplane is measurable remotely, from the ground. Parts are designed to specification, and to a predefined duty cycle. There is limited PV post product delivery. The customer can request reconfiguration, however at significant cost. Final assembly is in France, with various parts constructed across Europe. Previous experience of poor electronic proximity led to a USD$ 6 billion cost and three-year development time overrun on a previous product. E2 exhibits a medium-level of PM, which is influenced by medium levels of FS and tight IC (low PM).

E2 is a multi-tier SCC, and exhibits a high-level of SCT. The supply network has multiple tiers and suppliers within each tier. The network is global, with many suppliers, for example the airplane engine suppliers experiencing a high level of independence from the OEM. Early challenges with poor electronic integration with SCT partners in the 1970s have been overcome. The focus of this research is on the top three levels of the PA. The OEM not only assembles the TLA, but also many lower level sub-assemblies, for instance the wings of the plane. E1 is supplied by a tier-one supplier to the OEM for assembly into the wing structure for E2. The assembly process is standardised; however, there is a level of flexibility, with a moving production line. PP is confined to internal finishing of the airplane. E2 exhibits a high-level of SCCM.

E1 exhibits low levels of PM and SCCM at the aggregated level. Tight IC is the key driver of mirroring between PM and SCCM. Optional modularity attributes play a minor role in defining the levels of PM and SCCM for these UoA. PF is high, demonstrating the unique nature of the composite process, which has been developed over twenty years, and is being used for the first time. E2 exhibits a medium-level of PM and high-level of SCCM at the aggregate level. PRP is high with COEP prior to the commencement of product assembly. DA modularity is high, LL and PV modularity levels are low; PRP and PP levels are similarly low. DA and PF are the only optional attributes influencing the mirroring of PM with SCCM. The low-level of IC modularity, due to tight signal, energy, force and material interfaces, and varying levels of modularity present, results in a mismatch between the levels of PM and SCCM.

Table 3-20. Comparison of PM and SCCM for E1 and E2

	Aerospace co.											
	Fixed trailing wing edge for airplane E1 						**Aeroplane** E2 					
	Product modularity levels			Supply chain configuration modularity levels			Product modularity levels			Supply chain configuration modularity levels		
Mandatory variables	Function sharing (FS)	This UoA represents the first application of composite material in an airplane wing, and the first large scale application of automated fiber placement. This composite wing structure was delivered in late 2014, with first commercial flights in 2015. There is an extremely high level of function sharing. FS modularity is low.	Low	Supply chain tiering (SCT)	The components are manufactured by the tier one sole supplier, in the UK and integrated into the aiplane wing assembly. The span of network is low. SCT demonstrates a low level of modularity.	Low	Function sharing (FS)	The UoA is the complete airplane, launched in 1987. The product is an integral design (low PM), with levels of bus modularity and combinational modularity. There are varying degrees of PM present. The avionics and wings reflect high PM where the fuselage reflects medium PM.	Medium	Supply chain tiering (SCT)	This is a multi-tier SCC. The final aircraft is assembled at the OEM's facility in France; however, sub-asemblies are sourced globally. The Aerospace co.'s experienced weak electronic proximity; this has been strengthened. There is high cultural proximity, with long-term binding supplier agreements in place.	High
	Interface coupling (IC)	The aircraft wing provides multiple functions, including fuel storage. This UoA includes rear spars, rib posts, root joint fittings, vertical stiffeners, spar joints and main landing gear fittings. Interface coupling is extremely tight.	Low	Process postponement (PRP)	The fixed edge wing is built to order. COEP occurs prior to assembly process. Automated fibre placement, is followed by routing, followed by drilling, and assembly of fixed trailing edge components onto the frame. PRP modularity is high.	Low	Interface coupling (IC)	Reliability, safety, pressurisation safety margins, payload distribution, fixing points, service connections all lead to tight signal, energy, force, and material interface coupling. There are strict standards specified by regulatory agencies EASA and FAA. IC modularity is high.	Low	Process postponement (PRP)	The airplane is built to order. The cabin fit-out and external painting are the last postponed processes. COEP occurs prior to product assembly. PRP modularity is high.	High
Optional variables	Data access (DA)	There is no data storage or data access. Embedded sensor technologies are planned for future designs. DA is low level of modularity.	Low	Process flexibility (PF)	The process is standardised. The focus is based on advanced materials processing and utilisation of lean initiatives and concepts such as "Coefficient of Transportation Difficulty" (CTD). PF modularity is high.	High	Data access (DA)	Airplace connectivity (avionics) is often first tested on business jets. This airplane uses advanced avionics, governed by Airinc and IEEE standards. The airplane has satellite communications. DA modularity is high.	High	Process flexibility (PF)	There is an increased role for integrators in managing technology convergence. In-flight entertainment has a high rate of technology innovation. The airlines have developed clear standards for IFE suppliers to follow. PF is high.	High
	Limited life (LL)	Material design duty cycle is critical. There is a low level of LL modularity.	Low	Process re-sequencing (PS)	There is limited opportunity for process re-sequencing.	Low	Limited life (LL)	Material (design for life, duty cycles).	Low	Process re-sequencing (PS)	There is a move to increase SCCM, driven by global production requirements. PS is low.	Low
	Product variety in use (PV)	There is no flexibility in use, low level of PV modularity.	Low	Place postponement (PP)	This is a continuous build process. The product is delivered to a plant in the UK to be integrated into the final wing-frame. There is no opportunity for place postponement, due to design and tooling cost constraints.	Low	Product variety in use (PV)	Upgradeability and improvement programmes are the norm with airplane operators. Fuel efficiency drives technology improvement. Operators have a wide selection of options on cabin design.	Low	Place postponement (PP)	There are opportunities for place postponement at customer (carrier) locations. There is pressure to further modularise the SCC. PP modularity levels are low.	Low
	Level of PM	Low level of PM due to the design of the sub-assembly. This is a fixed trailing edge wing, with tight interface coupling.		Level of SCCM	Low level of SCCM due to standardised auto fibre placement and assembly processes.		Level of PM	Medium level of PM due to medium levels of function sharing and tightly coupled system interfaces.		Level of SCCM	High level of SCCM due to technical and economic considerations.	

3.8. WITHIN-CASE MIRRORING ANALYSIS

A within-case review re-examines the level two codes, for PM and SCCM. The mandatory SCCM codes SCT and PRP were developed during project two. Level three axial codes relate to the themes deduced from project one, together with relationships induced from the empirical research in project two. The theses deduced from project one and project two are shown in Appendix 3-10, Page 457. The level three codes focus on relationships emerging from the case studies. PM mirroring with SCCM relates not to the content of the project two attributes but to the causality amongst these attributes (Jehn, 1997).

3.8.1. Medical device company

A1 and A2 represent medical devices, which focus on patient safety. These designs reflect a medium-level of component independence, and interface standardisation (Sosa *et al.*, 2007). The OEM designs A1 and A2, with industrial design support provided by the tier-one manufacturer for A2. SCT reflects the requirement for low UMC, with a medium-level of economic and business involvement by the OEM, to ensure continuity of supply. For these devices the COEP occurs post manufacturing, with UoA built to the OEM's forecast. As a result, both UoA have a significant number of final SKUs, and low levels of re-configurability. PM mirroring with SCCM is attributable to the high-level of KC and ESI at the concept stage and a low propensity of both PA and SCC decoupling, shown in Figure 3-17. The causal links between PM and SCCM are bi-directional.

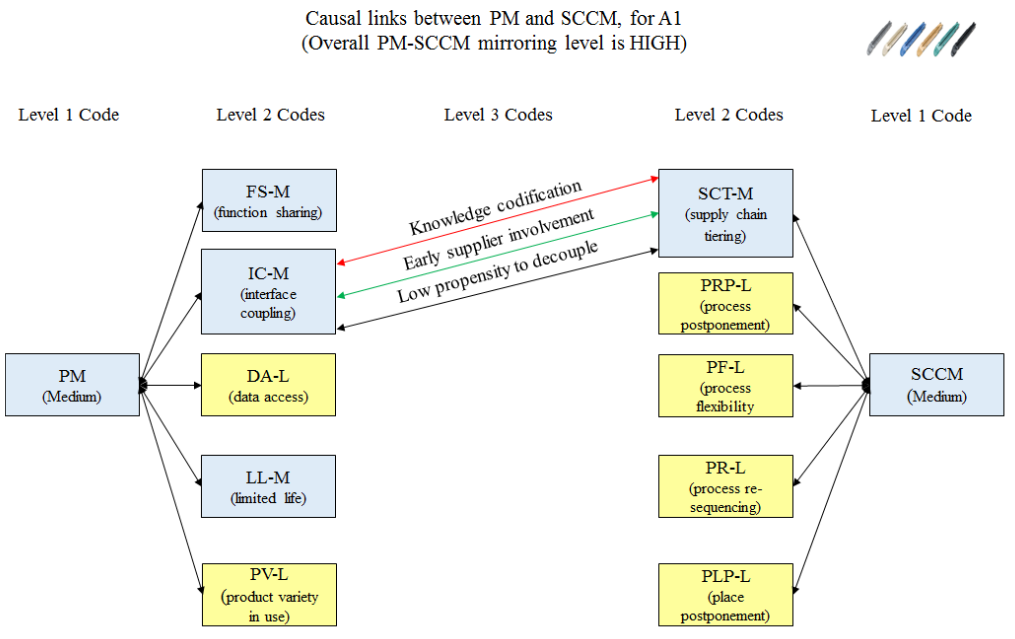


Figure 3-17. Causal links for PM and SCCM mirroring of A1

With A1 there is a high-level of PM mirroring with SCCM. For A1, the causal relationships highlight: 1) the strong co-ordinating role of the OEM, which provides KC; 2) ESI with a strong focus on materials science, geometric tolerancing and dimensioning, and 3) a low PD, resulting from the role regulatory compliance plays in ensuring product and process standardisation, see Table 3-21. PRP-L has less of an impact on the level of PM mirroring with SCCM since the COEP occurs post manufacturing. These consumable devices are comprised of a family of standard SKUs. The OEM controls NPD and SCC design, and is managing the causal relationships, shown below in Table 3-21.

Table 3-21. Causal relationships between PM and SCCM for A1

Causal relationships between PM and SCCM (A1)				
PM variable	**Causal relationship**	**SCCM variable**	**Level of mirroring**	**Explanation of causal relationships**
IC-M (medium coupling)	Knowledge codification (KC)	SCT-M (medium depth and breadth of network, together with legal involvement)	High	Interface coupling for this Class III surgical device is medium since there is a medium level of cross-dependency between the sterile stainless steel and plastic components. "This product lends itself to PM", interviewee. The component interfaces impose space constraints on the physical coupling of the modules, and need to be codified. This knowledge codification supports Global SCT which operates at medium depth and breadth. The knowledge transferred by the OEM to the suppliers is explicit, clearly codified, relatively easy to transfer and consists of product form factor, wire gauges and overall material specification.
IC-M (medium coupling)	Early supplier involvement (ESI)	SCT-M (medium depth and breadth of the network, and medium legal involvement)	High	Component tolerances are tight, "having vendor reps on-site with the R&D and manufacturing groups is important during the concept stage"; this interviewee. Suppliers provide materials innovation, during the concept stage of development, prior to technology phase gate zero (TRL-0). This early establishment of a new material specifications enabled a number of material alternative sources to be qualified, prior to product launch, which leads to a broader span of network, indicated by SCT-M. Class III devices require premarket approval by the Federal Drugs Association (FDA), as a result the OEM is required to oversee the quality and regulatory obligations of the supplier base, from the concept stage, this leads to a medium level of legal involvement by the OEM.
IC-M (medium coupling)	Low propensity to decouple	SCT-M (medium legal involvement by the OEM)	High	The interface coupling is medium with the staples constrained in the device, and released by a vascular stapler. The staples are of a specialist design and cannot easily be decoupled, therefore there is a low propensity for the staples to decoupled from the device, without the use of the vascular stapler. Federal Drugs Authority (FDA) registration of the product and related SCT, lead to a low propensity to decouple the relationships with the suppliers. This leads to specialist suppliers having a medium level of legal business involvement with the OEM.
Overall level of mirroring at product launch			High	

For A2 IC is medium, with the test strip and meter performing a single function; however, the test strip is easily replaceable. SCT reflects the requirement for low UMC, with a medium-level of economic and business involvement by the OEM, to ensure continuity of supply. ESI plays a significant role in achieving this interface mirroring, since user experience and user factors are required to be entered in the product feature set during the concept stage, shown below in Figure 3-18. There is a low PD at the product and SCC levels. A2 manufacturing can be easily outsourced without impacting on the IP, and there is a level of medium level of PRP (PRP-M) to support product labelling and language configuration post the COEP, shown below in Table 3-22.

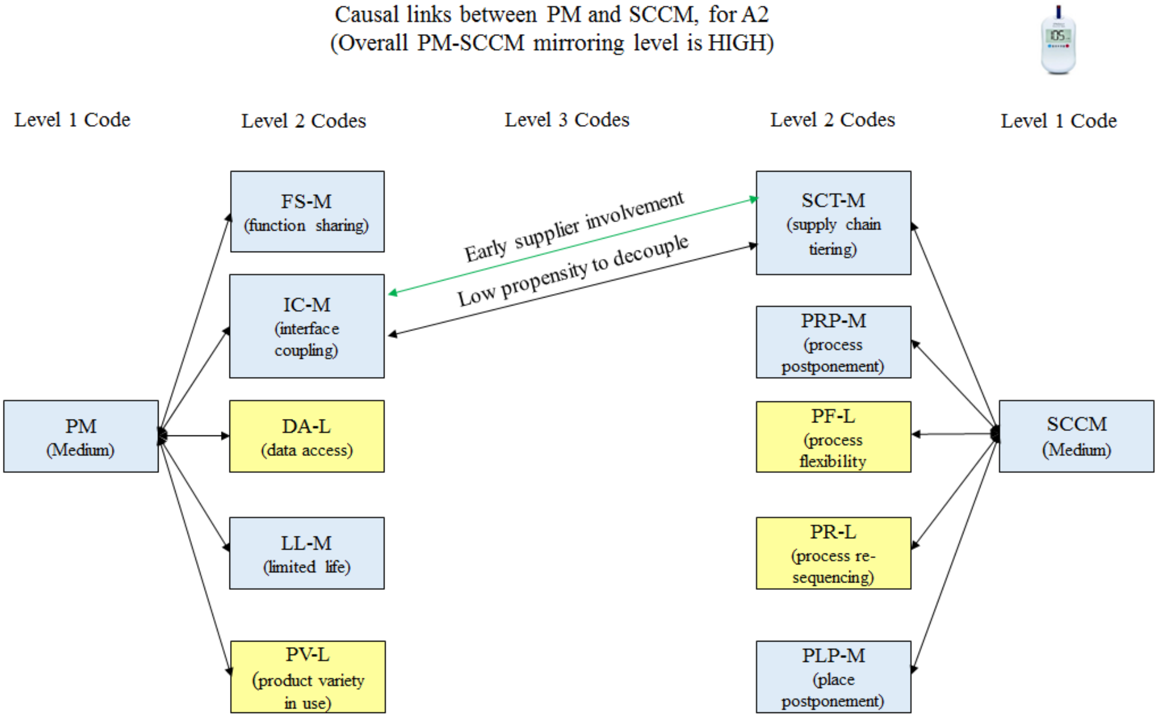


Figure 3-18. Causal links for PM and SCCM mirroring of A2

For A2, the causal relationships highlight: 1) ESI with a strong focus on materials and process validation and supplier cost, and 2) a low PD between IC-M and SCT-M, due to material and process validation, shown below in Table 3-22.

Table 3-22. Causal relationships between PM and SCCM for A2

Causal relationships between PM and SCCM (A2)				
PM variable	**Causal relationship**	**SCCM variable**	**Level of mirroring**	**Explanation of causal relationships**
IC-M (medium coupling)	Early supplier involvement (ESI)	SCT-M (medium breadth of the network)	High	This blood glucose test meter is a Class II medical device, with a combination of tight (test meter) and loose (removable test strip and rechargeable battery) interfaces. ESI for the test meter is required to ensure material equivalence, material qualification and process validation prior to FDA product release. This material and process validation require ESI with an Asia centric supply base. The OEM engages in component supplier selection and qualification, with the tier one meter manufacturer. ESI focuses on cost control of the meter, together with management of the knowledge required to control this regulated product and supply chain. ESI leads to the ability of the tier one meter supplier to provide DFx inputs to the concept team. These DFx inputs require medium term manufacturing agreements to allow this supplier to amortise this design investment. ESI also allows the meter supplier provide inputs on product industrialisation, working closely with component suppliers.
IC-M (medium coupling)	Low propensity to decouple	SCT-M (medium breadth of the network)	High	The meter is not designed for disassembly; with the exception of replacing the DC battery, therefore interface coupling is medium level. Process validation and product registration drives a low propensity to decouple the supply chain, with the strips manufactured by the OEM, the lancet, meter and other components supplied by regulated suppliers, this leads to a small number of suppliers; with a requirement for a medium breadth of SCT. Finished products are delivered by the tier one manufacturer to the OEM's global distribution centres.
Overall level of mirroring at product launch			High	

3.8.2. Domestic appliance company

B1 and B2 represent domestic appliances, which focus predominantly on innovative cost-efficient design. The OEM outsources the manufacturing of both UoA. Both products have Asia based supply networks. A tier-two or tier-three supplier acts as a primary supplier, co-ordinating the regional supply network. B1 exhibits tight IC (IC-L) and a medium level of SCT (SCT-M), and a lack of PM mirroring with SCCM, shown below in Figure 3-19.

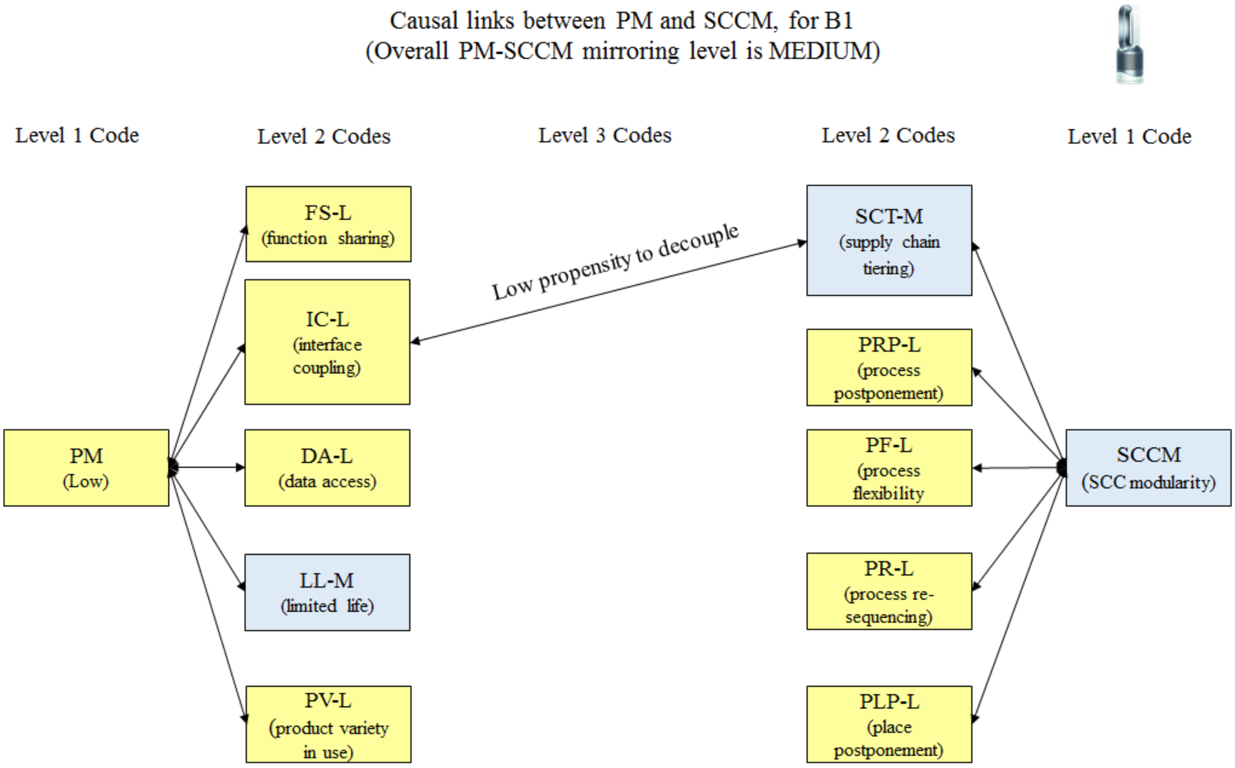


Figure 3-19. Causal links for PM and SCCM mirroring of B1

For B1, the causal relationships highlight low PD, IC-L, and SCT-M, and the benefit of the primary supplier in managing SCT-M, see Table 3-23. With B1, the PM mandatory attributes FS-L and IC-L are mirrored; however, the SCCM mandatory attributes SCT-M and PRP-L are not mirrored, resulting in lower mirroring between PM and SCCM. The OEM has appointed a primary supplier to take overall control of the SCC, including plastics tooling, plastics moulding, final product assembly and delivery to in-region distribution centres. The OEM offers limited variants of the initial product, to ensure the delivery of the marketing claim at launch.

Table 3-23. Causal relationships between PM and SCCM for B1

Causal relationships between PM and SCCM (B1)				
PM variable	**Causal relationship**	**SCCM variable**	**Level of mirroring**	**Explanation of causal relationships**
IC-L (tight coupling)	Low propensity to decouple	SCT-M (medium depth and breadth of the network and medium economic and legal business involvement by the OEM)	Medium	Interface coupling for this UoA is tight. "This product is 90% integral design", interviewee. The requirement for a low operating noise level drives a low propensity to decouple, since the modules need to 'fit' tightly together. At launch the product was designed as a single SKU, with a HEPA filter designed to remove formaldehyde from the air intake. The product supports a regional span of network, with the primary sub-assembler (PSA) responsible for injection mold tooling, plastic molding, final product assembly, test and distribution. The SCT is not designed for ease of decoupling, with the PSA controlling the majority of suppliers, located in Malaysia. The high cost of tooling limits the number of suppliers.
Overall level of mirroring at product launch			Medium	

B2 exhibits medium levels of IC-M and SCT-M, shown below in Figure 3-20. For B2, the causal relationships highlight the high PD, IC-M, and SCT-M and the benefit of the primary supplier in managing SCT-M, shown in Table 3-24. The high PD, IC-M, and SCT-M is supported by clear design and definition of the IC and SCT interfaces. This OEM designed and manufactures the proprietary digital motor for B2; the knowledge of this product does not need to be codified for exchange with other suppliers, only the interface connections require codification.

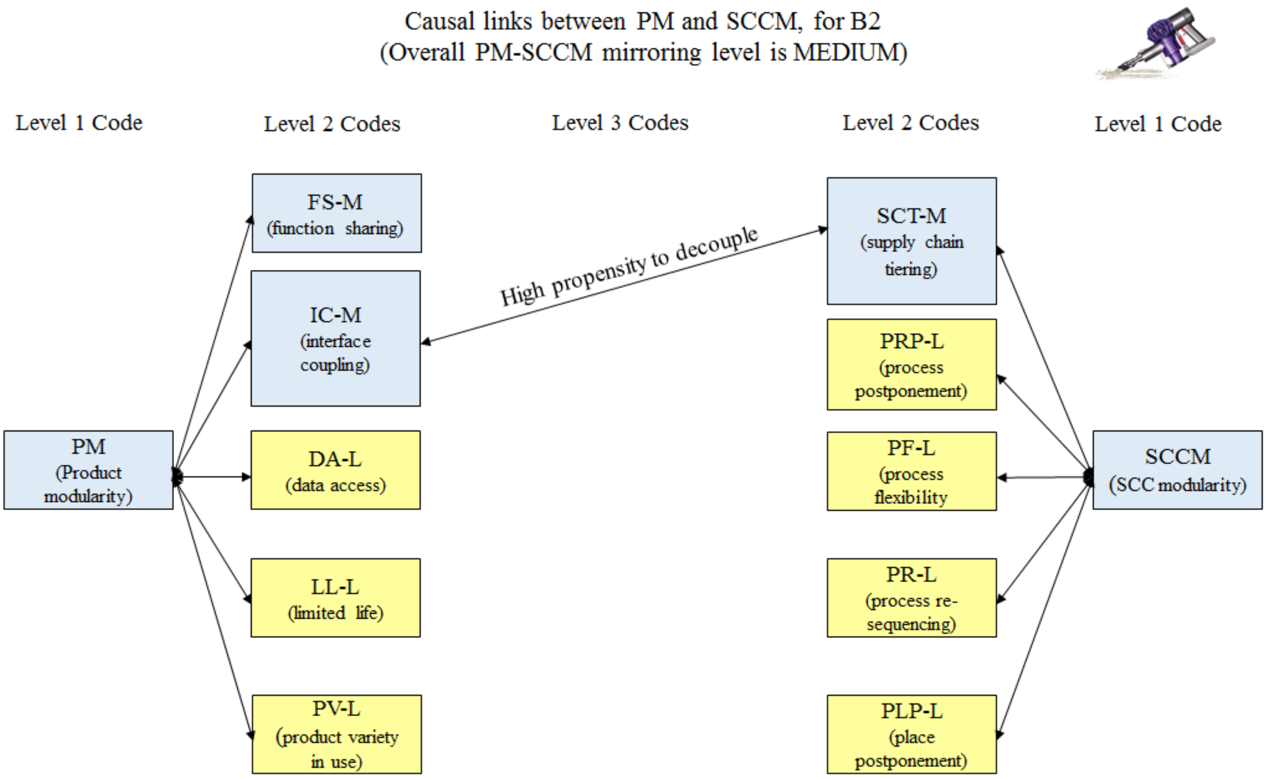


Figure 3-20. Causal links for PM and SCCM mirroring of B2

Table 3-24. Causal relationships between PM and SCCM for B2

Causal relationships between PM and SCCM (B2)				
PM variable	**Causal relationship**	**SCCM variable**	**Level of mirroring**	**Explanation of causal relationships**
IC-M (medium coupling)	High propensity to decouple	SCT-M (medium depth and breadth of the network)	High	Elements of the product are designed for ease of decoupling, including the canister and filter, which for the purpose of cleaning separate from the cyclone. This leads to a high propensity to decouple these interfaces. This high propensity to decouple supports a medium depth and breadth of SCT managed by tier two and tier three PSAs, based in Malaysia and the Philippines. The high propensity to decouple is achievable by the coordinating role of the PSAs, who manage component suppliers.
Overall level of mirroring at product launch			High	

3.8.3. Automotive company

C1 and C2 represent high performance utility vehicles, which focus on performance, safety and innovative product variety, shown below in Figure 3-21. C1 and C2 exhibit a medium level of IC-M and a high level of SCT-H. Both products are designed and manufactured by the same OEM, with global supply networks. Both UoA have a high level of process agility. The COEP is pre-manufacturing, with both products built to customer order in Europe. In the US the customer is offered standard configurations, with minor upgrade options, products are sold off the dealer forecourt. With a strong focus on product performance and safety, it is unlikely that FS and IC modularity will be reduced. As a result, it is unlikely that these UoA will move towards a mirrored relationship. Process agility will remain high to support the required levels of product custom configuration.

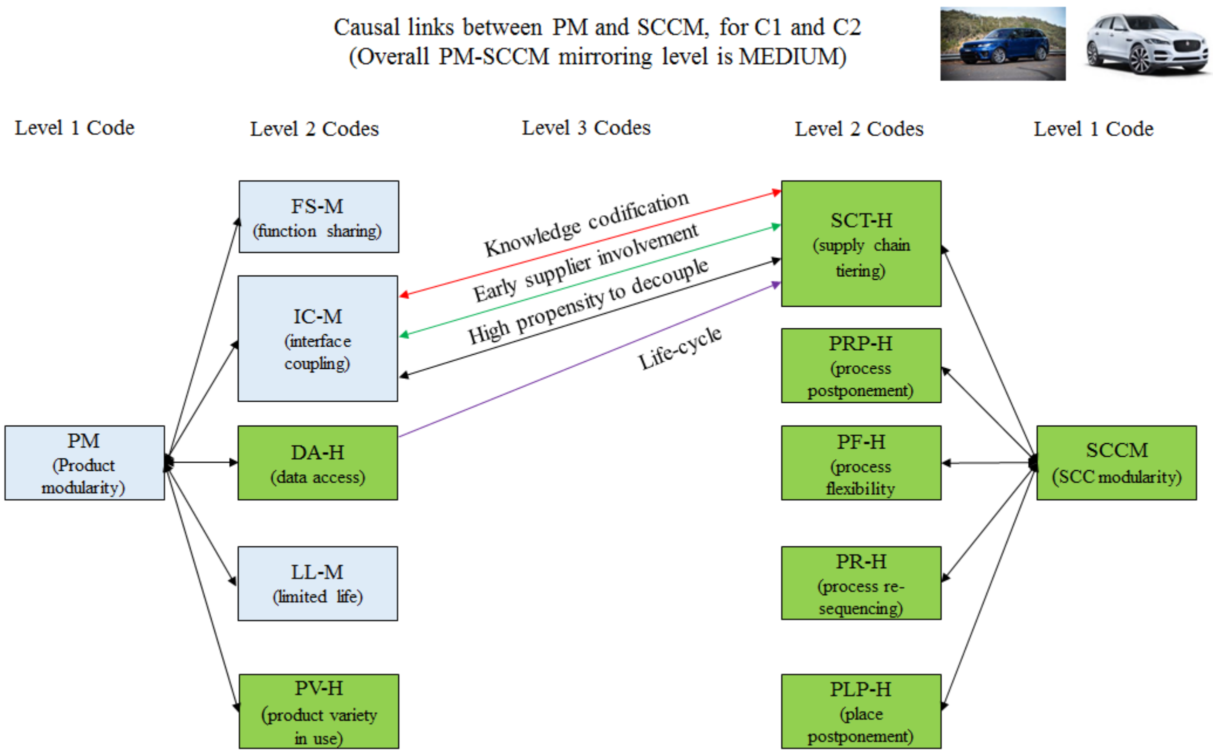


Figure 3-21. Causal links for PM and SCCM mirroring of C1 and C2

For C1 and C2 the causal relationships highlight: 1) clear KC of the PM and SCCM interfaces; 2) ESI due to the required technology development, with supplier capability playing a key role; 3) high propensity for IC-M and SCT-H to decouple, and 4) high DA-H requiring SCT-H over the PLC, as shown in Tables 3-30 and 3-31.

Table 3-25. Causal relationships between PM and SCCM for C1

Causal relationships between PM and SCCM (C1)				
PM variable	**Causal relationship**	**SCCM variable**	**Level of mirroring**	**Explanation of causal relationships**
IC-M (medium coupling)	Knowledge codification (KC)	SCT-H (high depth of the network, and a low level of legal business involvement)	Medium	At the top three levels of the bill of material (BOM) IC is medium. Cross car modules such as seating, navigation, audio/satnav, heating, lighting systems are cross-independent with some inter-dependency, for example where power or data communications are required, leading to medium interface coupling. Knowledge codification is required for communicating IC requirements between supply chain tiers. The OEM product champion co-ordinates this knowledge coding and dissemination which consists of codified cost, performance, environmental and interface data. Medium coupling of modules and KC supports a high level of SCT, and a low level of economic and legal involvement by the OEM. KC allows suppliers to share domain specific knowledge with the design team, leading to maintaining IC-M.
IC-M (medium coupling)	Early supplier involvement (ESI)	SCT-H (high depth of the network, and a low level of legal business involvement)	Medium	Module interface coupling tolerances are medium. The OEM requires ESI with tier one and tier two suppliers, who have access to new technology, and innovation to consider in cross car lines. For example co-innovation led to the ABS system developed by suppliers Bosch and ITT. ESI leads to a high depth of SCT, but does not lead to a high number of alternative suppliers for each item due to high innovation costs. Core tier one suppliers, for example the company who supply D1, and D2 are offered time to create innovative, reliable and cost efficient modules; therefore ESI allows for a lower level of involvement by the OEM with tier one and two suppliers.
IC-M (medium coupling)	High propensity to decouple	SCT-H (high depth of the network)	Medium	Modular design is required to provide customer selected options, at the top level assembly. IC-M is required to provide this customisation, and upgradability, with customisation being a key feature of the SUV market. This customisation requires close links with tier one and tier two suppliers, and the distribution network.
DA-H (high data access)	Life-cycle	SCT-H (high depth and breadth of the network)	High	With constant innovation in communications and sensor technology related to the automobile, there is a need for a life-cycle view, in providing access to the servo, and actuator modules, over the life-cyle of the design. Data access levels are increasing with the emergence of embedded electronics, wirelesss, bluetooth and software defined technologies. Often these communications technologies are first incorporated into concept vehicles. Automobiles need to be supported over their life-time supported by SCT.
Overall level of mirroring at product launch			Medium	

Table 3-26. Causal relationships between PM and SCCM for C2

Causal relationships between PM and SCCM (C2)				
PM variable	**Causal relationship**	**SCCM variable**	**Level of mirroring**	**Explanation of causal relationships**
IC-M (medium coupling)	Knowledge codification (KC)	SCT-H (high depth and breadth of the network, and a low level of legal business involvement)	Medium	At the top three levels of the bill of material (BOM) IC is medium. Cross car modules such as seating, navigation, audio/satnav, heating, and lighting systems are cross-independent with some inter-dependency, for example where power or data communications are required, leading to medium interface coupling. Knowledge codification is required for communicating IC requirements between supply chain tiers. The OEM product champion co-ordinates this knowledge coding and dissemination which consists of codified cost, performance, environmental and interface data. Medium coupling of modules and KC supports a high level of SCT, and a low level of economic and legal involvement by the OEM. KC allows suppliers to share domain specific knowledge with the design team, leading to maintaining IC-M.
IC-M (medium coupling)	Early supplier involvement (ESI)	SCT-H (high depth and breadth of the network, and a low level of legal business involvement)	Medium	Module interface coupling tolerances are medium. The OEM requires ESI with tier one and tier two suppliers, who have access to new technology, and innovation to consider in cross car lines. For example co-innovation led to the ABS system developed by suppliers Bosch and ITT. ESI leads to a high depth of SCT, but does not lead to a high number of alternative suppliers for each item due to high innovation costs. Core tier one suppliers, for example the company who supply D1 and D2, are offered time to create innovative, reliable and cost efficient modules; therefore ESI allows for a lower level of involvement by the OEM with tier 1 and 2 suppliers.
IC-M (medium coupling)	High propensity to decouple	SCT-H (high depth and breadth of the network)	Medium	Modular design is required to provide customer selected options, at the top level assembly. IC-M is required to provide this customisation, and upgradability, with customisation being a key feature of the SUV market. This customisation requires close links with tier one and tier two suppliers, and the distribution network.
DA-H (high data access)	Life-cycle	SCT-H (high depth and breadth of the network)	High	With constant innovation in communications and sensor technology related to the automobile, there is a need for a life-cycle view, in providing access to the servo, and actuator modules, over the life-cyle of the design. Data access levels are increasing with the emergence of embedded electronics, wirelesss, bluetooth and software defined technologies. Often these communications technologies are first incorporated into concept vehicles. Automobiles need to be supported over their life-time supported by SCT.
Overall level of mirroring at product launch			Medium	

3.8.4. Automotive driveline company

D1 and D2 are sub-assemblies of C1 and C2, designed and manufactured by a tier-one supplier. Sub-assemblies are designed and assembled in-house by the same tier-one supplier. This supplier also designed and assembles E1 for the aerospace company. D1 and D2 represent the high reliability, and high-performance drive-train for these utility vehicles. These UoA exhibit a low level of PM and SCCM, as shown below in Figures 3-22 and 3-23. Both UoA have local supply networks (SCT-L). The COEP occurs post manufacturing, with both products built to the OEM forecast.

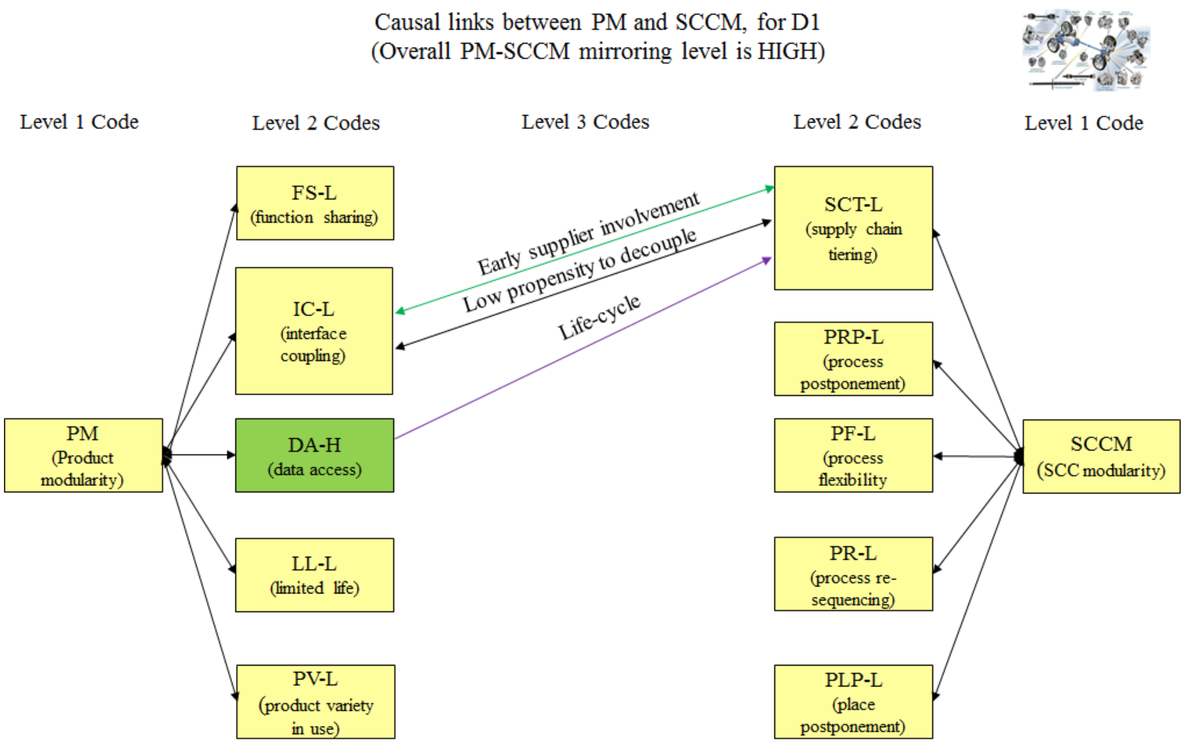


Figure 3-22. Causal links for PM and SCCM mirroring of D1

For D1 the causal relationships highlight: 1) ESI due to the required technology development, with supplier capability playing a key role; 2) low propensity for IC-L and SCT-L to decouple, and 3) high DA-H requiring SCT-L over the product LC, see Table 3-32. DA modularity is high in the case of D1, since servo and data communication technologies allow remote access to these modules. This trend will increase with the arrival of the semi- and fully autonomous automobile. Autonomous vehicles detect surroundings using radar, lidar, GPS, odometry, and computer vision. Advanced control systems interpret sensory information to identify appropriate navigation paths, as well as obstacles and relevant signage. The advanced control systems require access to the driveline.

Table 3-27. Causal relationships between PM and SCCM for D1

Causal relationships between PM and SCCM (D1)				
PM variable	**Causal relationship**	**SCCM variable**	**Level of mirroring**	**Explanation of causal relationships**
IC-L (tight coupling)	Early supplier involvement (ESI)	SCT-L (narrow depth and breadth of network)	High	This sub-assembly has tight interface coupling. The modules are application-specific, and have their own standards; therefore selection of modules requires ESI by application engineeering. IC knowledge, which consists of torque requirements, electronic and electrical connections, signal bus architecture, and interface tolerances, is shared early with suppliers. Often these modules are initially combined and performance tested in concept cars. This tier one supplier has a high level of knowledge sharing with the OEM who maintains a high level of involvement. This supplier is a leader across the entire range of driveline solutions, and is the sole source of drivetrains for the OEM, leading to a narrow depth and breadth of network.
IC-L (tight coupling)	Low propensity to decouple	SCT-L (narrow depth and breadth of network)	High	The modules operate inter-dependently, and are not easily decoupled. This high reliability leads to a low propensity to decouple. This tier one supplier of the complete drivetrain to the OEM is the sole supplier of these drivetrains, highlighting a narrow depth and breadth of supply, and a strong level of co-dependence, with the OEM depending on this tier one supplier for new technology innovation in areas such as fuel efficiency, autonomous control, and safety; therefore the low propensity to decouple is driven by a two way relationship, between the OEM and this tier one supplier.
DA-H (high data access)	Life-cycle	SCT-L (narrow depth and breadth of network, and high involvement by the OEM)	Low	There is a high level of data access, within the product design. The effect of the arrival of technologies such as radar, lidar, GPS, odometry, and computer vision, requires product design teams to look at means of upgrading these devices over the product life cycle. Over the life-cycle the automobiles are supported by the distribution network, with continuous support by suppliers and the OEM, supporting over the air software updates, and remote condition monitoring.
Overall level of mirroring at product launch			High	

D2 is a sub-assembly of D1, and represents the third level in the BOM for C1 and C2, shown below in Figure 3-23.

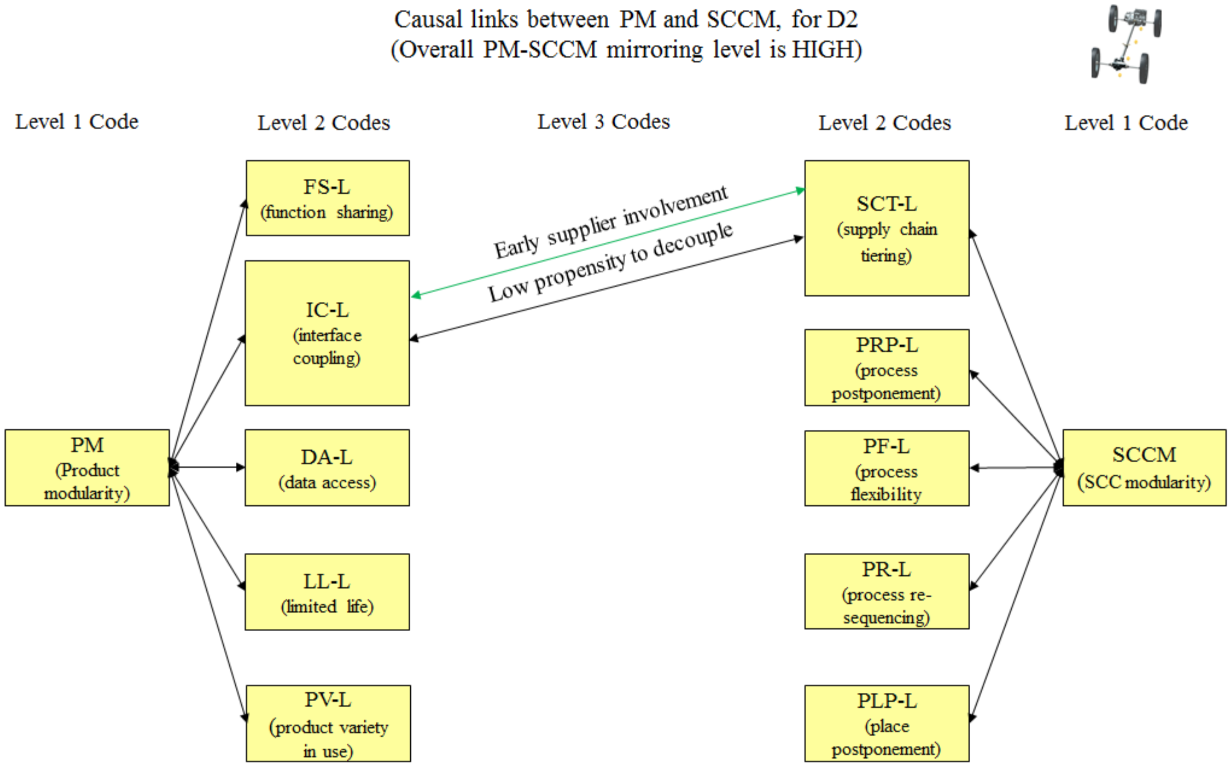


Figure 3-23. Causal links for PM and SCCM mirroring of D2

For D2, the causal relationships highlight: 1) the requirement for ESI between IC-L and SCT-L, significant component innovation is attributable to component suppliers, and 2) a low PD between IC-L and SCT-L, see Table 3-33.

Table 3-28. Causal relationships between PM and SCCM for D2

Causal relationships between PM and SCCM (D2)				
PM variable	**Causal relationship**	**SCCM variable**	**Level of mirroring**	**Explanation of causal relationships**
IC-L (tight coupling)	Early supplier involvement (ESI)	SCT-L (narrow depth and breadth of network)	High	This UoA relies on tight interface coupling of standard components. This driveshaft (D2) is delivered for integration in to the drivetrain (D1).Torque management and four-wheel drive systems are generally non-modular, each component being system-specific. With 30% of components in the driveshaft specific to customer applications there is a requirement for ESI at the concept stage to ensure component level innovation is supplied at the product concept stage and product performance specification is achieved at product launch. The Right First Time approach means limiting the depth and breadth of SCT, thus limiting supplier quality variation.
IC-L (tight coupling)	Low propensity to decouple	SCT-L (narrow depth and breadth of network)	High	The driveshaft is required to have tightly coupled interfaces, specified to perform for the serviceable lifetime of the automobile, and therefore has a low propensity to decouple. This tight coupling leads to the driveshaft being assembled in-house and delivered directly to the D1 assembly process; as a result the SCT has a low propensity to decouple and hence has a narrow depth and breadth.
Overall level of mirroring at product launch			High	

3.8.5. Aerospace and aero-structure companies

E1 is a sub-assembly of the complete airplane E2. This sub-assembly is co-designed with the OEM for E2. E1 exhibits a low level of PM and low level of SCCM, shown below in Figure 3-24. An objective of E1 is to reduce the payload of the airplane wing, reducing overall operating costs for E2. E1 has a local supply network (SCT-L), and is located close to the OEM’s wing assembly site in the UK. This composite process used in the assembly of E1 was in development for over of twenty years and ten years prior to E2 concept commencement. There is a requirement for high PF since this novel process requires continuous refinement (PF-H), shown below in Table 3-34.

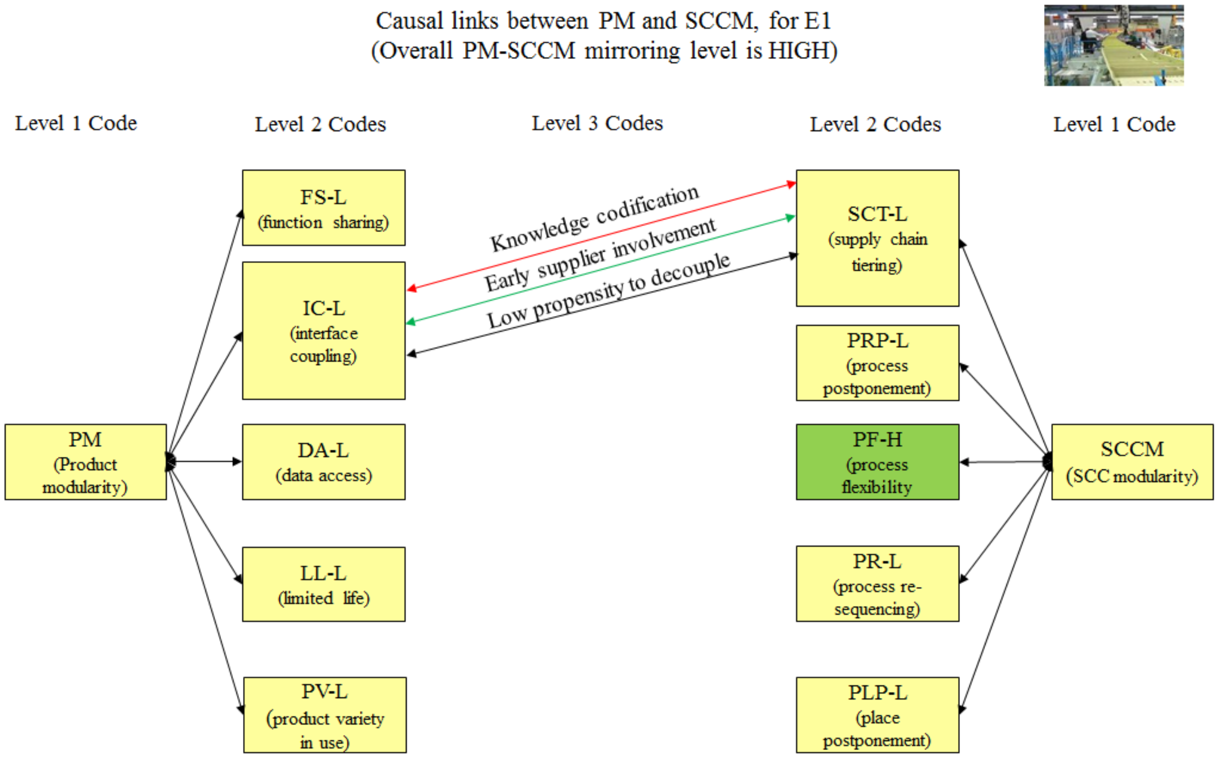


Figure 3-24. Causal links for PM and SCCM mirroring of E1

For E1 the causal relationships highlight: 1) KC between the NPD and SCC team leading to PM mirroring with SCCM; 2) ESI and customer involvement between IC-L and SCT-L, significant process innovation is attributable to composite material suppliers, and 3) a low PD between IC-L and SCT-L, see Table 3-34.

Table 3-29. Causal relationships between PM and SCCM for E1

Causal relationships between PM and SCCM (E1)				
PM variable	**Causal relationship**	**SCCM variable**	**Level of mirroring**	**Explanation of causal relationships**
IC-L (tight coupling)	Knowledge codification (KC)	SCT-L (narrow depth and breadth of network)	High	This sub-assembly has tight interface coupling which drive a high level of knowledge codification. The composite carbon material used in the construction of this UoA required extensive R&D involvement during the concept stage by this tier one supplier and the OEM. This captive supplier is contractally linked to the OEM through a low level of SCT modularity, and a high level relationship by the OEM.
IC-L (tight coupling)	Early supplier involvement (ESI)	SCT-L (narrow depth and breadth of network, high level of relationship between OEM and tier one supplier)	High	The interface coupling is tight, and therefore this integrated wing trailing edge assembly required ESI, with the OEM. ESI is required to ensure product and process reliability and to ensure the product performance specification is achieved prior to product sign-off. Supplier involvement is evident by the fact that these two companies spent over ten years bringing this composite material design to market. The tier one supplier provided design, development and productionisation services. SCT depth and breadth are low since this tier one supplier developed and provided the auto fibre placement and automated assembly processes, for this UoA.
IC-L (tight coupling)	Low propensity to decouple	SCT-L (narrow depth and breadth of network, high level of relationship between OEM and tier one supplier)	High	There is extremely tight IC with this product and an extremely high level of co-development between the OEM and tier one supplier, leading to a low propensity to decouple. A design and build risk sharing partnership was commirted by this supplier, with an investment of $280M over a five year period, with the suppliers engineering team dedicated to this programme.
Overall level of mirroring at product launch			High	

E2 exhibits a medium FS-M, shown below in Figure 3-25. E2 has a global supply network (SCT-H), high process postponement (PRP-H) and high PF (PF-H). Process agility will remain high to support the required levels of custom configuration. The COEP is post manufacturing and the final airplane is built to the OEM forecast, see Table 3-35.

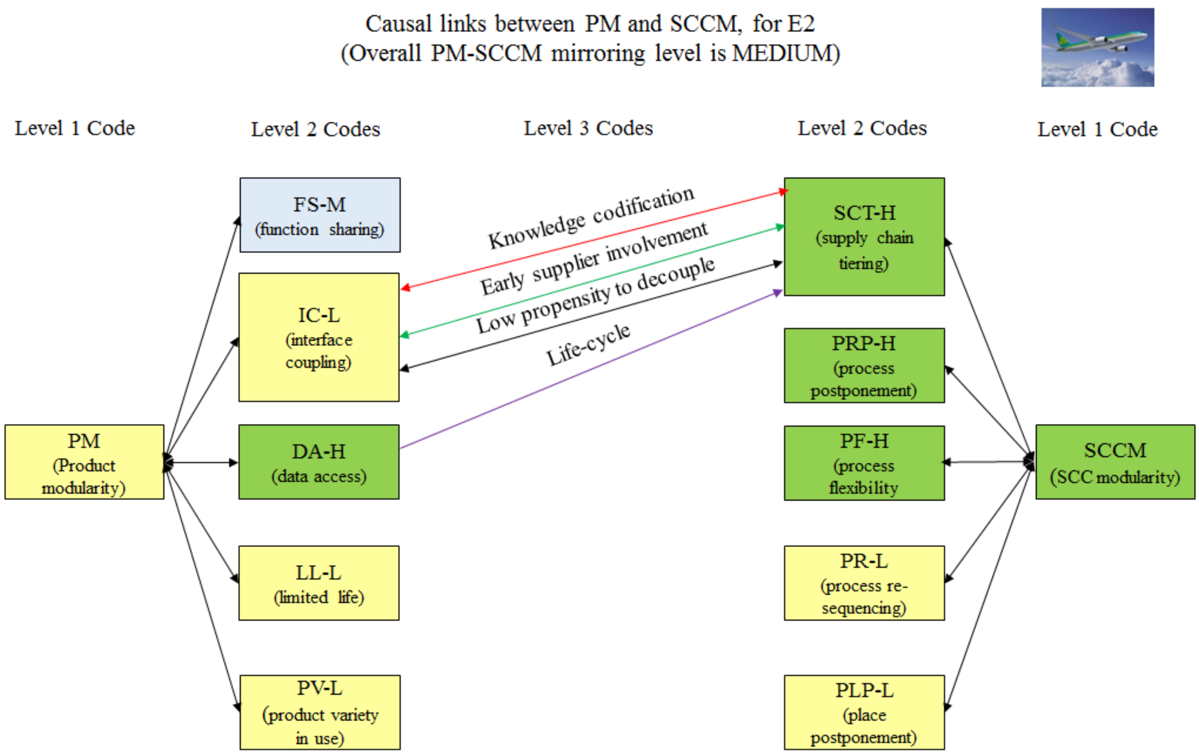


Figure 3-25. Causal links for PM and SCCM mirroring of E2

E2 causal relationships highlight: 1) the requirement for KC between IC and SCT; 2) ESI and early customer involvement in NPD and SCC design; 3) high PD between IC-L and SCT-H, and 4) DA-H requires SCT-H over the product LC.

Table 3-30. Causal relationships between PM and SCCM for E2

Causal relationships between PM and SCCM (E2)				
PM variable	**Causal relationship**	**SCCM variable**	**Level of mirroring**	**Explanation of causal relationships**
IC-L (tight coupling)	Knowledge codification (KC)	SCT-H (high depth, and breadth, of the network)	Medium	The product has tight interface coupling. This coupling requires codification of knowledge relating to interface tolerances to be exchanged with supply chain partners. Technology roadmaps are created for the structured PM data, and the less structured technology roadmaps of supply chain innovation, are shared during the concept stage with key suppliers. KC supports high depth and breadth of the network, with the OEM depending on suppliers for key areas of innovation improvement.
IC-L (tight coupling)	Early supplier involvement (ESI)	SCT-H (low economic and legal business involvement)	Medium	Interface coupling requires similar levels of technological capability between tier one suppliers and the OEM. New avionics controls for example are tried and tested initially by ESI in business jets, prior to integration into commercial airplanes. ESI leads to limited situations where the OEM needs to take control of the tier one supplier based on the need to reduce schedule, quality or cost risks.
IC-L (tight coupling)	Low propensity to decouple	SCT-H (low economic and legal business involvement)	Medium	With tight interface coupling, at the top three levels of the BOM there is a low propensity to decouple. With much technology innovation originating with tier one and tier two suppliers, this leads to a tightly coupled supply network.
DA-H (loose coupling for high data access)	Life-cycle	SCT-H (low economic and legal business involvement)	High	Controller Pilot data link communications, in-flight entertainment and remote data monitoring are examples of DA-H. Data access levels require extensive knowledge sharing between the OEM, and regulatory agencies, over the life-cycle of the product. There is a requirement from a regulatory and standards perspective for high levels of knowledge sharing over the life-cycle. Suppliers are required to partner with the OEM to deliver new communications technologies, since these technologies must co-exist and co-operate within the airplane.
Overall level of mirroring at product launch			Medium	

3.9. CROSS-CASE COMPARISON

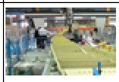
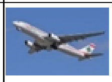
The focus of this cross-case comparison is on assessing the PM mirroring with SCCM hypothesis and how causal relationships affect the levels of each attribute. This empirical research developed three linking patterns associated with combinations of PM and SCCM attributes, ESI, PD and the life cycle perspective.

3.9.1. Product modularity

PM is deduced as a means of reducing product design complexity. This is not always achievable or desirable for new-to-market products where the focus is on meeting technical and customer specifications. All UoA exhibit low to medium levels of FS and IC mandatory attributes, see Table 3-36. For all UoA except E2, the level of FS was consistent with the level of IC. For example, where IC is tight (low PM), FS is high (low PM). For E2 while the IC is tight indicating low PM, FS is medium. This is because of the multitude of systems in an airplane, some of which are not inter-dependent.

B1, D1, D2, E1 and E2 have tight IC and depend on modular bus architecture to provide low levels of FS modularity, shown in Appendix 3-7, Page 455. A1 and B2 also require strong bus modularity for product stability, and medium level FS. C1, C2, D1 and E2 exhibit high DA modularity and require remote connectivity. A2, B1, C1 and C2 demonstrate medium levels of LL modularity at the system level. This is attributable to components or modules which have a shorter life expectancy than the system. C1 and C2 exhibit high levels of PM associated with PV modularity. All other UoA exhibit low levels of PM associated with the modularity in use, shown in Appendix 3-9., Page 457.

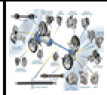
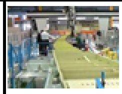
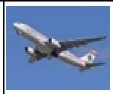
Table 3-31. Cross-case comparison of PM

Level of product modularity varables										
Company	Med device co.		Domestic appliance co.		Auto co.		Auto driveline co.		Aerospace co.'s	
Respondent	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
UoA										
Function sharing	Medium	Medium	Low	Medium	Medium	Medium	Low	Low	Low	Medium
Interface coupling	Medium	Medium	Low	Medium	Medium	Medium	Low	Low	Low	Low
Data access	Low	Low	Low	Low	High	High	High	Low	Low	High
Limited life	Medium	Medium	Medium	Low	Medium	Medium	Low	Low	Low	Low
Product variety in use	Low	Low	Low	Low	High	High	Low	Low	Low	Low
Level of PM	Medium	Medium	Low	Medium	Medium	Medium	Low	Low	Low	Medium

3.9.2. Supply chain configuration modularity

For A1, C1, C2 and E2, the OEM case company performs the role of the SCT integrator, see Table 3-37. With A2, B1 and B2, SCT is managed using tier-one, tier-two or tier-three suppliers. This decision relates to the capabilities of the primary supplier and the degree to which the PM and SCCM data are codifiable. The OEM has a low level of economic and legal business involvement with these primary suppliers, allowing them to remain independent and perform as an innovative SC partner.

Table 3-32. Cross-case comparison of SCCM

Level of supply chain configuration modularity										
Company	Med device co.		Domestic appliance co.		Auto co.		Auto driveline co.		Aerospace co.'s	
Respondent	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
UoA										
Supply chain tiering	Medium	Medium	Medium	Medium	High	High	Low	Low	Low	High
Process postponement	Low	Medium	Low	Low	High	High	Low	Low	Low	High
Process flexibility	Low	Low	Low	Low	High	High	Low	Low	High	High
Process re-sequencing	Low	Low	Low	Low	High	High	Low	Low	Low	Low
Place postponement	Low	Medium	Low	Low	High	High	Low	Low	Low	Low
Level of SCCM	Medium	Medium	Medium	Medium	High	High	Low	Low	Low	High

The level of SCCM is high for complex top-level assemblies such as the automobiles and airplane (C1, C2 and E2). This reflects the requirement for medium to high levels of SCT for global supply networks, and high levels of PRP. There is a low level of process agility (PF, PR and PP) for medical devices and domestic appliances since these are standard SKUs, built to forecast, and not requiring process or PP. Process agility is also at a low level for lower-level sub-assemblies D1, D2 and E1, which are built to forecast. Further results on cross-case SCCM, are shown in Appendix 3-9, Page 457.

3.9.3. PM mirroring with SCCM

There is strong evidence of PM mirroring with SCCM for the medical devices A1 and A2, where product module and SCC interfaces are matching, as shown below in Table 3-33.

Table 3-33. Cross-case comparison of PM mirroring with SCCM

Level of PM and SCCM											
Construct	Company	Med device co.		Domestic appliance co.		Auto co.		Auto driveline co.		Aerospace co.'s	
	Respondent	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
	UoA										
Product modularity	Function sharing	Medium	Medium	Low	Medium	Medium	Medium	Low	Low	Low	Medium
	Interface coupling	Medium	Medium	Low	Medium	Medium	Medium	Low	Low	Low	Low
	Data access	Low	Low	Low	Low	High	High	High	Low	Low	High
	Limited life	Medium	Medium	Medium	Low	Medium	Medium	Low	Low	Low	Low
	Product variety in use	Low	Low	Low	Low	High	High	Low	Low	Low	Low
	Level of PM	Medium	Medium	Low	Medium	Medium	Medium	Low	Low	Low	Medium
Supply chain configuration modularity	Supply chain tiering	Medium	Medium	Medium	Medium	High	High	Low	Low	Low	High
	Process postponement	Low	Medium	Low	Low	High	High	Low	Low	Low	High
	Process flexibility	Low	Low	Low	Low	High	High	Low	Low	High	High
	Process re-sequencing	Low	Low	Low	Low	High	High	Low	Low	Low	Low
	Place postponement	Low	Medium	Low	Low	High	High	Low	Low	Low	Low
	Level of SCCM	Medium	Medium	Medium	Medium	High	High	Low	Low	Low	High
Overall level of mirroring		High	High	Medium	High	Medium	Medium	High	High	High	Medium

The PM mirroring with SCCM theory emerges from the coding in project two, the four linking pattern codes induced from this empirical research are KC, ESI, PD and life cycle; these are discussed in the following section.

3.9.3.1. Knowledge codification

KC relates to tight to medium IC across all levels of SCT, as shown below in Table 3-13. With A1, C1 and C2, there is a strong focus on technology innovation, see Table 3-39. With the high geographic spread of the network, KC is required to access this innovation, and create a knowledge base of components and their interactions (Sanchez, 1996). E2 has a strong focus on technology innovation, and its incorporation in new product design. Research into complex airplane and sub-assembly production systems identifies the importance of the overlap between partners' knowledge bases (Brusoni and Prencipe, 2001). The need for knowledge duplication between alliance partners means that a key issue for the efficiency of alliances relative to individual companies is the amount of common knowledge required for effective knowledge integration (Grant and Baden-Fuller, 2004). KC supports PM mirroring with SCCM for A1 and E1; in both cases KC is required to reduce the knowledge complexity between the OEM and the supply network.

A1, C1, and C2 have low to high SCT depth and breadth, and common causal links to KC. There are differences in the causal KC links for the five UoA, shown in Figure 3-26.

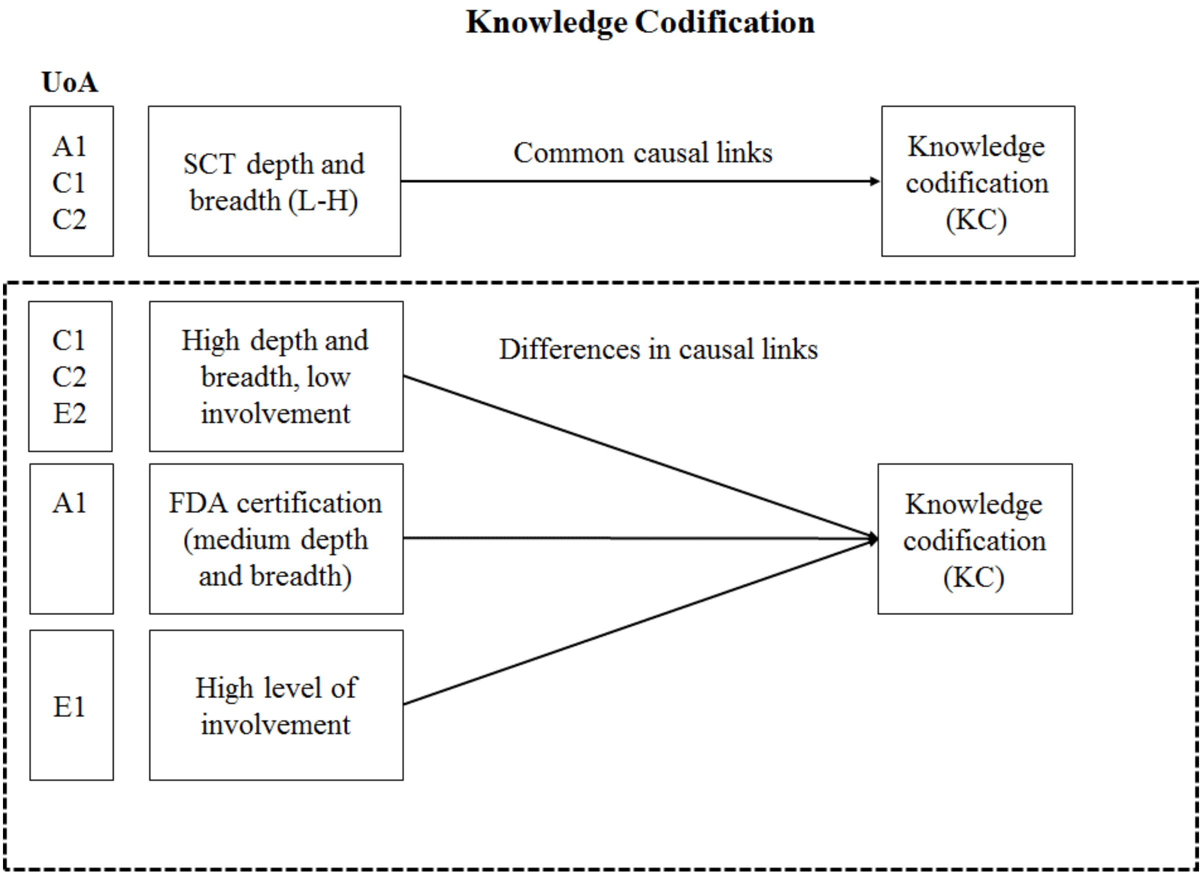


Figure 3-26. Knowledge codification

The reasons with the differences in KC are below in Table 3-39. Knowledge sharing is bi-directional between PM and SCCM, and supports mirroring, it does not however drive mirroring.

Table 3-34. Knowledge codification (PM – SCCM linking pattern)

UoA	PM	Causal link	SCCM	Level of mirroring	Explanation of similarities	Explanation of differences
A1	IC-M	Knowledge codification	SCT-M (medium depth and breadth, with medium economic business involvement).	High	KC is used to codify knowledge at the product interfaces. Knowledge sharing is bi-directional. In general the level of IC does not appear to impact the use of KC and therefore does not drive mirroring.	C1 and C2 have extensive SCT depth and breadth, where A1 has medium SCT depth and breadth. A1 requires an FDA certified supplier network.
C1			SCT-H (high depth and breadth, with low economic business involvement).	Medium		
C2						
E2						The aero-structure co, has extremely tight interface coupling, and a low level of SCT. E1 has low SCT in terms of lower depth and breadth, with high involvement with the OEM which contributes to intensive knowledge sharing and codification, which also drives the tight IC.
E1	IC-L (tight)		SCT-L (low depth and breadth, with high economic business involvement).	High		E1 has low SCT in terms of low depth and breadth with high involvement with the OEM, which contributes to intensive knowledge sharing and codification, which is also driven by the tight IC.

3.9.3.2. Early supplier involvement

The rate of technology change, the levels of supplier expertise and the requirement for early process validation are primary drivers for ESI. All products, except for B1 and B2, required ESI. Evidence shows ESI as one of the strongest causal links between PM and SCCM. In the case of B1 and B2, the product and its sub-assemblies and modules, including the digital motor and cyclone technology, are designed by the OEM. In the case of the medical device suppliers, they are involved early in the product design and process validation. The automotive suppliers were involved in drivetrain technology development, while the aerospace supplier was involved in the early process development and validation of composite materials. ESI supports PM mirroring with SCCM for A1, A2, D1, D2, C1, D2 and E1, shown below in Figure 3-27. ESI is required where IC is tight to medium, to ensure interface tolerances are developed across the supply network.

ESI relates to a small number of suppliers and reflects their core capabilities. SCT depth and breadth is medium not high, and the OEM's have a medium level of economic involvement. Many of these suppliers tend to become sole sourced suppliers for the components and sub-assemblies they supply. ESI in the case of IC-M – SCT-H is supported in the literature for example with C1 and C2, however these cars do not show a high level of mirroring. With these UoA FS and IC are medium level, there is mirroring of these attributes is at the product level but not between the product and its SCC, since SCCM is high.

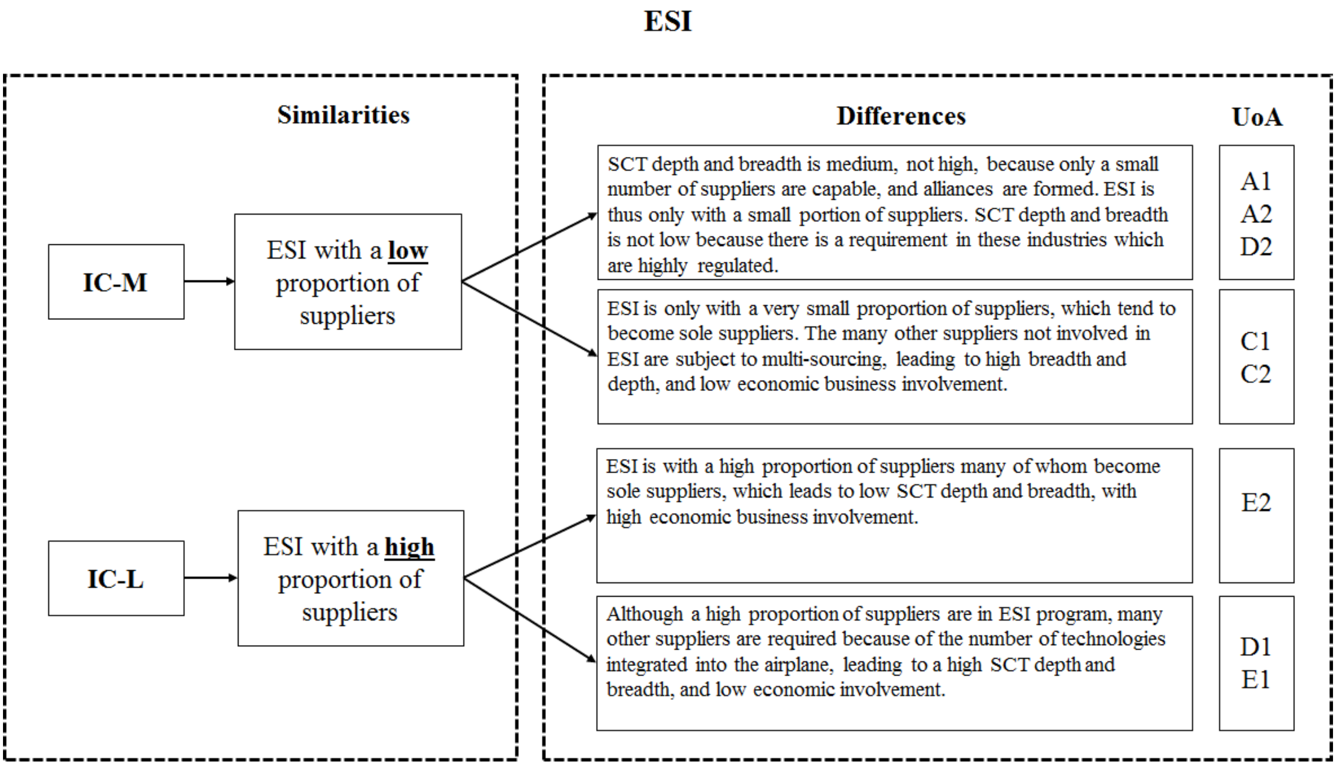


Figure 3-27. Early Supplier Involvement

ESI linking patterns differ depending on the IC-L and IC-M, shown below in Table 3-40.

Table 3-35. Early supplier involvement (PM – SCCM linking pattern)

<table>
<tr><th>UoA</th><th>PM</th><th>Causal link</th><th>SCCM</th><th>Level of mirroring</th><th>Explanation of similarities</th><th>Explanation of differences</th></tr>
<tr><td>A1</td><td rowspan="5">IC-M</td><td rowspan="8">Early supplier involvement</td><td rowspan="3">SCT-M (medium depth and breadth, with medium economic business involvement).</td><td rowspan="3">High</td><td rowspan="5">All five UoA are experiencing a high rate of technological change. Much of the technological innovation is originating with key suppliers. Medium levels of loose coupling allow easier supplier involvement in the product architecture design. The IC-ESI causal link occurs through ESI. These companies operate in regulated industry sectors where new product concepts require rigorous validation and acceptance testing prior to launch, using compliant quality systems. ESI is therefore crucial.</td><td rowspan="5">The trend in the medical device market is toward an increased number of alliances (SCT-M) between medical companies, molders, and raw material suppliers. The automotive co. has a greater span of network, which contributes to a medium level of PM-SCCM mirroring. This also renders it difficult to engage all key suppliers, due to both the span of network, and a lower level of economic and legal business involvement.</td></tr>
<tr><td>A2</td></tr>
<tr><td>D2</td></tr>
<tr><td>C1</td><td rowspan="3">SCT-H (high depth and breadth, with low economic business involvement).</td><td rowspan="3">Medium</td></tr>
<tr><td>C2</td></tr>
<tr><td>E2</td><td rowspan="3">IC-L (tight)</td><td rowspan="3">D1 E1 and E2 all have tight interface coupling, which contributes to a level of application engineering involvement, which leads to ESI with a high proportion of suppliers.</td><td rowspan="3">E2 is an OEM, where E1 and D1 are tier one suppliers. There are tighter levels of SCT with the tier one suppliers, which contributes to PC-SCCM mirroring for these two UoA. E2 however builds the top level assembly in-house, and builds many of the level 2 assemblies in-house also.</td></tr>
<tr><td>D1</td><td rowspan="2">SCT-L (low depth and breadth, with high economic and legal involvement).</td><td rowspan="2">High</td></tr>
<tr><td>E1</td></tr>
</table>

3.9.3.3. Propensity to decouple

Where there is low PD, IC is tight to medium level and SCT is low to medium level. Low PD illustrates mirroring between PM and SCCM except for B1. In the case of B1, IC is tight, whilst there is a medium level of SCT, shown below in Figure 3-28.

C1 and C2 have a medium level of IC (IC-M) and high PD due to the many different systems in the car, from heating, to electrical, navigation, infotainment, and seating. E2 has a high level of IC (low IC modularity) and high PD due to the many different systems in the fuselage, cockpit and airplane wings.

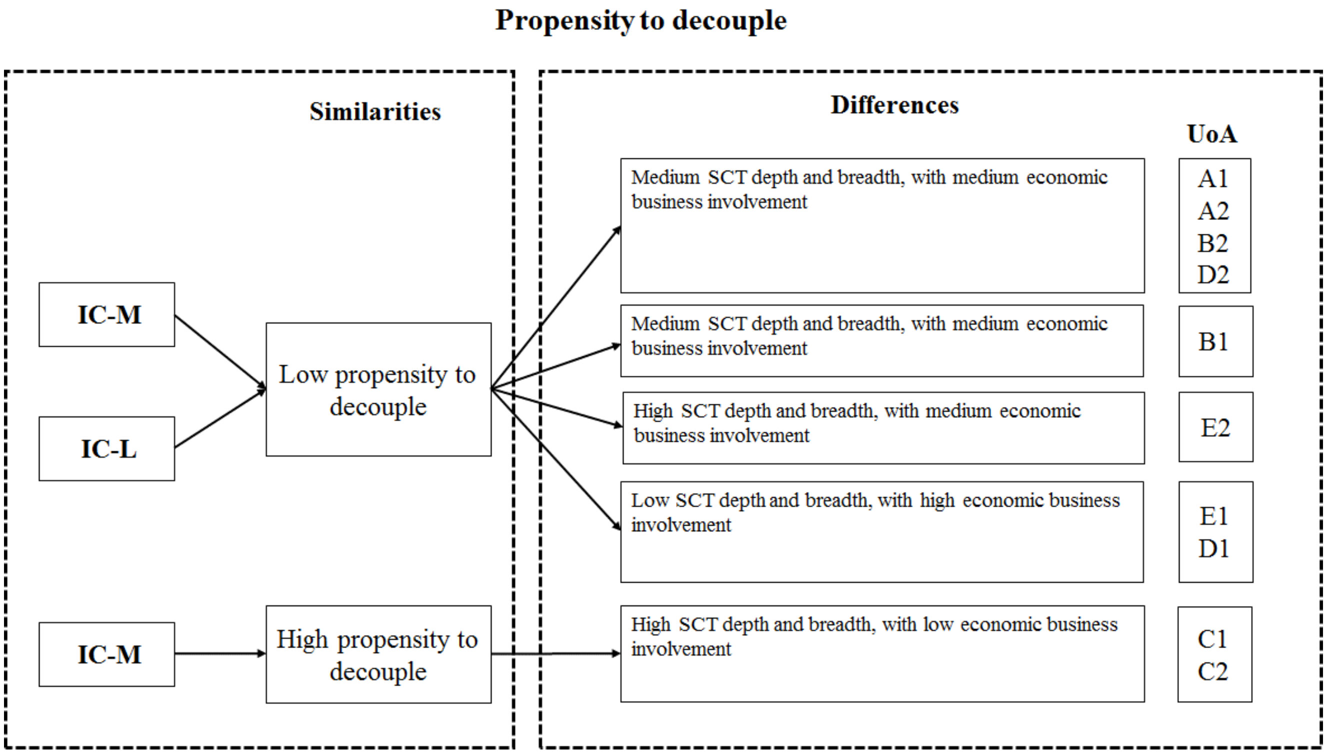


Figure 3-28. Propensity to decouple

PD is equally a strong causal link, supporting mirroring. IC-M has a low and high PD, whilst IC-L (tight coupling) has a low propensity only, shown below in Table 3-41. Low and high PD lead to mirroring. Low PD relates to tight to medium tight module interfaces, leading to medium SCT depth and breadth, with medium economic business involvement. High PD appears to relate more to standard components, and less to custom or customer-specific designed parts, as in the cases of D1 and E1.

Table 3-36. Propensity to decouple (PM – SCCM linking pattern)

Propensity to decouple

UoA	PM	Causal link	SCCM	Level of mirroring	Explanation of similarities	Explanation of differences
A1 A2 B2 D2	IC-M	Low propensity to decouple	SCT-M (medium depth and breadth, with medium economic business involvement)	High	IC is medium, for these four UoA. The products are required to discharge surgical staples (A1); accept single-use blood test strips (A2); provide ease of disassembly for product cleaning (B2), and provide ease of disassembly for product serviceability (D2), which contributes to medium IC. Most of the interfaces remain tightly coupled leading to a low propensity to decouple in general. This contributes to a redued depth and breadth of SCT and increases the level of mirroring.	
B1	IC-L (tight)	Low propensity to decouple	SCT-M (medium depth and breadth, with medium economic business involvement)	Medium	IC is tight across these UoA in general. These products range from medium to high complexity, which accounts for the low to levels of SCT present.	In the case of B1 interface coupling is tight, due to the tight product noise specification. There is medium depth and breadth since the OEM working with the tier 1 and tier 2 suppliers are required to deliver exceptionally tight component tolerances, on plastic, and metal parts, to deliver the product noise specification.
E2	IC-L (tight)	Low propensity to decouple	SCT-H (high depth)	Medium		E2 has a tight IC and low propensity to decouple due to the high level of system integration required. This requires multiple system integrators, which increases the depth of the supply chain.
E1 D1	IC-L (tight)	Low propensity to decouple	SCT-L (low depth and breadth, with high economic business involvement)	High		D1 and E1 are sub-assemblies. The low propensity to decouple contributes to sole sourcing of these UoA, which results in a low breadth of SCT, and a high level of economic business involvement. The low propensity to decouple also leads to fewer tiers in the supply chain.
C1 C2	IC-M	High propensity to decouple	SCT-H (high depth and breadth, with low economic business involvement)	Medium	IC is medium level but there is a high propensity to decouple across many interfaces due to many different systems in the car, from heating, to electrical, navigation, infotainment, seating, etc., which are more loosely coupled, leading to a high propensity to decouple, which contributes to a high number of tiers in the supply chain, and multiple sourcing. Multiple sourcing contributes to lower economic involvement.	

3.9.3.4. Life cycle perspective

Rapid advances in sensor and communications technologies are requiring designers to take an LC perspective on product and SCC design. The one PM attribute related to the life cycle causal link to SCCM is DA, shown below in Figure 3-29. DA links to all levels of SCT. Many new-to-market products do not have DA at the time of launch; however, the ability to add increasing DA during the PLC is a key consideration for the automotive and aerospace sectors. C1, C2 and E2 illustrate a high level of mirroring between PM and SCCM, with the life cycle perspective as the linking mechanism. D1 is sole sourced, for this reason there is a high economic business involvement by the OEM.

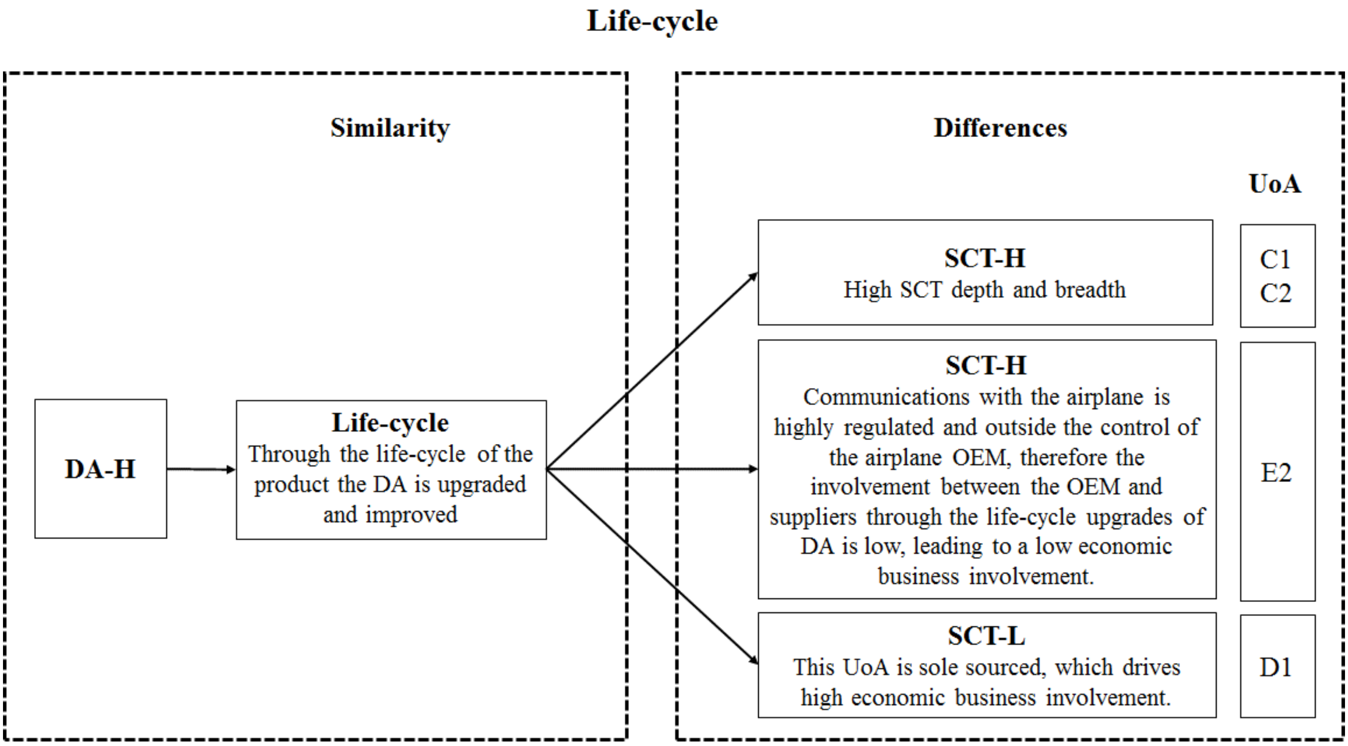


Figure 3-29. Life cycle perspective

The life cycle causal link relates to the DA attribute, shown below in Table 3-42.

Table 3-37. Life cycle perspective (PM – SCCM linking pattern)

UoA	PM	Causal link	SCCM	Level of mirroring	Explanation of similarities	Explanation of differences
C1	DA-H	Life-cycle	SCT-H (high depth and breadth)	High	C1, C2 and E2 are finished products. There is considerable evolution in electronics control, and data communications in both the automotive and aerospace sectors. Since these technologies require considerable development through the life of the product, a life cycle approach is required by these UoA to allow for product data access and upgradeability, as these new technologies develop. This contributes to a high SCT and a high level of mirroring.	Increased safety and smarter energy are some of the benefits of Vehicle-to-everything (V2X) technologies. The life cycle approach to DA contributes to a high depth and breadth of SCT because of field testing of these technologies, as they are released over the coming years. Further, with the advent of the software-defined car OEMs and Tier-1 suppliers need to have the tools and the platform necessary to enhance security in real time and in a seamless manner.
C2						
E2			SCT-H (low economic business involvement).	High		Satellite communications allows direct access to airplanes, with enhancements in sensor technology more functions of an airplane can be monitored from the ground. There is paramount focus on data security. In some instance for example in-flight entertainment airlines have taken back control from suppliers, standards are rigorous in managing this data control.
D1			SCT-L (high economic business involvement).	Low	D1 is the complete driveline for C1 and C2, it contains many control modules which require DA over the life cycle of the product.	For D1 a life cycle approach for DA contibutes to a high involvement by the OEM, since D1 is sole sourced with a tier 1 supplier.

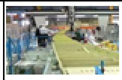
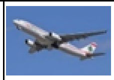
3.10. FINDINGS AND DISCUSSION

Prencipe and Brusconi's research into aero engines and other complex production systems identifies the critical importance of overlaps between product design, SCC and partners' knowledge bases, where the OEM company acts as overall knowledge integrator (Brusoni and Prencipe, 2001). A key issue for efficient Product and SC integration is the amount of common knowledge required for effective knowledge integration (Grant and Baden-Fuller, 2004). PM mirroring with SCCM requires integrative strategies for early sharing of knowledge and information with suppliers (Ragatz *et al.*, 1997). The SLR identified the requirement for mirroring; however, previous research fails to test this hypothesis due to the lack of development of the SCCM construct. Therefore, the first research question for the multiple case study research is research question two: *"how can SCCM be* *conceptualised considering modularity principles and contemporary supply chains?*", and the second research question for the multiple case study research is research question three: *"how is the mirroring of product modularity and supply chain configuration modularity manifested?"*.

3.10.1. Research question two

The development of SCCM attributes has been deduced from prior research, and empirically tested during project two, shown below in Table 3-43. These attributes take into consideration contemporary multi-tier supply chains and the delivery of product variety, in an efficient and responsive manner. The selected UoA provide a range of measures of the SCCM attributes. The selection of SCT as a mandatory SCCM attribute reflects the depth, breadth and geographic spread of contemporary supply networks, while economic and legal business involvement further relate to relationships within SCC networks. The selection of PRP as a mandatory SCCM attribute reflects the requirement for late stage product customisation and the provision of product variety in many contemporary supply chains. However, the research evidence shows poor mirroring links between PRP and PM, since PRP is primarily performed by individual companies, or tiers, in the SC. There are strong arguments within-case and across-case for the five SCCM attributes deduced from the literature.

Table 3-38. SCCM attributes or variables

Level of SCC modularity variables										
Company	Med device co.		Domestic appliance co.		Auto co.		Auto driveline co.		Aerospace co.'s	
Respondent	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
UoA										
Supply chain tiering	Medium	Medium	Medium	Medium	High	High	Low	Low	Low	High
Process postponement	Low	Medium	Low	Low	High	High	Low	Low	Low	High
Process flexibility	Low	Low	Low	Low	High	High	Low	Low	High	High
Process re-sequencing	Low	Low	Low	Low	High	High	Low	Low	Low	Low
Place postponement	Low	Medium	Low	Low	High	High	Low	Low	Low	Low

Given the limitations of process postponement (PRP) as mandatory attribute, described above, supply chain tiering (SCT) was taken as the main attribute in determining the overall SCCM level. SCT has four dimensions as defined by Hieber (2002). The higher economic and legal business involvement, the lower SCT modularity, while the higher the span of the network (depth, breadth and geographical spread) the higher the SCT modularity. The evidence across the four dimensions of SCT for the ten UoA were consistent with each other, except for geographical spread which was high compared to the overall SCT level of medium for A1, A2, B1 and B2, shown below in Table 3-44. Further, geographical spread did not feature in the mirroring causal links between PM and SCCM whereas the other three dimensions of SCT were affected by the mirroring of modularity. The conclusion is that geographical spread is not a relevant dimension of SCT modularity for contemporary supply chains.

SCT modularity and hence the network span, was high for C1, C2 and E2, all of which are the most complex and top-level cars and an airplane. For the other top-level products A1, A2, B1 and B2 which were much less complex SCT modularity was medium-level, whereas, for the sub-assemblies D1, D2 and E2, SCT was low.

The optional SCCM attributes; PF, PR and PP, plus PRP, relate to process agility (Feitzinger and Lee, 1997). These four attributes are high for C1 and C2, which require process agility due to the high levels of customisation and product variety required, whereas all the other products exhibited no process agility except for A2, E1, and E2, where some level of customisation was required. Low levels of process agility were found in the remaining A1, B1, B2, D2 and E1. These are standard products, using common parts, assembled and distributed using standardised configuration processes, requiring lower levels of process agility.

Table 3-39. OEM economic and legal business involvement in supply network

	Company	Med device co.		Domestic appliance co.		Auto co.		Auto driveline co.		Aerospace co.'s	
	Respondent	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
	UoA										
PM	Function sharing	Medium	Medium	Low	Medium	Medium	Medium	Low	Low	Low	Medium
	Interface coupling	Medium	Medium	Low	Medium	Medium	Medium	Low	Low	Low	Low
SCCM	Supply chain tiering	Medium	Medium	Medium	Medium	High	High	Low	Low	Low	High
	Process postponement	Low	Medium	Low	Low	High	High	Low	Low	Low	High
SCT is the primary SCCM variable	Depth of the network	Medium	Medium	Medium	Medium	High	High	Low	Low	Low	High
	Breadth of the network	Medium	Low	Medium	Medium	High	High	Low	Low	Low	High
	Geographical spread of the network	High	High	High	High	High	High	Low	Low	Low	High
	Economic and legal business involvement	Medium	Medium	Medium	Medium	High (low involvement)	High (low involvement)	Low (high involvement)	Low (high involvement)	Low (high involvement)	High (low involvement)

SCT is the primary SCCM variable

3.10.2. Research question three

Dyer (2000) indicates that 'in the cases where there is low margin for error in cost, quality, and customer service, a key predictor of product market success is the fit between PA and SCA'; this research expands on Dyer's claim, by investigating the level mirroring between PM and SCCM, post product launch, and understanding how mirroring is manifested at both a macro and micro-level. Three causal variables ESI, PD and life cycle approach were established between PM and SCCM.

At a macro-level mirroring is the extent to which SCC knowledge elements and the products, going through the SCC, vary from those of an ''ideal'' profile, or 'strategic type' (Zajac *et al.*, 2000). Holtta and Salonen (2003) mention decreased time to market as a benefit of mirroring PM with SCC without providing recommended modularity methods. The mirroring of PM and SCCM is investigated in this research, and forms the basis for addressing the existing lack of a framework for mirroring PM with SCCM (Agyapong-Kodua *et al*., 2012, p. 826). PA is composed of components and modules, which are interfaced to one another, through coupling. Similarly, SCC is composed of nodes and process activities at these nodes, which interface to one another through transfers of material, energy and information (Baldwin, 2008). The mirroring of these two constructs is addressing the 'ideal' profile, through which products are configured and delivered to their respective customers. There are two perspectives on mirroring taken in this study: macro level and micro level. Macro-level mirroring will be considered first, based on the modularity levels indicated by the PM and SCCM mandatory attributes, FS, IC, SCT and PRP, deduced from the literature.

At the macro level six of the ten UoA exhibit high level of mirroring, whilst four, the air purifier, aeroplane and cars exhibit a medium level of mirroring. The reasons for this medium level of mirroring are different. In the case of the automobiles they exhibit high levels of modularity on all SCCM attributes and medium levels of modularity on PM mandatory attributes. In the case of the airplane it exhibits high levels of modularity on the mandatory SCCM attributes, but low to medium levels of modularity on the mandatory

PM attributes. All three of these products are highly complex top-level assemblies and this contributes to the high levels of SCT and PRP. However, the PM level is medium rather than high due to interface couplings often being tight rather than loose, which is associated with modularity. For the cars and the airplane products the tight interface couplings are due to the level of system integration required to deliver the performance levels required by the market. For the air purifier there is a similar situation where PM is low due to IC being tight to deliver high product performance levels (low noise levels) but the SCCM is medium due to a medium level of SCT.

Whilst the mandatory and optional attributes were deduced from the literature, the optional attributes are not required in all cases. Mandatory PM attributes FS and IC are closely aligned as are the SCCM attributes SCT and PRP. IC is measured on a scale from tight to loose where loose denotes ease of de-coupling, whereas SCC coupling is measured against the levels of flexibility in the SCC process to meet the COEP. Higher levels of PRP combine with higher levels of SCT to deliver increased levels of SCCM. Loose IC is a pre-requisite for PRP (Mason-Jones *et al.*, 2000).

The drivetrain (D1), driveline (D2) and trailing edge for airplane wing (E1), which exhibit low modularity levels, exhibit mirroring between PM and SCCM. IC is tight for these high reliability, integrated sub-assemblies, and SCT is low. D2 exhibits low levels of modularity on all attributes. D1 exhibits a high modularity level only on the data access attribute, due to the requirement for communication with some of the integrated system electronics. E1 exhibits a high modularity only on PF, since this is a recently developed process technology using composite material for the body of this large airplane sub-assembly.

Three UoA with medium levels of modularity exhibit mirroring between PM and SCCM. The air purifier has tight IC, low FS, and low requirement for PRP, and exhibits a medium level of SCT. The automobile products exhibit a medium level of PM, and medium level of mirroring. The medium level of FS is required since there are multiple systems within the car, which are not directly related. The third UoA with medium levels of modularity, and medium level of mirroring is the airplane. It exhibits a medium level of FS, since many of the systems in an airplane are not directly related.

From a micro-level perspective, causal links were established between PM attributes and SCCM attributes. The primary PM linking attribute is IC and the primary SCCM linking attribute is SCT. FS and PRP did not feature in the causal links. However, it is clear from the evidence that FS and IC are synchronized with each other across all UoA except with the airplane. FS is medium rather than high because of the high number of independent systems, therefore IC appears to be closely linked to FS. PRP did not feature in any of the causal links but unlike FS it is not always synchronized with the other mandatory attribute SCT, with three UoA it is different. Further, while SCT is a multi-dimensional attribute which encompasses span of the SC and levels of involvement across the SC, PRP is focused exclusively within one tier or organisation within the SC. It therefore appears to be a poor indicator of SCCM, as supported by the lack of causal links with PM mandatory attributes.

The causal links are ESI, PD and life cycle. Knowledge codification whilst it supports mirroring and is a causal link it does not contribute directly to linking these attributes. The level of IC does not appear to impact the use of KC, and therefore does not drive mirroring. Based on the evidence ESI supports mirroring, in the case of the five case companies a low number of key suppliers in the case of the medical devices, cordless vacuum cleaner, auto-driveline and aero-structures companies tend to support a higher level of mirroring. In these five cases much of the innovation was internal, from the digital motor manufactured by the cordless vacuum cleaner OEM to the components and sub-assemblies manufacture by the auto-driveline and aero-structures company’s. Products with a low PD also appear to have a higher level of overall mirroring, where there is medium SCT depth and breadth and medium economic business involvement. Product’s with a high PD such as the cars illustrate a lower level of mirroring. The one PM attribute related to the life cycle causal link to SCCM is DA. DA links to all levels of SCT.

Therefore, ESI and PD are the two primary causal linking mechanisms, contributing to mirroring of these constructs. ESI relates to a small number of suppliers and reflects their core capabilities. SCT depth and breadth is medium not high, and the OEM's have a medium level of economic involvement. Many of these suppliers tend to become sole sourced suppliers for the components and sub-assemblies they supply. Both low and high PD lead to mirroring. Low PD relates to tight to medium tight module interfaces, leading to medium SCT depth and breadth, with medium economic business involvement. High PD appears to relate more to standard components, and less to custom or customer-specific designed parts, as in the cases of D1 and E1. ESI within the automotive sector is supported in the literature, interestingly C1 and C2 do not show a high level of PM mirroring with SCCM. With these UoA both FS and IC are medium level, there is mirroring of these attributes at the product level but not between the product and its SCC, since SCCM is high. The reason SCCM is high is due to the high level of SCT, since parts are sourced regionally and globally.

3.10.3. Research hypothesis one

Research hypothesis one, developed during project one, indicates that PM and SCCM tend to be mirrored in terms of modularity. Sub-assemblies D1, D2 and E1 achieved PM mirroring with SCCM prior to product launch; the SCCM make versus buy interfaces mirror the module BOM, and the products are standardised to the point where they do not consider optional attributes, except for DA with UoA D1. With these UoA production concerns drive the formation of modules rather than product design features.

E2 does not demonstrate a close relationship between mandatory PM attributes at product launch. There are medium to high levels of SCT and PRP at launch for E2. The PM attributes for E2 migrated to a closer relationship through successive engineering changes, post product launch.

The TLA products require higher levels of SCT and PRP due to their regional and global supply networks, and demand for late stage customisation, post COEP. As many products migrate to platform designs, the aim is to provide increasing product variety, driving increased PM mirroring with SCCM. Where there is a low level of PM to SCCM mirroring, SCCM is generally at a higher modularity level than PM, indicating that further customer centric design focus is achievable, through follow-on variants of these UoA focusing on increased levels of PM. For example, the assembly processes for A1 have become increasingly automated since product release in 1995. The level of SCT has increased since product release in 2009 for B2, indicating an increase in SCCM for these UoA, see Table 3-45. With B1, there are opportunities to combine plastic and metal parts which will increase the level of PM, and reduce the number of module and component interfaces. Recent variants of B1 have incorporated DA, which requires increased levels of PM. With B2, opportunities exist to increase PM by reducing the number of glue joints in the design.

Wolter and Veloso (2008) make an argument for PM, in pointing out the obsolescence risk and the need to preserve outside options creates forces, causing fragmentation. Organisations and industries experiencing modular innovations may have a propensity to break apart. Helfat and Campo-Rebado (2009) show that vertically integrated organisations may choose to stay integrated, even when the underlying technical system is modular, if they anticipate that the designs will become reintegrated later.

There are ongoing discussions within these companies with respect to further increases in the levels of process automation, and increased SCCM. In summary, there is strong evidence that hypothesis one is positive, and both PM and SCCM tend to be mirrored post product launch. This conclusion is supported by research on PM and SCCM at an industry level (Fine, 1995). Fine's double-helix model illustrates how industry and product structures evolve from vertical/integral to horizontal/modular and back (Fine, 1995, p. 63). Fine and Whitney (1999) analysed OM at four levels: 'intra-company'; 'inter-company'; 'supply network'; and 'industry', in the context of make versus buy decisions. They study PA along the modular-integral spectrum, viewing integral SCC as vertically-integrated with a single company owning the SC and modular SCC as horizontal and disintegrated. They view SCC as continuously integrating and disintegrating.

3.11. CONTRIBUTIONS

Project two addresses the conceptualisation of SCCM. This empirical research has developed a better understanding of the manifestation and tendency towards mirroring, between PM and SCCM, including the identification of causal links, and a description of how these links work. This increased understanding contributes to both literature and design practice.

3.11.1. Contributions to research

Project two makes three contributions to the literature with the: 1) development of the SCCM construct allowing hypothesis one to be tested, using systems and knowledge-based theories; 2) development of an understanding of the manifestation of mirroring between PM and SCCM, and a discussion of where hypothesis one is supported and where it is not supported, and 3) identification of causal links between PM and SCCM. The case studies illustrate the roundabout nature of the development process of new product and SCC design rules. This research supports the sequencing (tie-patterned scheduling) of knowledge creation, storage and use, by individuals in the NPD process, building on the work of Grant (1996).

The first contribution to research, is the development of the SCCM construct with the axiomatic design framework developed by Suh (1990) taken as a start point in developing the SCCM construct. This framework focuses on the interrelationships between the product, SCC, physical domain and the customer. Modular design allows for decoupling of the SCC sequence, SCC form, process and place post-postponement. Companies that develop design-driven innovations step back from user requirements to take a broader perspective on SCC. The context in which products are being used is changing, with technologies, products, and services are shaping the context. With PM two mandatory attributes function sharing and interface coupling (Ulrich, 1995; Baldwin and Clark, 2000) represent the functional product requirements. From this finding it was decided to select the two mandatory attributes that represent SCC process attributes. The attributes deduced from the literature are supply chain tiering (Hieber, 2002), and process postponement (Khiang *et al.*, 2004). SCT and PP are relational assets to function sharing and interface coupling, since products are built and configured within different geographic, time and sequence domains. Suh takes the physical context constraints and customer requirements in to consideration. These are incorporated in to this research by optional PM and SCCM attributes or indicators. The optional PM attributes deduced from the literature cover limited life, data access, and product use modularity types (Arnheiter and Harren, 2005). The optional SCCM attributes are required to support this modularity typology.

SCT is the main indicator of SCCM as it spans the supply chain, where process postponement is confined to a single supply chain tier, and is only present where there are high levels of customer configuration. The optional SCCM attributes deduced from the literature are process flexibility, process resequencing, and place postponement (Feitzinger and Li, 1997). These were selected to address the requirements for accessibility, flexibility, integration and responsiveness in contemporary supply chains.

The second contribution, is the development of an understanding of the manifestation of mirroring between PM and SCCM. This research evaluates the mirroring of PM and SCCM, using KBT to address the knowledge required to mirror these constructs, after Fixon (2005). The empirical research in project two illustrates that PM is manifested through interface coupling and SCT. For example, a high-level of mirroring is manifested as loose product interface coupling and a high-level of supply chain spread, with low legal and economic involvement, by the focal company, with tier-one, and lower-tier companies. Product interface coupling is closely related to function sharing, with loose interface coupling associated with low levels of function sharing.

Hypothesis one is upheld for six UoA. The research discovered two situations where H1 does not apply, and where interface coupling and SCT are not mirrored. The first is where there is a pre-existing SCC delivering modular products. This research upholds and expands on the observation of Novak and Eppinger (2001), who use the property rights approach to argue that complexity in product design and vertical integration of production are complements. Companies often launch complex new to market products in existing SCC to capture the benefits of their investment in the skills needed to coordinate the development of complex designs. The product specification is integral and does not lend itself to decoupling. In this single case there was an absence of ESI, and the supply chain life cycle was not taken in to consideration. Sorkun and Furlan (2016) made a similar observation in stating that low levels of PM and SCCM lead to transactional inefficiency, and advocate the benefits of mirroring in driving efficient NPD and SCC.

The second situation, is applicable to products which offer a high level of customer configuration, and is supported by high levels of process postponement, with high SCT spread. The interface coupling is not loose as might be expected, due to the high levels of functional performance required.

The empirical research confirms that at the top-level of the product assembly, low levels of PM and SCCM are not observed in practice, confirming the work of Ülkü and Schmidt (2011), except with process industries, which are outside the scope of this research. Low levels of PM and SCCM are observed at lower levels of the product assembly. The research confirms that SCCM offers defined module interfaces, supporting knowledge sharing throughout the product life cycle (Chandra and Grabis, 2016; Cabigiosu and Camuffo, 2017).

The third contribution, is the identification of the causal links between PM and SCCM. Results show that the mirroring hypothesis is contingent on a set of three distinct, although interdependent, causal links: 1) propensity to decouple modules; 2) early supplier involvement, and 3) product and SCC life cycle alignment. A low propensity to decouple modules leads to a high proximity in SCT, whereas a high propensity to decouple leads to a lower proximity in SCT.

ESI exists for all the UoA, which belong to regulated industries. Within these industries ESI is not just about avoiding costly recalls, penalties, and lawsuits, it is integrated with broader supplier governance and relationship management. ESI within these regulated industries depends on knowledge codification, to prevent I.P. infringement. ESI where interface coupling is tight focuses on application specific design inputs, whilst ESI where interface coupling is medium focuses on early supplier selection and qualification, and a broader spread of the SCT. These findings build on the work of Petersen *et al.* (2005) who posit that ESI in setting business metrics and targets for the NPD project are positively associated with NPD team effectiveness.

Nepal and Monplaisir (2009) using a multi-objective optimisation model attempt to balance the trade-off between cost minimisation and maximising the compatibility of members of the supply chain. This research assessed the knowledge that is required to be exchanged between NPD and SCC, at the concept stage using multi-objective optimisation models. The life cycle perspective takes a longer-term view on knowledge integration. For new to market products life cycle planning focuses on specific life cycle requirements following user needs and technology capabilities.

KBT was used during project two to create new knowledge (Hakanson, 2010). Product and SCC architectures are constantly dealing with mechanical, electrical, power, electrostatic discharge, data and other product interfaces, and with organisational, economic, legal, electronic, cultural, and other SCC interfaces. The causal links address these interfaces, and mirror them, at the concept design stage. The PM mirroring with SCCM framework potentially leads to further strategic knowledge development and technology development from component to the top-level assembly.

There is a low to medium-level of SCC involvement with the automobiles and domestic appliances, at the concept stage. MacDuffie (2013) maintains that the formation of modules in automobiles is driven by production concerns rather than product design features. This claim is supported by this research. This partially explains the low involvement of SCC at the product concept stage, as much of the SCCM focus is on production design.

This research identifies situations where hypothesis one is less desirable. The expectation was that there would be a high-level of mirroring for the automotive company, since there is a significant amount of outsourcing of design, production and customisation in this sector. However, the complete modularity integration has not become standard yet. This research supports the findings of Pandremos *et al.* (2009), in identifying a medium level of mirroring, at the top-level of automotive product design, where FS and IC are medium-level, and where SCCM is strong. This finding is supported by research which emphasises rapid, innovative vehicle design; a high degree of outsourcing with key suppliers, and high levels of trust with these suppliers, enabling support for inter-operability, and cost reduction through supplier innovation (Dyer, 2000). These elements work together in building strong SCCM. The automotive company offers a high-level of generalisability in terms of strengthening hypothesis one, supported by the auto-drivetrain company which provides the bus architecture. In addition to building internal PRP, external partners are also selected to provide post COEP product customisation services.

Hypothesis one is less desirable for fast-follower products at the concept stage, with low ESI and propensity to decouple. Where prospector companies who produce innovative technology take an aggressive new product-market position within broadly defined markets, and tend to be industry pioneers in the creation and development of new SC technologies (Walker and Ruekert, 1987, p. 16), fast follower companies are content to learn from these prospector companies, and focus less on speed to market, but technology development followed by NPIR. These UoA illustrate a low-level of PM mirroring with SCCM. This research argues that fast follower companies may not be able to launch product in a transactionally efficient manner if they fail to design for modularity at the concept stage.

3.11.2. Contributions to practice

Project two identifies three primary contributions to practice, the contingent factors that should be incorporated in to a mirroring framework; the identification of risks that require a focus within the mirroring framework, and the identification of different levels of PM mirroring with SCCM.

The first contribution to practice takes in to consideration that whilst six UoA support H1, four UoA reject this hypothesis, whilst the research settings were similar. The mismatches between PM and SCCM are caused by contingent factors that hinder the ability of PM to shape SCCM. This finding is consistent with research by D'Adderio and Pollock (2014). These contingent factors represent additional attributes or variables that intervene in the adjustment process between PM and SCCM. Improved quality, reliability, and cost at product launch, is achieved by considering the contingent factors: 1) complexity of the product architecture, high complexity requires increase levels of modularity and mirroring; 2) customer requirements definition at the concept stage; 3) SCC performance assessment at the concept stage for closed-loop SCC; 4) level of SCC process capability within the supply network, higher levels of capability encourage increased levels of modularity and mirroring, and 5) FAC at the product concept stage.

The second contribution to practice, is the identification of risks associated with mirroring PM with SCCM. An expropriation risk can persist at any point where innovators must disclose information to external providers of SCC functions that must be implemented to deliver a product innovation to market. It is at the concept stage that patents can be especially potent. Kenneth Arrow drew attention to this sensitive post-invention but pre-commercialization juncture by describing a dilemma that has since become known as 'Arrow's Paradox' or the 'disclosure paradox' (Arrow, 1974). A second risk may arise where intense component technological change calls for collaborative relationships with suppliers and SC partners, regardless of the PA. If companies fail to recognise this, they might develop market relationships that do not curb high transactions costs associated with the uncertainty of the environment and the opportunism of suppliers. A third risk relates to the loss of coordination among organisational units, or companies involved in product development. Complex and innovative product architectures require tight integration between the units that develop the different modules (Sosa *et al.*, 2004). If managers do not build strong links between development units, coordination is likely to suffer, and errors or performance penalties are likely to occur.

This third contribution to practice, relates to the identification of different levels of PM mirroring with SCCM, which indicate different expectations form the mirroring process. Innovative product technologies in general, require low levels of mirroring at product launch. Low-level product assemblies in general require low levels of mirroring at product launch. Fast-follower products in general do not necessarily require mirroring at product launch. Top-level assemblies which have high levels of SCCM, in general require low to medium levels of PM, to balance serviceability, product performance and reliability. Non-configurable regulated products in general require medium-levels of mirroring at product launch.

3.12. LIMITATIONS

Project two has limitations that should be discussed. One of these limitations is that it was conducted over a two-year period, during which some UoA were launched and underwent changes in PA and SCA post-launch that strengthened the 'mirroring' hypothesis. These temporal changes fell outside the scope of this research. The single temporal dimension of this research did not allow the research to capture changes to hypothesis one, as products evolved through the Stage Gate® process.

This work contributes to managing the NPIR for new to market products, with certain limitations, the first is its generalisability. The research sample is limited to ten UoA, from the manufacturing sector. Further research may expand on the number of UoA, and include service industries. Greater generalisability requires research into a larger number of companies, with varying product concept development times.

Another limitation might arise from researcher bias as is the nature of qualitative research. The researcher has broad experience with and an informed opinion about produce and SCC designers and this cannot be eliminated from the analysis and synthesis of the research.

A further limitation relates to contextual factors; all companies are large MNC's and market brand leaders, further research might include small to medium sized companies. These 'prospector' companies are all high performing entities who effectively manage responsiveness, quality of knowledge, knowledge access, knowledge intensity, and learning capacity. Prospector supply chains must adopt a problem-solving orientation while also drawing extensively on knowledge embedded in the SC. The results represent an innovative product portfolio. Different levels of product innovativeness may have a moderating effect on the use of the PM mirroring with SCCM framework.

3.13. IMPLICATIONS FOR FURTHER RESEARCH

Whilst the findings of this study significantly advance the conversation regarding how SCC and NPD knowledge can be mirrored, there are interesting questions left to pursue. If PM mirroring with SCCM is influential how can it come about? What role to intervention mechanisms, applied at the concept product development stage, play in supporting and strengthening the mirroring process?

Extending this study by investigating these intervention mechanisms was the objective of project three, described in the next chapter. During project three, KBT will focus on knowledge exchange processes within the knowledge-based (epistemic) communities of NPD and SCC (Hakanson, 2010), using CD, FC and FAC mechanisms. The purpose of project three is to strengthen the mirroring of PM with SCCM, demonstrating the effect of intervening mechanisms in mirroring PM and SCCM. Systems thinking usually refers to nonlinear systems where through intervening CD, FC, FAC mechanisms the evolution of the system is possible, and the system can display emergent properties. Project three considers the intervening mechanisms, or sustaining principles that can be applied when designing for (parts of) a circular system to ensure mirroring of PM with SCCM. Research question four: "*how do co-development, feedback control and feedforward control systems affect the mirroring of modular product design and modular supply chain configuration after product launch?*", seeks to identify the levels and types of systems control suited to mirroring PM with SCCM. The effect of these intervening mechanisms on the causal relationships between PM and SCCM is the basis of the three research hypotheses, which are tested in project three.

3.13.1. Research hypothesis two

Co-development (CD) of PA and SCC leads to enhanced mirroring between PM and SCCM. Co-development at the concept stage includes product specification, supplier selection, materials selection, experimental product and process design, and the construct of a meta-model relating suppliers' characteristics and SCC costs.

3.13.2. Research hypothesis three

The mirroring between PM and SCC is enhanced by systems FC at the conceptual product development stage. Fast feedback loops at the concept stage is required to influence subsequent choices. Feedback permits NPD teams to operate NPD effectively, and efficiently adapt to unpredictability.

3.13.3. Research hypothesis four

The mirroring between PM and SCC is enhanced by feedforward anticipatory control (FAC) at the conceptual product development stage. Feedforward anticipatory control at the concept stage adopts a systems approach to dealing with such areas as globalization and resilience related challenges. FAC is needed to design complex supply chain networks, with increasing numbers of entities and relationships.

SECOND EMPIRICAL STUDY

PROJECT 3

4.1. INTRODUCTION

Project one, identified the requirement for KBT to strengthen the mirroring of PM with SCCM, due to the inability of GST to handle extreme complexity, and more critically overcome the conservative bias of the systems perspective. KBT contributes to the mirroring hypothesis by integrating and aggregating PM and SCCM knowledge. Within supply chains other assets cannot easily be substituted for knowledge (Hult *et al.*, 2004). As discussed in project one, modularity is a strategic approach to NPD that can be used to increase the variety of products with improved delivery and flexibility (Lau *et al.*, 2007). As deduced in project two, NPD and SCC capabilities involve knowledge codification, protection and exchange. Project two uncovered risks associated with a lack of mirroring of PM and SCCM, and makes the argument for the development of a mirroring framework. Sorkun and Furlan (2016) highlight several risks in failing to recognise 'the effects of contingency factors on the alignment between organisational and PA'. The manifestation of mirroring discussed in project two and the findings of research question three provide the foundation for the empirical research in project three.

Research question four includes three intervening mechanisms deduced from project one: 1) CD of PM with SCCM at the product concept stage; 2) FC at product launch; 3) FAC at product; and three additional factors which emerged from the research that followed inductive strategy; 4) supplier capability and early involvement; 5) complexity of information exchanged, and 6) codifiability of PM and SCCM knowledge. Research question four: "*how do co-development, feedback control and feedforward control systems affect the mirroring of modular product design and modular supply chain configuration after product launch?",* seeks to determine the effect of intervening mechanisms in strengthening the mirroring relationship between PM and SCCM. Project three builds on the work of Gereffi *et al.* (2005), who found that global value chain linkage patterns can be associated with predictable combinations of three distinct variables: 1) the complexity of information exchanged between value chain tasks; 2) the codifiability of that information; and 3) the capabilities resident in the supply base. Project three tests the level of involvement of intervening mechanisms, deduced in project one, and the levels of these mechanisms in strengthening PM mirroring with SCCM.

Backward and forward compatibility is often a problem for product and SCC development because companies generally have static knowledge bases. A company can choose to provide backward and forward design and SCC compatibility to component suppliers. The objective of project three is to identify conditions where CD, FC and FAC strengthen the causal links between PM and SCCM, improve NPD and SCC mirroring, and address knowledge disclosure, SCC collaboration and co-ordination risks, identified in project two, shown below in Figure 4-1.

Project three discusses each contingent factor, listed in Section 1.4, Page 32, highlighting approaches that can be used in conjunction (not in contrast) with the modularity theory to explain the PM mirroring with SCCM hypothesis. A contingent view reconciles the two opposing views of the mirroring hypothesis, enhances its ramifications for the theory of the company, and provides insights for practitioners. The level of common bus modularity present in the PA, and the COEP emerged from the level-three coding as key independent variables however, these variables are not sufficiently strong to warrant further research.

Concurrent development means developing the product and all its associated process, that is, manufacturing, service, and distribution, at the same time. This definition highlights two essential elements of CD: synchronous communication and cross-functional integration (Swink, Sandvig, and Mabert, 1996). Blackhurst *et al.* (2005) recognise benefits in configuring supply chains concurrently with NPD at the product concept stage. “The concept stage marks the transition from the problem space to the idea or solution space” (Burchill and Fine, 1997, pp. 466-7). There are however inherent underperformance risks associated with relying solely on CD; for this reason, the addition of FC and FAC is required to control the NPD control system. CD does not necessarily pick up on risks associated with SCT. *“Sometimes airplane manufacturers take over the supplier, to ensure continued or improved supply, if the OEM fails to have a* *positive influence over that supplier",* interviewee for UoA E2. With multi-tier supply chains, it was discovered in project two that it might be necessary to take a direct role in managing lower tier suppliers.

FC is required to evaluate how effectively NPD goals are met, and allow NPD management to meet NPD objectives. The downside of FC may be time lag, depending on when feedback occurs. The product design may have transitioned past the concept stage before design feedback is received. FAC complements FC by focusing on system inputs. FAC monitors inputs which are known to affect system output and uses these inputs to prognose and feedforward corresponding control actions to counter any disturbing actions encountered. Where FC represents a form of closed loop, FAC represents a form of open loop control system.

The NPD concept stage concludes with the concept selection, in an iterative process of combining and improving product concepts. Since product and SCC ideas are clarified and developed further during the detailed product design stage, the scope of the empirical research in project three is extended to the detailed product design stage. Descriptions of the CD, FC and FAC intervening mechanisms are shown below in Table 4-1. Appendix 4-1, Page 460 shows the links between project one and project three.

Table 4-1. Construct descriptions

Intervening mechanisms	Description	Source of reference
Co-development	Co-development is the early involvement of a cross-functional team in a process to plan product, process, and manufacturing activities simultaneously. It has been operationalized to include cross-functional teams, concurrent workflows, and early involvement, Koufteros et al. (2005, p. 334). Co-development is "intended to cause the developers, from the outset, to consider all elements of the product life cycle from concept through disposal, including quality, cost, schedule, and user requirements" Institute for Defense Analyses (IDA) Report R-338.	Koufteros, X.A., *et al*. (2005) "Internal and external integration for product development: The contingency effects of uncertainty, equivocality, and platform strategy", *Decision Science*, Vol. 36, No. 1., pp. 97-133.
Feedback control	Feedback is information about the gap between the actual performance level achieved and the reference performance level set, in a closed-loop system. It looks at lagging indicators. The stage-gate® model establishes control at the gates.	Ramasprasad, A. (1983) "On the Definition of Feedback", *Behavioural Science*, Vol 28, No. 1, pp. 4-13.
Feedforward anticipatory control	Feed forward planning and control or anticipatory control in which preventative action is taken before the difference between planned and actual performance occurs. It looks at leading indicators. The Stage-Gate® model establishes control during the stages. It includes anticipatory feedback; anticipating deviations; anticipatory control; expected profitability of outputs; expected outcomes; anticipating needs and trends.	Koontz, H. and Bradspies, R. W. (1972), "Managing through Feedforward Control", *Business Horizons,* Vol. 15, No. 3, p. 25.

Research question four is an exploratory question rather than quantitative, and is appropriate for the case study method (Yin, 2014). Case study research is continued during project three to develop and test the confirmability of hypotheses two, three and four. Case study research produces findings relevant and useful to practice. Case studies use interpretive data, and adopt an existential philosophical approach to generating knowledge (Mitroff and Mason, 1982; Meredith *et al.*, 1989). The three hypotheses look at the use CD, FC and FAC as an overarching conceptual framework for mapping PM with SCCM, and assessing the use of these intervening mechanisms in achieving PM mirroring with SCCM, shown in Figure 4-1.

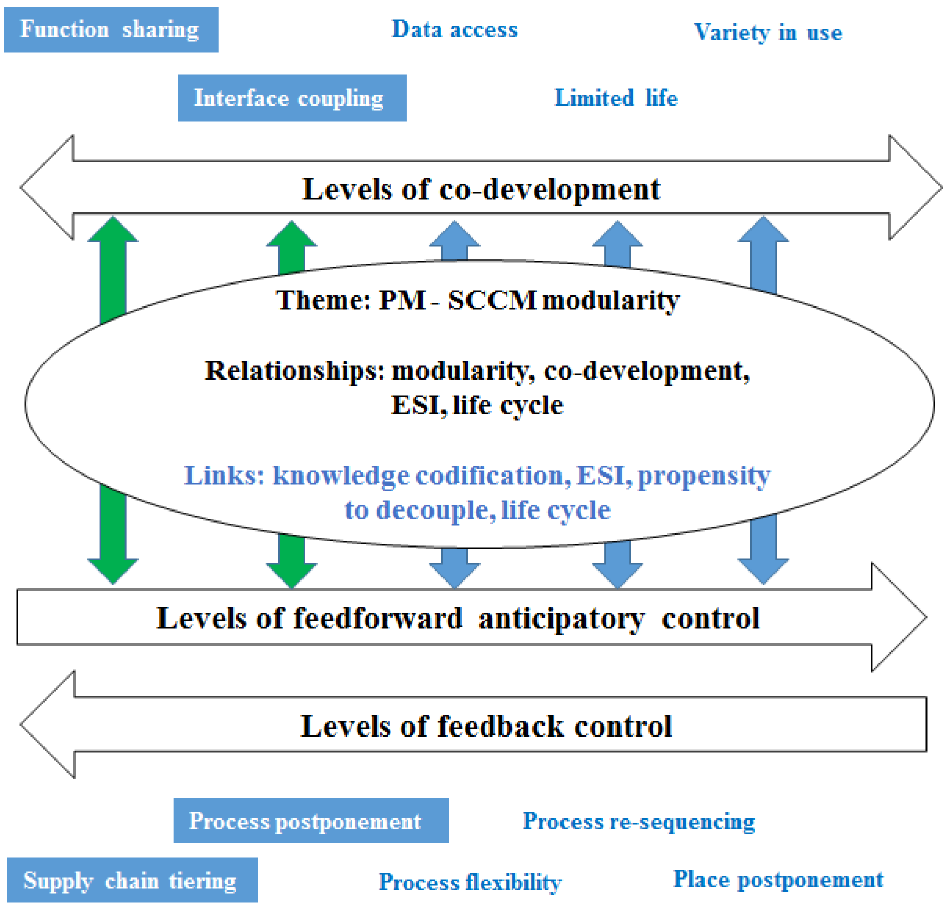


Figure 4-1. Intervening mechanisms deduced from literature

NPD requires inter-company multi-disciplinary teamwork, and knowledge exchange. Upgrading multiple modules simultaneously is difficult, and requires fluid task structures that emphasise experimentation, design testing and validation. Because of the increasing pace of technology change, hidden interdependencies can pop up unexpectedly, such as the emergence of a new company or change in regulation, which create new interdependencies mid-process (Tjosvold, 1986). Modular PA offers defined module interfaces, supporting independent design and manufacturing (Baldwin and Clark, 2000). Modular SCC offers defined SC interfaces, supporting PM.

Many companies have embedded co-development and concurrent design thinking into their SCC processes (Khan *et al.*, 2012); however, previous research considers SCC late in the product design process. The systems approach stresses there are inputs and outputs, and feedback and feedforward loops at each stage of the process (Wiener, 1950, 1953; von Bertalanffy 1950). Koontz and Bradspies (1972) adopted FC and FAC systems; to the development of a NPD portfolio, using the Stage-Gate® process (Baker and Bourne, 2014, p. 43), as shown below in Figure 4-2.

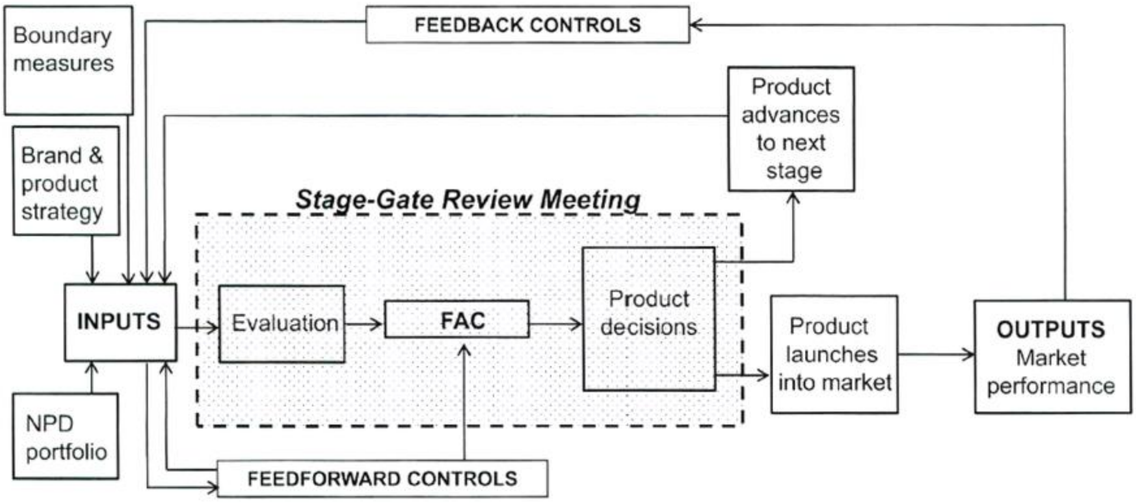


Figure 4-2. Product review control system
Source: Baker and Bourne (2014)

Since product and SCC ideas are developed further during the detailed product design stage, the scope of the empirical research in project three focuses on the period from concept development to post product launch, shown in Figure 4-3.

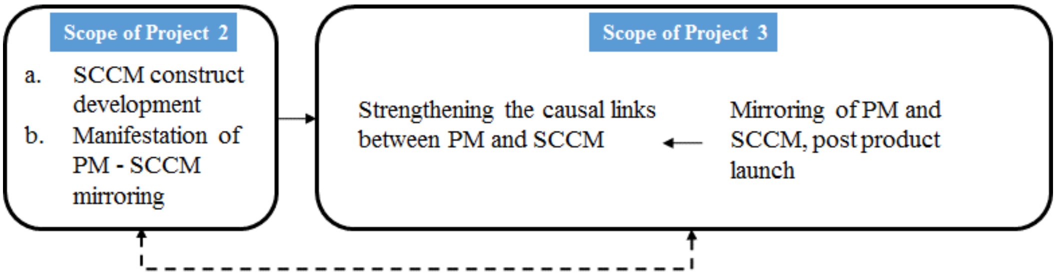


Figure 4-3. Scope of Project three

4.1.1. Rationale for project three

Project two identified arguments for the use of intervening mechanisms in the mirroring of PM with SCCM. Sorkun and Furlan (2016) indicate that a low level of mirroring between PM and SCCM can lead to transactional inefficiency. The first argument for concurrent mirroring of product and SCC module interfaces, is in reducing the expropriation risk and building IP protection. Complex relationships between NPD and SCC require a micro-level focus on modular design; modular interface development, and IP. KBT supports information hiding as a means of controlling complexity. With the automobile, each module is informationally isolated, which partially explains a fifty percent reduction in the concept to launch cycle time for C2. Information hiding led to the aerospace company being able to outsource the NPD and SCC for the fixed trailing edge wing for E2. This argument supports the requirement for CD amongst organisational units involved in conceptual NPD. Complex and innovative PA require a tight integration between the units that develop different modules (Sosa *et al.*, 2004).

Hypothesis two proposes that *co-development of product architecture and supply chain configuration leads to enhanced mirroring between product modularity and supply chain configuration modularity.* If managers fail to recognise the concurrent nature of design and build strong links among development units, coordination is likely to suffer; performance errors and penalties are likely to result. The notion that PM and SCCM knowledge can be protected by breaking it up requires CD, FC and FAC. In many sectors, including medical devices, product and process concepts require early validation.

"Because of process settings differing between what in effect are similar production lines, it is important to first validate a product concept in one process, until it is proven", interviewee for A2. *"Performance testing is part of the requirements gathering prior to concept development",* interviewee for A2.

The second argument for intervening mechanisms involves intense component technological development and the requirement for early component performance feedback. Digital design, testing and simulation are common in automotive and aerospace, where there are a multitude of design iterations to be considered at the conceptual NPD stage. The domestic appliance company took 5,127 prototypes and five years to perfect the dual cyclone used in developing B2, this led to 'possibly the world's most efficient and power-dense digital motor' (O'Brien, 2015). Companies are under increasing pressure to reduce the new product introduction rate (NPIR). *"It is a pretty catastrophic situation if one moves the product introduction date, timelines are pretty tight",* interviewee for D1. Combining CD, FC and FAC, reduces transaction costs associated with the technology and market uncertainty. Hypothesis three proposes that *the mirroring between product modularity and supply chain configuration is enhanced by systems feedback control, at the conceptual product development stage.*

The third argument for intervening mechanisms relates to continuous technology change, and globalised supply networks. *"With global networks localised manufacturing must be considered at the concept stage, for product validation purposes, this is new for our company",* interviewee for C1. For new-to-market products, there is a time delay in assessing these changes. Companies are adopting visioneering, boundary controls and FAC at the conceptual stage to improve NPD, to increase the prospects of product success. FAC measures that look ahead to assess future performance or target outputs, shown above in Figure 4-2. FAC has been defined as "anticipatory control in which preventative action is taken before the difference between planned and actual performance occurs" (Ishikawa and Smith, 1972, p.166). Hypothesis four proposes that *the mirroring between product modularity and supply chain configuration is enhanced by feedforward anticipatory control, at the conceptual product development stage.* The originality of the model proposed is in the tagging of knowledge modules that support the mirroring of PM with SCCM. "*Product concept definition is tied to the technology release level (TRL) at phase gate zero, here the product becomes more scientifically proven, and becomes more applicable to the product",* interviewee for UoA A1.

A fourth argument for the use of intervening mechanisms relates to product complexity, rapid product obsolescence; the emergence of new markets, and increased market and technology uncertainty (Sanchez, 1995). These factors require rapid resource allocation during the early NPD concept stage. *"What complexity does is if anything it tends to mean we have to be much more structured in the way we design. We must make sure we understand the impact of the changes in the way we design. We have to make sure we understand the impact of the changes and the behaviour we might introduce in a new product",* interviewee for D1. The trade-off between accelerated time-to-market and product performance is of continuing concern. Accelerated new product introduction rates (NPIR) may lead to improved time and performance of new product development activities (Nepal *et al.*, 2005), and market share gain (Brown and Eisenhardt, 1995), on the other hand reducing NPIR is only advisable when this does not limit the probability of success of the final product (Griffin and Page, 1993).

4.1.2. Structure of paper three

This paper is structured as follows: Section 4.2 discusses theoretical positioning and the intervening mechanisms; Section 4.3. discusses the research design, case selection and research strategy; Section 4.4. addresses the rigour applied in the case studies and data collection; Section 4.5. provides the research findings and discussion; Section 4.6. discusses the contributions of the three research hypotheses; Section 4.7. provides recommendations for further research.

4.2. THEORETICAL POSITIONING

Despite early attention, little has been published on coordinated product and SC design (Lee and Sasser, 1995; Joglekar and Yassine, 2001). An integrated systems framework emerged from the SLR as the preferred framework for mirroring PM with SCCM, shown below in Figure 4-4. Companies that face rapid technology and market changes must adopt an organisational design that is efficient in acquiring and processing knowledge. Wheelright and Clark (1992) describe an organisational design as an 'integrated problem solving' approach which includes an early involvement of constituents who belong to a cross-functional team and work concurrently across the different phases of product development. Adopting a systems theory to develop the three research hypotheses, reinforces that systems are forward and reverse focused: open and closed, circular and non-circular, observable and non-observable in design.

The systems perspective emphasises the importance of connectivity and multivariable cause-and-effect relationships. In practice, several FC and FAC loops may occur simultaneously, in parallel, in series, or in parallel and series combinations. Time delays in NPD or SCC development necessitate the use of FAC, which represents a form of open loop control. The intervening mechanisms CD, FC and FAC are deduced from the literature, and incorporated in the conceptual framework model. The mirroring hypothesis is itself an intervening mechanism for coordinated product and SC design, shown below in Figure 4-4. CD is the prevalent intervening systems control mechanism, shown in Appendix 4-2, Page 461.

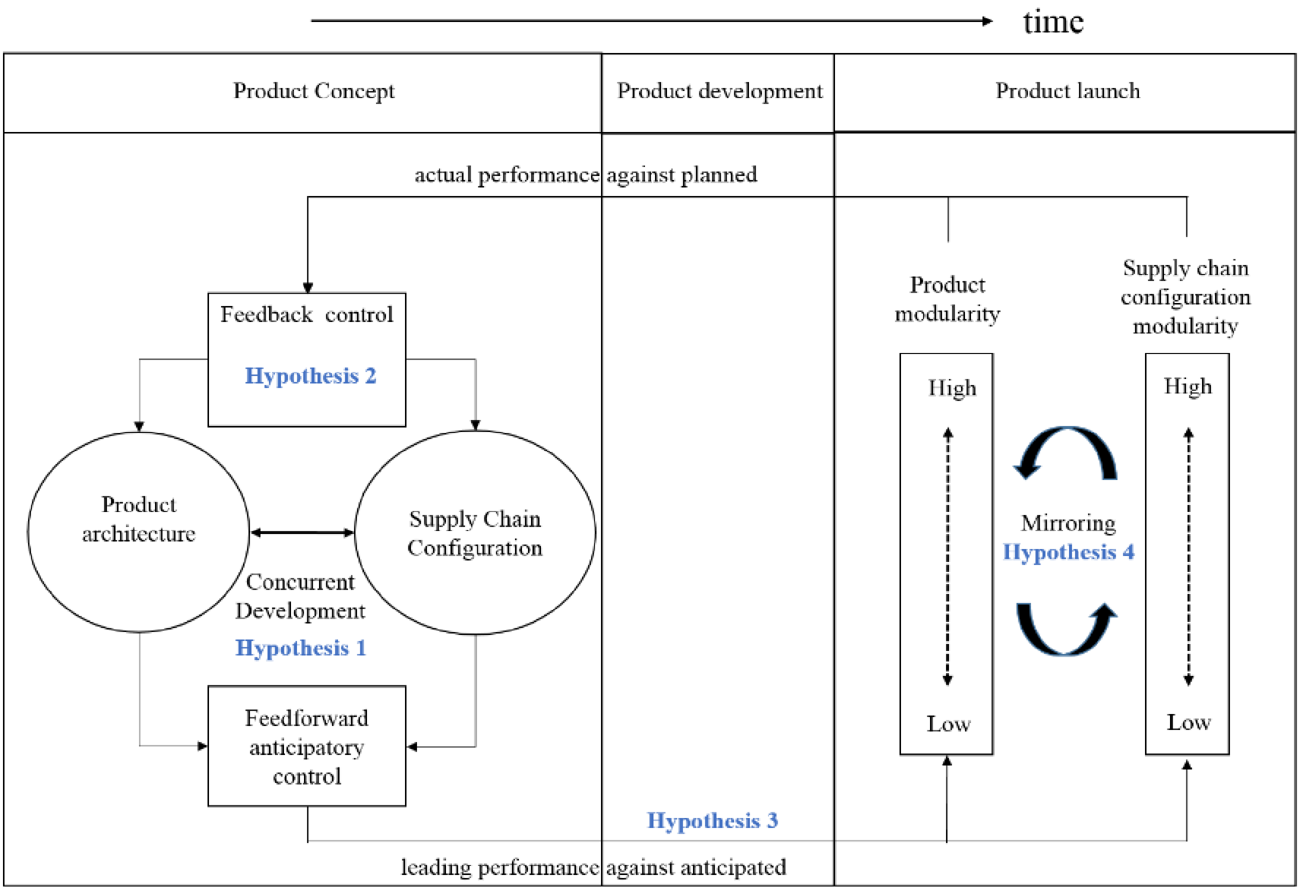


Figure 4-4. Research hypotheses

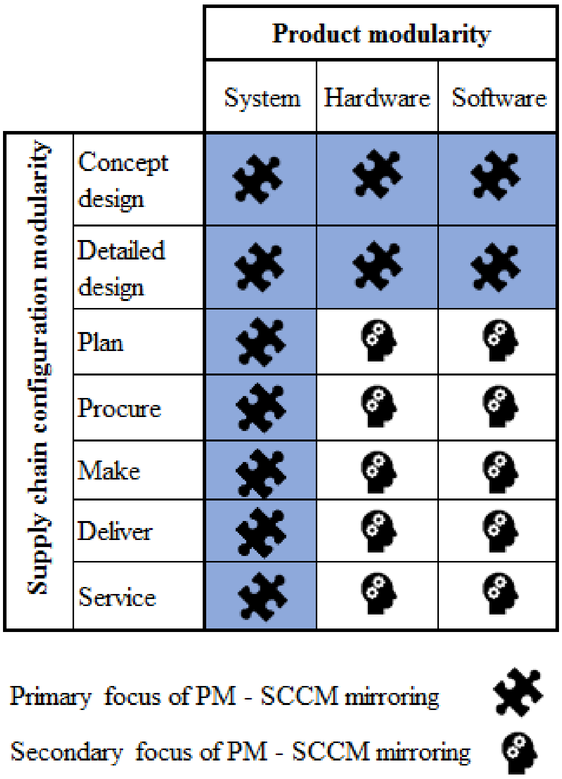
Complex adaptive systems (CAS) theory builds on the concept of GST (von Bertalanffy, 1950; 1968) and consists of a network of interacting, independent and adaptive agents. In the case of NPD and SCC systems, the agents interact by creating and exchanging knowledge. The main distinguishing feature between CAS with the general systems view, is that the CAS expresses a degree of emergence and self-organisation, based on the system's history. From the SCC standpoint, this highlights the need to develop mirroring "systems that lead towards adaptive, flexible and coherent collective behaviour" (Surana *et al.*, 2005, p. 4235). The literature shows a broad spread of research covering the source, make and deliver horizontal SC tiers, shown in Appendix 4-2, Page 461. CD is the sole intervening mechanism employed amongst the papers identified. This finding does not mean that FC and FAC are not used; these mechanisms are not, however, highlighted in this literature. Focusing on the SC tiers, the literature review highlights five papers covering the automotive sector and five covering domestic appliances. There is only one paper covering the aerospace sector, whilst no paper was found covering the medical device sector.

“The knowledge-based theory of alliance formation has been inhibited by a simplistic view of alliances as vehicles for organisational learning in which strategic alliances have presumed to be motivated by companies' desire to acquire knowledge from one another” Grant and Baden-Fuller (2004, p. 61). These authors argue the primary advantage of alliances over both companies and markets is in accessing rather than acquiring knowledge. Building upon the distinction between the knowledge generation ('exploration') and knowledge application ('exploitation')”, they show that ‘alliances contribute to the efficiency in the application of knowledge; first, by improving the efficiency with which knowledge is integrated into the production of complex goods and services, and second, by increasing the efficiency with which knowledge is utilised. These static efficiency advantages of alliances are enhanced where there is uncertainty over future knowledge requirements and where new products offer early-mover advantages’.

4.2.1. Intervening mechanisms

At the product TLA, there are three general classifications of NPD: system, hardware and software. At the TLA there are six general classifications of SCC design elements: design, plan, procure, make, deliver and service. The three intervening mechanisms are primarily focused on mirroring of PM and SCCM at the system, hardware and software levels, with all SCC level tasks, and for all concept and detailed design tasks, shown below in the shaded area in Table 4-2. These intervening mechanisms take into consideration system, hardware and software requirements from planning through to product serviceability. The focus of mirroring at the system level extends to product service; the focus of mirroring at the product hardware and software levels was restricted to product concept design and detailed design.

Table 4-2. Primary area of mirroring



CD system control is multi-directional, whilst FC (*ex post*) and FAC (*ex-ante*) system controls are unidirectional. These three types of knowledge creation are depicted in cybernetics, systems and control theory (von Bertalanffy, 1950; 1968), and in GST (Kristianto *et al.*, 2012). Where mirroring is not achieved, the three hypotheses are assessed. Contingency factors may indicate that either single-loop or double-loop learning is required to achieve the desired mirroring.

Multi-disciplinary design also requires pre-selected team design. Take, for example, the direct current (DC) motor that was designed by the domestic appliance company. Consider, if the DC motor as a technical system were to be designed by two different technology domain specialists (mechanics and electronics), then the first step would be to divide the task of designing the system between these areas of expertise. Depending on the technical discipline from which the system is viewed, the system may exhibit different architecture and functionality. The mechanical engineer might be concerned with fastening the motor and damping system vibration, where the electronics engineer may be concerned with DC voltage read-out. The domestic appliance company designs are controlled by the mechanical engineering team because of the high levels of mechanical content of these products. The mechanical team takes the overall NPD lead, and co-opts domain expertise from other technology domains, for example software design and power engineering.

Knowledge is an important intangible asset for the NPD team at the concept stage. Project three develops an empirical model to analyse how the modes of knowledge conversion affect the mirroring of PM and SCCM (Nonaka and Takeuchi, 1995). These four modes of knowledge conversion are: socialisation, externalisation, internalisation and combination. Socialisation is often achieved through story-telling. Since SCC is often inter-company, externalisation becomes increasingly important. Internalisation is achieved through team experiments, whilst combination includes documenting and communicating the proof of concept. In the technology sectors included in this research, there are limitations to the traditional sequential approach of the Stage-Gate® process (Cooper, 2008), or more holistic scrum approach (Takeuchi and Nonaka, 1986), to CD. Early and sharp product definition and flexible development models can delay the product concept freeze point (Iansiti, 1995; Mascitelli, 2011). Construct measures and indicators are generated by reviewing relevant systems and product development literature in the following sections.

4.2.2. Co-development (H2)

CD is the early involvement of a multi-functional team in the NPD and SCC process concept development. It has been operationalised to include cross-functional teams, concurrent workflows, and early involvement (Koufteros *et al.*, 2005). CD is the practice of designing products in multi-functional teams with all functional specialties working together from the product concept development stage, including marketing, applications engineering, procurement manufacturing, distribution and after-market services (Portioli-Staudacher *et al.*, 2003). CD orchestrates the participation of purchasing, manufacturing, distribution and after-sales support functions early in the NPD concept stage. This early involvement builds trust, allows information sharing and seeks integrative NPD solutions. Lower development lead-time, lower development cost and minimum rework are among the achievements of such CD systems (Nategh, 2009). Over time, researchers have identified increasing modularity in organisational design, where hierarchical organisations are disaggregated into loosely coupled production systems (Sanchez and Mahoney, 2000; Schilling, 2000; Hoetker, 2006). This production system, whilst offering opportunities for contract manufacturing, alternative work arrangement and various strategic alliances, requires an increased focus on CD.

Hölttä-Otto *et al.* (2005) state that well-defined modules with easily decoupled interfaces can provide design freedom. Modular product design based around modular organisation design facilitates CD and reduces communication cost (Gershenson *et al.*, 2003). There is always a need for inter-organisational collaboration to develop successful modular product (Schilling and Steensma, 2001). In this research the focus is on the level of participation of knowledge experts responsible for SCC at the product concept design stage, and the effectiveness of their involvement at the NPD concept stage in achieving mirroring of PM with SCCM. Three aspects of CD distinguish it from conventional approaches to product development: 1) cross-functional integration, 2) concurrency, and 3) clear communications.

The CD variables deduced from the literature in project one are shown below in Table 4-3. Swink *et al.* (1996) use multi-case analysis to review the different levels and types of CD. Dowlatshahi (1999) presents a comprehensive list of SCC functions involved in CD. Olivetto (2000) uses the orchestra as a metaphor to explain the level of concurrency within PA and SCA development. Tracey (2004) adopts a SC management (SCM) approach to the CD of the product specification, finding product development a difficult construct to operationalise.

Table 4-3. Co- development construct measures and indicators

Construct	Measures or indicators	Reference
Co-development (CD)	(1) Level of concurrent development (2) SCC functions involved in CD team (3) Level of concurrency between PA and SCA (4) Concurrent development of product specification	Swink *et al.* (1996) Dowlatshahi (1999) Olivetto (2000) Tracey (2004)

CE which focuses primarily on the technical requirements of product development and its manufacturing process, is often used interchangeably with co-development (CD). Academic research in CE peaked in the mid-1990s, shown below in Figure 4-5, but remains a nascent research area, driven by technological advancements, varying industry clock speeds, and shorter product life cycles.

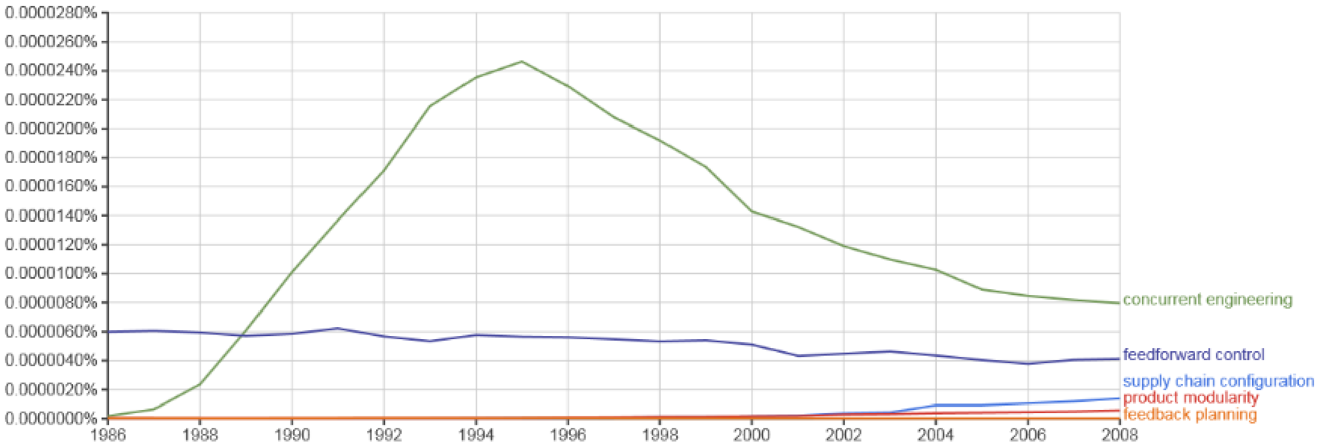


Figure 4-5. References to moderating mechanisms in academic literature

Four levels of CD were deduced from the literature: (1) the level of CD engaged in by the company for the UoA, at the conceptual stage; (2) the SCC functions involved in the CD team, ranging from materials sourcing, manufacturing and test engineering, distribution analysts, and after-sales solutions architects; (3) the level of project concurrency between SCC and PA team members; and (4) the CD of the product specification, taking SCC and PA considerations into account. Research indicates the necessity for cross-functional collaboration, between NPD and SCC, with the level of concurrency as a measure for NPD performance (Prasad, 1996).

Early team involvement is essential for cycle time and product innovation improvement. Two of the CD's guiding principles are integration and parallelism (Burton *et al.*, 1988; Baregheh *et al.*, 2009). These guiding principles are closely aligned with the mirroring hypothesis. Gan and Grunow (2013) focus on integration and parallelism, using a design attribute trade-off framework, shown below in Figure 4-6. CD designs are continuously reviewed; early experimentation is often the best means of deciding among competing product directions, with the focus being on design optimization, not project management. The CDA-TOP model offers a framework supporting CD, from product-centric and SCC-centric design perspectives, at the system, product and operations levels. This research is focused on the long-term SCC planning horizon.

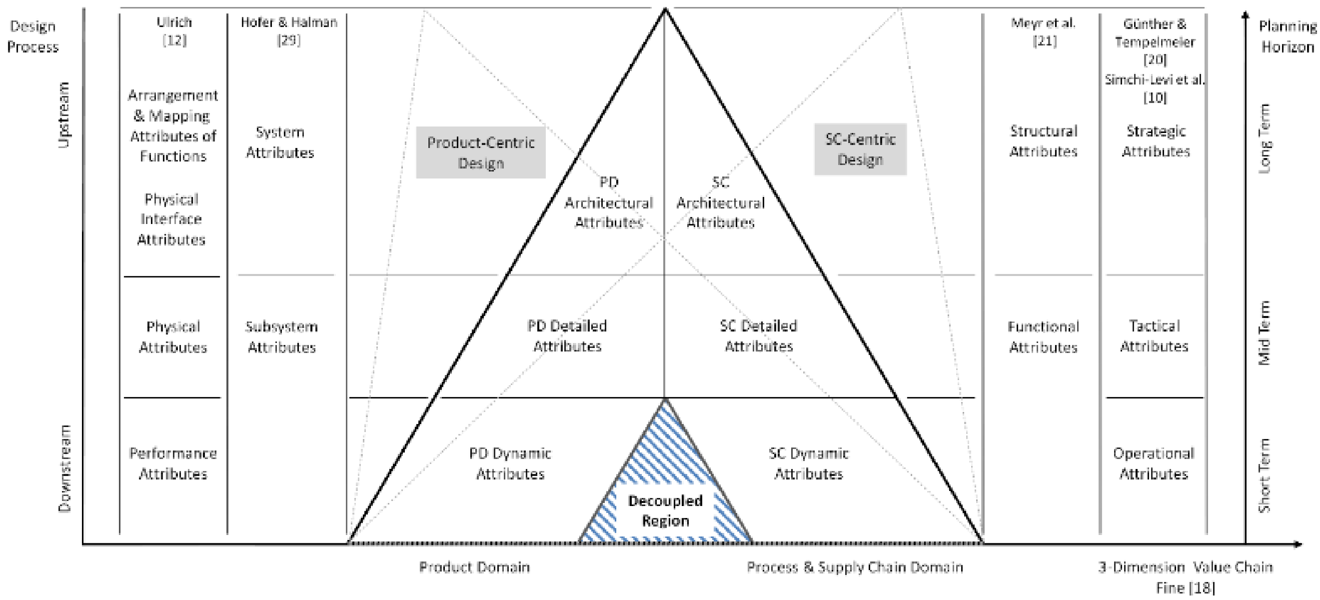


Figure 4-6. Concurrent Design attribute-trade-off pyramid (CDA-TOP)
Source: Gan and Grunow (2013)

Anderson (2004) highlights the requirement for the core development team to come together, early in the product concept stage, with a methodical product definition, as opposed to a vague product definition, shown below in Figure 4-7. Anderson is indicating that CD contributes to PM mirroring with SCCM. Project three is designed to empirically test the strength of this argument, across the medical device, domestic appliance, automotive and aerospace industries.

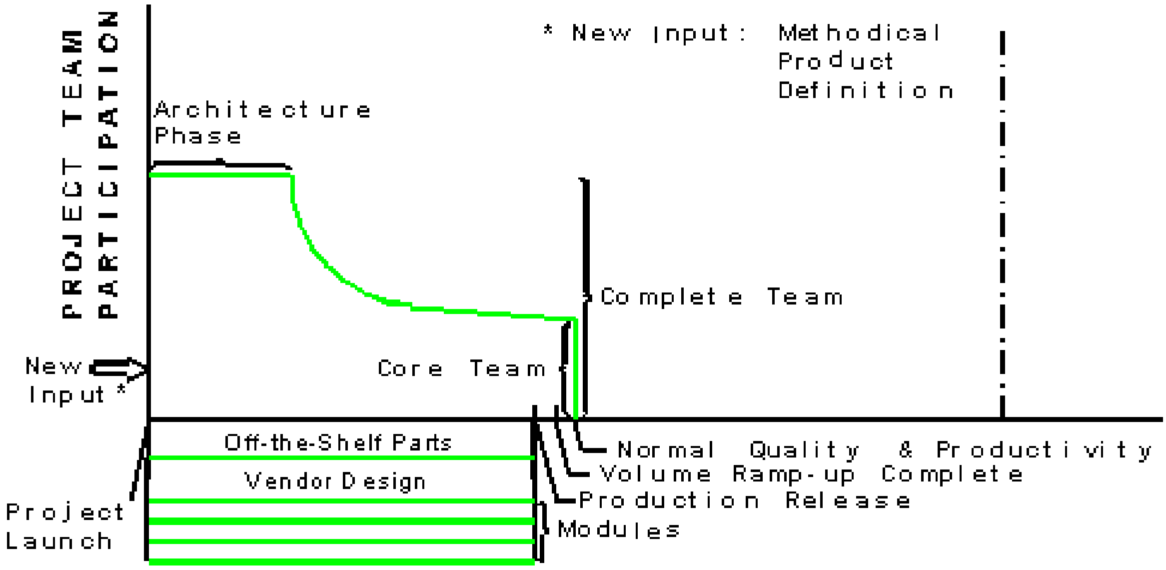


Figure 4-7. Concurrent development
Source: Anderson (2004)

CD is the predominant intervening mechanism employed in NPD, deduced from the literature, as shown in Appendix 3-12, Page 459.

4.2.3. Feedback control (H3)

Feedback is information about the gap between the actual performance level achieved and the reference performance level set, in a closed-loop system, and looks at lagging indicators. Systems theory assumes that there are inputs into the process, outputs from the process and the monitoring of deviations from the plan captured in the FC loop. The Stage-Gate® model establishes control at the Stage-Gate® exits (Ramasprasad, 1983). In a FC system, the output corrections are fed back into the system or process, shown below in Figure 4-8.

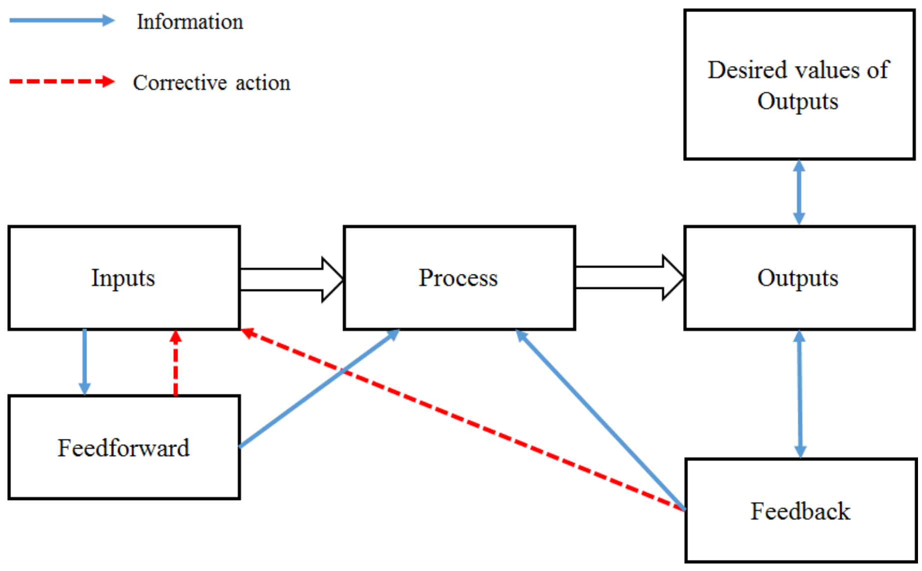


Figure 4-8. Feedback and feedforward control

Wiener (1950) states that the principle of FC is where 'behaviour is scanned for its result, and the success or failure of this result modifies future behaviour'. Wiener is also attributed with the term 'anticipatory feedback' which is recognising that there are time lags between when deviations are noticed and when system corrections must be made (Ishikawa and Smith, 1972). Von Bertalanffy (1950), a biologist, discusses systems, the regulation of systems, open and closed systems, perpetual change in open systems and systems theory, defining the general principles of dynamic interaction. He notes the use of feedback in communication and control within social systems. The theory advocates the use of systems thinking to understand the interaction of inputs and the environment, and recognising the use of controls in the system. Integration is a core principle of FC.

A further dimension of systems theory is incremental improvement. The first FC measure assesses product and SCC performance against predefined product and process specifications, at predetermined measurement points. FC uses lagging performance indicators, to provide control information. Performance targets and metrics need to be established, together with continuous data collection and knowledge sharing. The construct variables measure the level of product and SCC performance at each Stage-

Gate® exit, prior to product launch. In all sectors within this research there is a focus on NPIR. The second measure of FC covers the level of SCC assessment taking place at the concept stage. The third measure of FC is NPD lead-time goal achievement. The potential benefits of PM seem compelling and the importance of PM in reducing NPD time is recognized (Sanchez and Mahoney, 1996; Danese and Romano, 2004; Jacobs *et al.*, 2007) empirical studies demonstrating PM effect on NPIR are scarce. The fourth CD measure is the level of PA versus SCA performance trade-off analysis conducted at the product concept stage. Gan and Grunow (2013) focus on PA versus SCA design attribute trade-off and analysis, shown above in Figure 4-6.

FC can be a challenge for new-to-market products, at the concept development stage, where there are limited component feedback data. For non-platform products, the likelihood is that there is component technology, or SCC process technology knowledge available, possibly in other industry sectors. The third engineer recruited by the domestic appliance company who worked on the first vacuum cleaner (DC01) product design states that 'we are on a design-build-test loop' (Shaer, 2015). Over the course of an average week, the company's new product innovation team come up with a dozen prototypes, which are modelled, submitted for feedback and shared with other engineers. All key performance parameters are measured. Through almost endless product design repetition, this company, using FC, continues to develop innovative product extensions. For example, heavy duty testing on the first cyclone vacuum cleaners led engineers to realize that a by-product of the suction was a so-called Coanda effect, where air could be directed to spit out as quickly as it had come into the vacuum cleaner. This discovery led to an air-blade hand dryer design. This design led to the air multiplier, which led to the air purifier (Shaer, 2015). The air purifier (AP) is one of the UoA of this research.

Single-loop learning involves learning from the consequences of previous actions to develop successful patterns of behaviour. This type of learning results from FC generated by a process of observing the consequences of actions and using this knowledge to adjust subsequent actions to avoid similar mistakes in the future (Argyris and Schon, 1974). These authors exemplified the single-loop learning process with a thermostat that detects when it is too hot or cold in a room and adjusts by turning the heating or cooling unit on or off. Budgets act the same way as thermostats in controlling unit level spending. Single-loop learning solves problems as presented but cannot discover why the problems arose in the first place (Argyris and Schon, 1996). If the wrong targets are set, the single-loop learning system is helpless to alter them. Hypothesis three states that *the mirroring between product modularity and supply chain configuration is enhanced by systems feedback control, at the conceptual product development stage.* FC variables are shown below in Table 4-4. Ramasprasad links the Stage-Gate® process (Cooper, 2008) with PA performance as a key measure of FC. Stalk and Hout (1990) highlight the importance of the SCC performance variable at the NPD Stage-Gate® release point. Cooper (2008) addresses NPIR lead-time as an important FC variable. Francisco *et al*. (2012) address the requirement for a trade-off measure to evaluate NPD and SCC.

Table 4-4. Feedback control construct measures and indicators

Construct	Measures or indicators	Reference
Feedback control (FC)	(1) Product assessment at each stage gate exit (2) SCC performance assssemnt after concept stage (3) NPD leadtime goal achievement metrics (4) PA versus SCA performance trade-off analysis	Ramasprasad (1983) Stalk and Haut (1990) Tu & Vonderembse (2004) Cooper (2008) Francisco *et al.* (2012)

4.2.4. Feedforward anticipatory control (FAC)

FAC feeds additional correcting inputs into the process or system, before the outputs occur, to prevent unwanted or undesired variations (Koontz and Bradspies, 1972), shown in Figure 4-8. FAC is defined as an 'anticipatory control in which preventative action is taken before the difference between planned and actual performance occurs' (Ishikawa and Smith, 1972; Easterby-Smith *et al.*, 1994) and involves 'future directed controls' (Koontz and Bradspies, 1972; Patton, 1987; Ettlie and Elsenbach, 2007). FAC is defined as an 'anticipatory control in which preventative action is taken before the difference between planned and actual performance occurs', focusing on strategic uncertainties (Ashish and Merges, 2004). FAC is an approach to address the time delay problems of FC, where performance is fed back after occurrence of the event, causing persistence of 'deviation from plan'. Notable characteristics of FAC are the timing when the control is applied, before the deviation from plan occurs, and its association with planning. Systems theory proposes the use of FAC in social systems.

"During the late 1950s the concept of environment was introduced to organisation analysis. Prior to this the closed systems view predominated" (Denzin, 1978, p.77). In systems theory, an open system does not have an FC loop to control its output. In an open system, the output of the system is not fed back in to the system, for control or operation, shown in Figure 4-8. An example is the required noise level for the AP (B1). The domestic appliance company is seeking to maintain a low noise (dB) level at increasing air speed rates. In this case, there is no FC loop; noise measurements are required to be taken independently. FAC adopts a future-directed view, where "Future-directed control allows managers to see problems coming in time to do something about them" (Koontz and Bradspies, 1972, p. 25). Most managers consider the problem of control to be one of early recognition of deviations so that correction can be applied promptly. FAC requires an organisation to be integrated. Taking the example of inventory control, the costs of holding excessive inventory are proportional to the time the excess inventory is held. FAC addresses the time delay problems of FC, where performance is fed back, after occurrence of the event. Whilst real-time information availability is important, for many FAC systems, the experienced PA and SCA knowledge and judgement of subject matter experts may be sufficient to indicate future deviations from planned results. "Astute managers ask to see their problems in time to do something about them" (Koontz and Bradspies, 1972, p. 36). The key problem with FAC systems is that in practice except for trivial cases, it is impossible to model systems with adequate 'requisite variety' (Ashby, 1964) and accuracy needed to accommodate all possible disturbances. The output of such 'open systems' will inevitably drift away from the required condition, over time. 'Consequently, it will usually be necessary to employ a combination of FC and FAC' (Fowler, 1999). The first FAC measure is closely related to the NPD perspective for new-to-market products. The NPD team is often tasked with a unique selling hypothesis, which the product will deliver to the market. The second measure assesses the level of FAC employed to deliver SCC requirements. This is closely related to the third measure of SCC goal achievement. The final measure assesses the use of NPD and SCC architectural tools. FAC can be used to deduce the likelihood of NPD failure (Ettlie and Elsenbach, 2007). Hypothesis 4; *the mirroring between product modularity and supply chain configuration is enhanced by feedforward anticipatory control, at the conceptual product development stage.* The four FC variables are shown below in Table 4-5.

Table 4-5. Feedforward anticipatory control construct measures and indicators

Construct	Measures or indicators	Reference
Feed forward anticipatory control (FAC)	(1) Level of FAC to deliver product concept (2) Level of FAC to deliver SCC requirements (3) SCC goal achievement (4) Level of product and SCC architectural tools	Koontz and Bradspies (1972)

4.3. METHODOLOGY

This Section begins with an overview of what is covered in the methodology discussion. Project one, highlighted a lack of development of the SCCM construct, together with a gap in knowledge of PM mirroring with SCCM. Project two covered how PM mirroring with SCCM is manifested. Project three uses the same UoA to assess the effects of intervening mechanisms on PM mirroring with SCCM. Limited prior research on PA and SCA mirroring means that themes and patterns need to be developed (Eisenhardt, 1989). This Section explains and provides justification for the methodological approach used in project three.

4.3.1. Overview

The aim of project three was to investigate intervening systems' mechanisms as a means of improving the mirroring of PM with SCCM, answering research question four. The methodology is similar, to project two. Case selection and UoA are similar, to project two. The research design, including the guidance implications derived from the project one and project two, are discussed in this Section.

4.3.2. Research design

Case studies and further interviews were conducted in project three, with the same cases selected for project two. As was the case with 'The case method lends itself to early, exploratory investigations where the attributes or variables are still unknown, and the phenomenon not well understood' (Meredith, 1998), this is equally true in project three where the CD, FC and FAC constructs can be misunderstood by practitioners. In a review of selected papers from the SLR, CD is the only intervening mechanism referenced in the academic literature, shown in Appendix 4-2, Page 461. This research introduced the FC and FAC mechanisms. The predominance of research has been in the electronics sector with twelve papers covering this domain. There are five papers in the automotive sector and five in the domestic appliance sector. There is one paper in aerospace and no papers in the medical device sector. Twelve additional papers did not reference any product sectors.

The key strength of the case study approach is that it does not isolate the phenomenon under study from the context in which it exists. Ragin (1987) states that case-orientated research is based on the application of multiple methods which seek to account for all deviating cases, and therefore creates a rich dialogue between theory and evidence. This is significant for the proposed research concerning the mirroring of PM with SCCM since this body of research is limited. The conditions that Yin (2014) proposes when case study research is appropriate are: the form of the research question; whether the researcher has control of, or access to, the actual behavioural events under study; and the degree of focus on contemporary, as opposed to historical, events. This research is explanatory in nature. A survey would be an inappropriate approach because many of the concepts, such as CD, FC and FAC, are not generally understood and are open to misinterpretation.

PM mirroring with SCCM is a phenomenon that the researcher had no control over, but did have access to, since it is a contemporary phenomenon. Data were collected from multiple sources and multiple viewpoints. Three primary sources of evidence were used: research papers, archived records in the form of reports and press releases, and interviews. These sources are among those outlined by Yin (2014), as primary sources of evidence in qualitative research. All products are designed in-house, and have a strong architectural design focus.

The research hypotheses and moderating mechanisms were deduced from the literature. In addition, an inductive approach was used to identify further contingency factors, regarding mirroring. No inductive theorizing was conducted in this empirical research. One problem with the inductive method is the notion that data can be decoupled from theory. Deduction, on the other hand implies that theories without facts are possible (Bjørnar, 1998).

This research is carried out as case studies, with links to theory (Bjørnar, 1998). A semi-structured interview protocol was developed, for conducting the case studies. Questionnaire surveys are useful when the research goal is to provide a description of the incidence or prevalence of a phenomenon (Yin, 2014). An early revision of the research questionnaire was tested using telephone interviews with three knowledge experts, shown in Appendix 4-3, Page 462. The interviews were structured around open questions, which allow for an open exchange of knowledge. Case studies were developed based on semi-structured interviews, multiple data sources, informal meetings, secondary data, published reports, and research papers. The research moved from interpreting existing studies, to structured interviewing, and case studies. Meredith *et al*. (1989) define that there is truth 'out there', independent of human experience, and 'in here', based on individual interpretation. They also assert 'the critical issue is between reliability and external validity; the most valid information is obtained by direct involvement with the phenomenon'.

4.3.3. Case selection

The same cases used in project two were selected for project three. The cases and companies were selected from different positions in the SC to obtain different manifestations of SCCM. Project two highlighted that the automotive and aerospace sectors accounted for the most academic references on modularity from amongst the four industrial sectors selected, with many of these publications referencing modularity-based SC practices as a means of managing product complexity (Novak and Eppinger, 2001). The rapid growth in market share by the airplane OEM during the 1990s, over its main rival, is partly attributed to this OEM's use of modular design. Where the main competitor employed two-hundred and sixteen workers for every airplane produced, the OEM had one-hundred and forty-three workers, a productivity difference of fifty-one percent (O'Grady, 1999). The medical device and domestic appliance sectors were selected, since these are undergoing significant technological change. The automotive and aerospace OEMs', tier-one and tier-two suppliers were selected to assess the effect of a vertical SCC, since there was a high level of academic papers selected in project one, covering the automotive sector, shown in Appendix 4-2, Page 461. Separate interviews were conducted with the same research participants as in project two.

4.3.4. Units of Analysis

The UoA are identical to those selected for project two. The aim was to assess the levels of intervening mechanisms associated with the PM and SCCM mirroring for these UoA, shown in Table 4-6.

Table 4-6. Units of Analysis

Units of Analysis (UoA)										
Company	Med device co.		Domestic appliance co.		Auto co.		Auto driveline co.		Aerostructure co.	Airplane co.
UoA	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
	Surgical cartridge	Blood glucose meter	Air purifier	Cordless vacuum cleaner	4-Wheel drive SUV	4-Wheel drive CUV	Automotive driveline	Automotive drive shaft	Fixed trailing edge for airplane wing	Wide-bodied airplane
										

The ten products selected have been recently launched except for A1, which has been in the market for twenty years. A1, however, has not been replaced in the market, to-date. Variants of D1 and D2 are designed into UoA C1 and C2. E1 is a sub-module of E2, whilst the medical device, domestic appliance and automotive products are delivered to end users. The auto-driveline and airplane products are delivered to business partners.

Within-case and cross-case analyses of these UoA are presented in this chapter, as shown below in Figure 4-9.

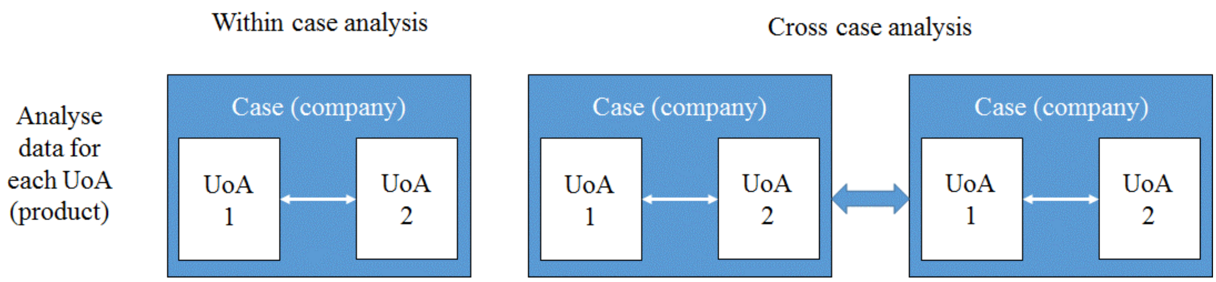


Figure 4-9. Within-case and cross-case comparison framework

4.3.5. Research strategy

The case companies are the same OEMs and first tier suppliers as selected for project two. The case companies have developed strong brand platforms and are using PA to offer product variety, and maintain market leadership positions. In addition, these companies realise that much product innovation originates within the supplier base. In total sixteen interviews were conducted during project three, shown below in Figure 4-10. Due to confidentiality and the protection of intellectual assets, it has not been possible to compare competing companies in the same sector.

Prior to each case study, a research protocol was provided to each interviewee. Preparatory phone calls were organised to explain the research domain, the central research question, and the goals of the case study, in advance of the case study being conducted. A confidentiality agreement was provided to each company in advance of the research commencing. Some companies elected not to enter into this confidentiality agreement. A general list of secondary questions was developed including the research concern, theoretical framework, and goals of the study, and maintained throughout the data collection process, following the recommendations of Auerbach and Silverstein (2003, p. 44).

The CD, FC and FAC construct measures deduced from the literature were used as the basis of the questionnaire for the pilot interviews. The questionnaire does not constrain the case studies, but used as a supporting mechanism, improving the validity of the case studies. The questions were revised following the pilot study, to more accurately capture these moderating mechanisms. The final questions resulted from the pilot interview transcripts, journals, documents and literature. It is the ability to show how themes and concepts systematically interrelate that leads to the development of theory (Easterby-Smith *et al.*, 1994, p. 55).

A secondary coding cycle commenced immediately after the first case study, with the medical device company. The codes were further developed after each case study. This process required follow-up conversations with case study participants. Secondary coding cycle methods require "classifying, prioritizing, integrating, synthesizing, abstracting, conceptualizing and theory building" (Saldana, 2009, p. 45). The analytic goals of secondary coding and data analysis are to narrow the number of themes being explored, and to develop an overarching theme" from the data. Saldana (2009) calls this an 'integrative theme that weaves various themes together into a coherent narrative'. The final list of questions is shown in Appendix 4-3, Page 462. In general, data collection and analysis formed an iterative process between general systems theory and the data collected. All deviating cases are accounted for. 'One non-conforming case is sufficient to challenge a theory that should encompass it' (Harrison, 2002). During project three the focus was primarily on within-case analysis. The cross-case analysis uses Pettigrew's framework and searches for linking patterns. Where there are elements in common these are identified as evidence of possible 'universal best practice'. Uniqueness of elements may be context specific; these are also discussed. It should be considered that case studies often produce findings that are high on relevance but low on accuracy and repeatability. They are suitable for exploratory (theory building) and explanatory studies (theory testing) of contemporary phenomena. A well thought out research design leading to high validity (construct, internal and external) can combat many of the shortcomings of the case study technique.

	Project 3 Interviews	Number of interviews
1	Generate Research propositions.	
2	Interview respondents from both design and supply chain teams.	10
3	Analyse data, generate report, and fine-tune questionnaires, for follow-up interviews.	4
4	Team interviews to validate results.	2
	Total Interviews	16

Figure 4-10. Project three interviews

Two sample interview transcripts from Project three are shown in Appendices 4-16 and 4-17, Pages 502 – 514.

4.4. RIGOUR IN CASE STUDIES

Rigour was applied during project three in the same manner as in project two. For an understanding of how rigour was applied, see Section 4.4. Interviews and documents remain the primary methods of data collection in project three.

4.4.1. Construct validity

Care has been taken in establishing appropriate operational measures for each of the intervening mechanisms. The operationalisation of these concepts involved the rigorous development of concept measures. Triangulation was achieved by using different methods, data sources, and knowledge experts from the same case company. The construct attributes were assigned equal weightings in assessing the overall level of each construct.

4.4.2. Internal validity

Strong focus was placed on establishing causal relationships between the PM and SCCM attributes, identifying the level of each intervening mechanism and related conditions.

4.4.3. External validity

The research results discuss the extent to which the findings from each case study are generalisable beyond the immediate case. Generalisability is traced back to the general systems theory (Yin, 2014).

4.4.4. Data analysis

With the data summarised and coded into descriptive codes the analysis turned to investigating possible patterns between the PM and SCCM constructs and the intervening mechanisms, Appendix 4-4, Page 463. The codes were deduced from the literature. Pattern coding is a means of grouping descriptive codes into smaller sets of inferential pattern codes.

Appendix 4-4, Page 463, represents the three primary intervening mechanisms (code types), and the three levels (low, medium and high) of each of the variables (level two codes) for each of these intervening mechanisms.

Appendix 4-5, Page 464 represents the three intervening code types; 1) constructs (intervening mechanisms); 2) relationships or links to NPD and SCC, and 3) axial themes. These axial themes; 1) supplier capabilities; 2) complexity of the information exchanged; 3) codifiability of this information, and 4) COEP, were deduced from the literature, and are shown as level three codes.

The data coding involves identifying the causal relationships between the level two PM and SCCM codes and the levels of intervening mechanism present in these relationships. The causal relationships are similar, to project two, shown below in Table 4-7.

Table 4-7. Coding patterns

Intervening mechanism pattern codes			
Code	**Description**	**Type**	**Code type**
CD	Co-development of NPD and SCC	Intervening mechanism	Category code
FC	Feedback control of NPD and SCC performance	Intervening mechanism	Category code
FAC	Feedforward anticipatory control of NPD and SCC performance	Intervening mechanism	Category code
ESI	Early supplier involvement	Causal relationship	Thematic code
KC	PM and SCCM knowledge codification	Causal relationship	Thematic code
LC	Life-cycle concept	Causal relationship	Thematic code
PD	Propensity to decouple	Causal relationship	Thematic code

Figure 4-3, coding diagram, below shows the level one, two and three codes. All codes were deduced from project one. The level three codes were tested in project two, with ESI, PD and LC supporting hypothesis one, and KC weak in its level of support for hypothesis one.

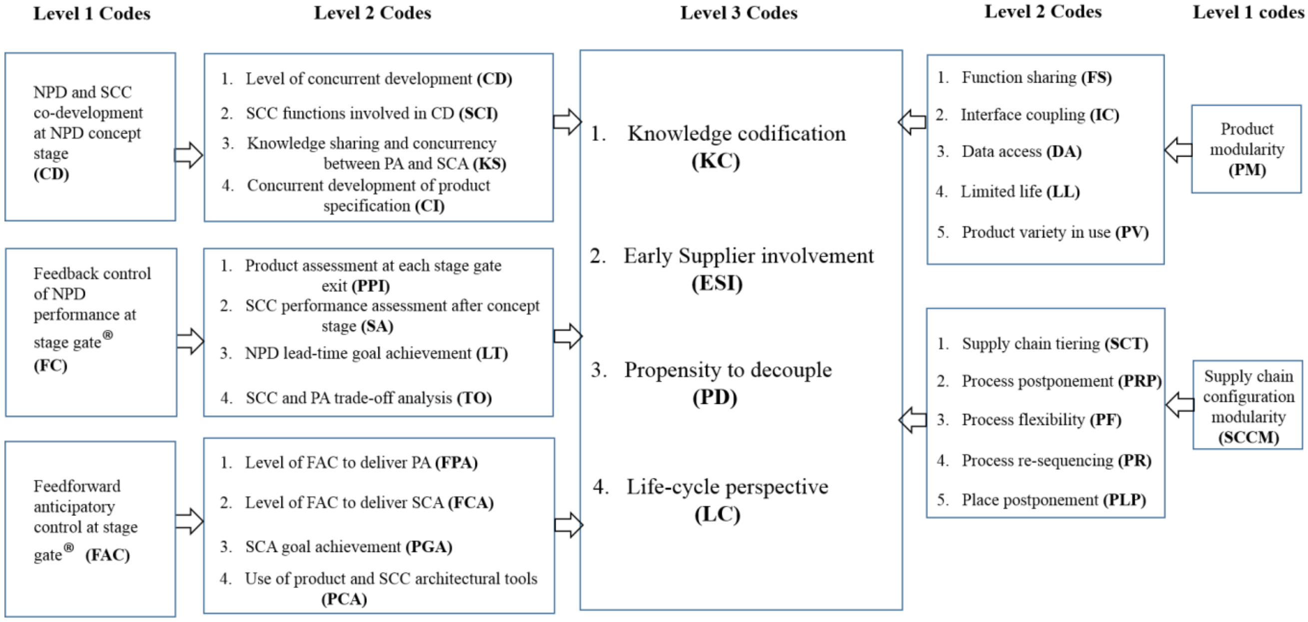


Figure 4-11. Project three coding diagram

Further details of these codes are discussed in Appendices 4-6, to 4-10. These appendices show the level of each intervening mechanism variable and an aggregate level of each intervening mechanism present for each of the UoA.

4.5. FINDINGS AND DISCUSSION

The levels of co-development, are shown in Appendix 4-12a, Page 482. Four UoA, D1, D2, E1 and E2 show a high level of CD on the four CD variables assessed; 1) overall level of CD; 2) SCC involvement at the concept stage; 3) Knowledge sharing, and 4) concurrent development of the product specification. All ten UoA show a high level of co-development of the product specification, all UoA with exception of the domestic appliance products show a high level of CD. The domestic appliance products show a low level of knowledge sharing at the concept stage.

The levels of feedback control, are shown in Appendix 4-13a., Page 484. Four UoA, A2, B2, D1, and D2 show a high level of FC on the four attributes addressed; 1) Product assessment at the stage gate exit; 2) SCC performance after concept stage; 3) NPD lead-time goal assessment, and 4) Product – SCC process performance trade-off analysis at the concept stage. All UoA except for B1 performed product performance assessment prior to stage-gate exit, in the case of B1 a product as could proceed to the next stage without successful completion of all performance test. This company employ a manufacture for design approach, which allows for the delivery of innovative design, which is unconstrained by SCC design. In some instances, modularity is sacrificed for the sake of the design. All UoA except for A1 and C2 undertake a high level of Product to SCC performance trade-off assessment.

The levels of feedforward anticipatory control, are shown in Appendix 4-14, Page 488. All UoA except A2 use trade-off analysis to assess PA and SCA, and six UoA show a high overall level of FAC intervention. No UoA show a high level of FAC on the four attributes addressed; 1) level of FAC to deliver PA; 2) level of FAC to deliver SCC; 3) SCC goal achievement, and 4) use of PA and SCC architectural tools.

4.5.1. Within-case analysis (medical device)

The concurrent development, feedback control and feedforward anticipatory control variables for A1 and A2 are shown in Appendices 4-7, Pages 468-70.

4.5.1.1. Within-case analysis - A1

A1 displays a low PD, and a high level of mirroring between the PM and SCCM constructs, shown below in Table 4-8. The levels of CD and FAC are high, which indicate close multi-functional team involvement at the concept stage, as highlighted by interviewee A1, shown in Appendices 4-6, Pages 465-67, with a focus on delivering the defined PA and SCC goals for this new-to-market product. Knowledge codification does not rely on intervening mechanisms; this is likely to be delivered through close KS between the PA and SCC design experts at the concept stage. ESI is restricted to a limited used of FC, with a medium level of SCC performance assessment after the concept stage.

The causal relationships linking PM and SCCM are shown below in Figure 4-12. Overall, the high levels of dimensional and mechanical complexity of this device are managed through a high level of PA and SCC co-development at the concept stage. There is use of FAC control to ensure the materials and dimensional properties of this device are met, leading to a PD. FC is limited to SC capability assessment.

Table 4-8. Causal linking relationships - A1

Causal relationships between PM and SCCM for A1				
PM variable	**Causal relationship**	**SCCM variable**	**Explanation of causal relationships**	**Level of mirroring**
IC-M (medium coupling)	Low propensity to decouple	SCT-M (depth and breadth)	CD is a core practice, with KS used to analyse product and process constraints, whilst concurrently developing the product specification. FAC takes scientific research in to consideration in defining the product architecture with FAC tied to the Technology Release Level (TRL) process, in focusing on product cost, process flexibility and process yield using modelling tools.	High
IC-M (medium coupling)	Knowledge codification	SCT-M (depth and breadth)	Knowledge sharing occurs between SCC and product design. Product complexity requires that product interface tolerances are shared at different levels of the SCT. During the concept stage material and process capabilities are refined.	High
IC-M (medium coupling)	ESI (Early supplier involvement)	SCT-M (economic and legal business involvement)	ESI occurs in conjunction with early customer (medical practitioner) involvement. Early SCC focus was on process reliability and SCC performance assessment for the initial product release. There is a medium level of economic and business involvement by the OEM.	High
Overall level of mirroring at product launch			A strong focus on CD leads to a strengthening of the coupling within this device, whilst a focus on FAC is used to balance SCC considerations at the concept stage.	High

Co-development (CD)				Feedback control (FC)				Feedforward control (FAC)			
Co-development	SCC involvement	Knowledge sharing	Concurrent spec. dev.	Product assessment	SCC assessment	NPI lead-time assessment	Performance assessment	FAC to deliver PA	FCA to deliver SCC	SCC goal achievement	Use of tools for FCA

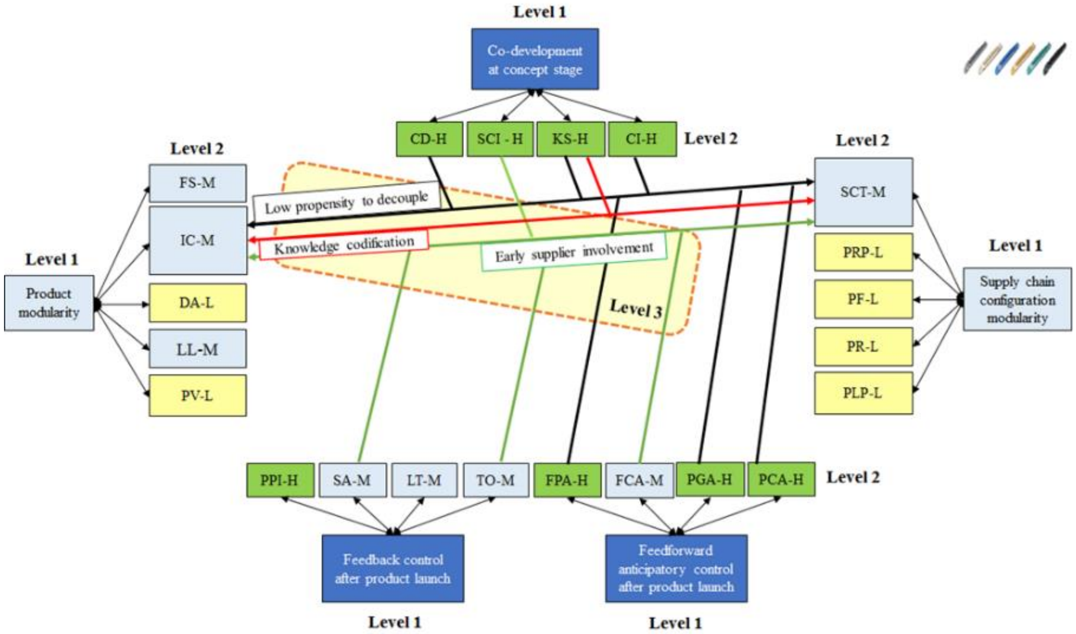


Figure 4-12. Causal relationships and intervening mechanisms - A1

4.5.1.2. Within-case analysis - A2

A2 displays a low PD, with a high level of mirroring between the PM and SCCM constructs, shown below in Table 4-9. The levels of CD are high, and the levels of FAC are medium, which indicates close multi-functional team involvement at the concept stage, and a focus on delivering the defined PA and SCC goals for this new-to-market device, at the concept stage. Knowledge codification shows a strong correlation with the high level of SCC assessment and NPI lead-time assessment. There are TTM pressures launching these blood glucose meters to market, and the tier-one meter manufacture plays a key role in meter design, product validation and SC co-ordination. Because this is a platform product, there is significant use of FC from previously launched variants of this product. The intervening mechanisms primarily focus on strengthening the low PD between IC and SCT. This related to the regulations within the medical devices sector and the strong technical, digital and format factor interfaces required by these regulated devices.

Table 4-9. Causal linking relationships - A2

Causal relationships between PM and SCCM for A2					Co-development				Feedback control				Feedforward control			
PM variable	**Causal relationship**	**SCCM variable**	**Explanation of causal relationships**	**Level of mirroring**	Co-development	SCC involvement	Knowledge sharing	Concurrent spec. dev.	Product assessment	SCC assessment	NPI lead-time assessment	Performance assessment	FAC to deliver PA	FCA to deliver SCC	SCC goal achievement	Use of tools for FCA
IC-M (medium coupling)	Low propensity to decouple	SCT-M (breadth)	Interface coupling is medium, as is SCT with CD a core competency. KS and CI were deployed between the OEM and tier one meter supplier to deliver the product specification. There are medium levels of FAC required to ensure SCC is appropriately set up and managed.	High												
IC-M (medium coupling)	ESI (Early supplier involvement)	SCT-M (depth and breadth)	ESI with a focus on Supplier quality occurs at the concept stage, with the focus on material evaluation, process validation, yield improvement analysis, and lead-time goal assessment. A low level of FAC is required, since these are platform products, and there is existing product and SC performance feedback.	High												
Overall level of mirroring at product launch			A strong focus on CD and FC leads to a strengthening of the coupling within this device.	High												

The causal links between PM and SCCM, for A2 are shown below, in Figure 4-13. Both CD and FC are strong intervening mechanisms. In this case there is strong ESI, which benefits from strong FC. ESI is required within the regulated medical devices sector.

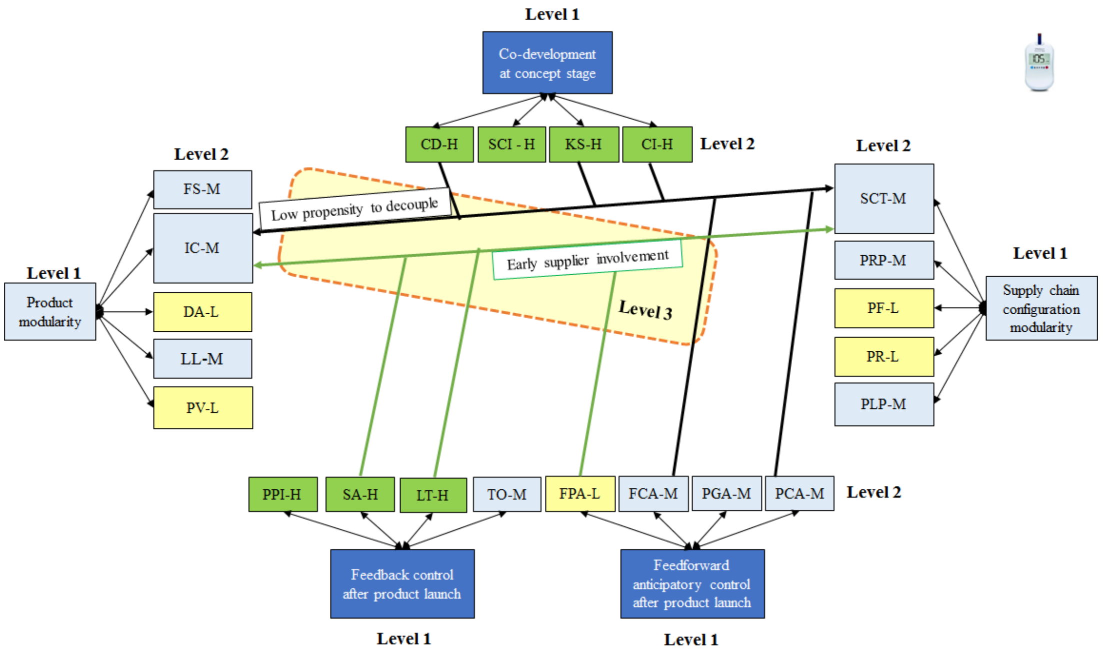


Figure 4-13. Causal relationships and intervening mechanisms - A2

4.5.1.3. Within-case findings - medical company

The medical device company demonstrates a high level of CD on all the CD variables, shown below in Table 4-10. There are high levels of knowledge sharing and early customer (practitioner) involvement in the PA design of A1, whilst there is FC data on the A2 design, from previous variants of this product released to the market. The overall goal of managing NPD is to influence economic outcomes. The CD control system encourages innovation, whilst feedback speed at the concept stage, is assisted where a product has variants of the design, already in the field.

Table 4-10. Within-case intervening mechanisms – A1 and A2

UoA	PM	Causal link	SCCM	Level of mirroring	Comments
A1	IC-M	Low propensity to decouple	SCT-M (economic and legal business involvement)	High	CD is a core practice, with KS used to analyse product and process constraints, whilst concurrently developing the product specification. FAC takes scientific research in to consideration in defining the product architecture with FAC tied to the Technology Release Level (TRL) process, in focusing on product cost, process flexibility and process yield using modelling tools. There are medium levels of FAC required to ensure SCC is appropriately setup and managed.
A2			SCT-M (breadth)		
A1	IC-M	Knowledge codification	SCT-M (depth and breadth)	High	Product complexity requires that product interface tolerances are shared at different levels of the SCT. Knowledge sharing occurs between SCC and product design, refining material and process capabilities.
A1 & A1	IC-M	Early supplier involvement	SCT-M (depth and breadth)	High	With changes to rules governing good manufacturing practices (GMPs) in 1996, the FDA placed increased emphasis on medical OEM's placing controls on their component suppliers to ensure that those components are safe and effective for the use for which they are designed. As a result, OEMs require suppliers to implement GMP-compliant quality and process validation. These device firms require evidence that devices have been verified or manufactured using validated processes. The trend in the medical device market for polymer-based products specifically is toward an increased number of alliances (SCT-M) between medical companies, molders, and raw material suppliers (NJ Hermanson, "Growth of Plastics Use in Medical Devices is Spurred by Cost-Cutting," Modern Plastics, (November 1998): A-30)

4.5.2. Within-case analysis (domestic appliances)

The CD, FC and FAC variables for B1 and B2 are shown in Appendices 4-8, Pages 471 73.

Within-case analysis for the domestic appliances in general illustrates low levels of intervening mechanisms. A low PD, is the single causal link between PM and SCCM. The focus of B1 is on meeting a specific noise specification, using concurrent product and SCC specification development. When a company communicates and articulates a performance specification, this develops the organisations capacity to make sound economic decisions, and empowers the NPD team to innovate, unencumbered by analysis or facts at the concept stage. Design simulation tools are being used by this company to reduce the reliance on physical prototyping, shown below in Table 4-11 and Figure 4-14.

4.5.2.1. Within-case analysis - B1

Table 4-11. Causal linking relationships - B1

Causal relationships between PM and SCCM for B1					Co-development				Feedback control				Feedforward control			
PM variable	**Causal relationship**	**SCCM variable**	**Explanation of causal relationships**	**Level of mirroring**	Co-development	SCC involvement	Knowledge sharing	Concurrent spec. dev.	Product assessment	SCC assessment	NPI lead-time assessment	Performance assessment	FAC to deliver PA	FCA to deliver SCC	SCC goal achievement	Use of tools for FCA
IC-L (tight coupling)	Low propensity to decouple	SCT-M (depth and breadth)	Elements of CD are used to deliver the product specification which requires tight coupling, though SCC is considered late in the concept stage. Suppliers are not involved early, and there is a low level of KS. Suppliers are requested to deliver parts to a defined specification. There is a notable absence of feedback control whilst FAC is used to focus on concurrent development of the product specification.	Medium												
Overall level of mirroring at product launch			There is a medium level of mirroring of PM and SCCM. The focus is on materials selection by the OEM, rather than supplier involvement at the concept stage.	Medium												

CD, FC and FAC are all medium level with this UoA, which is a technology advanced fast follower product.

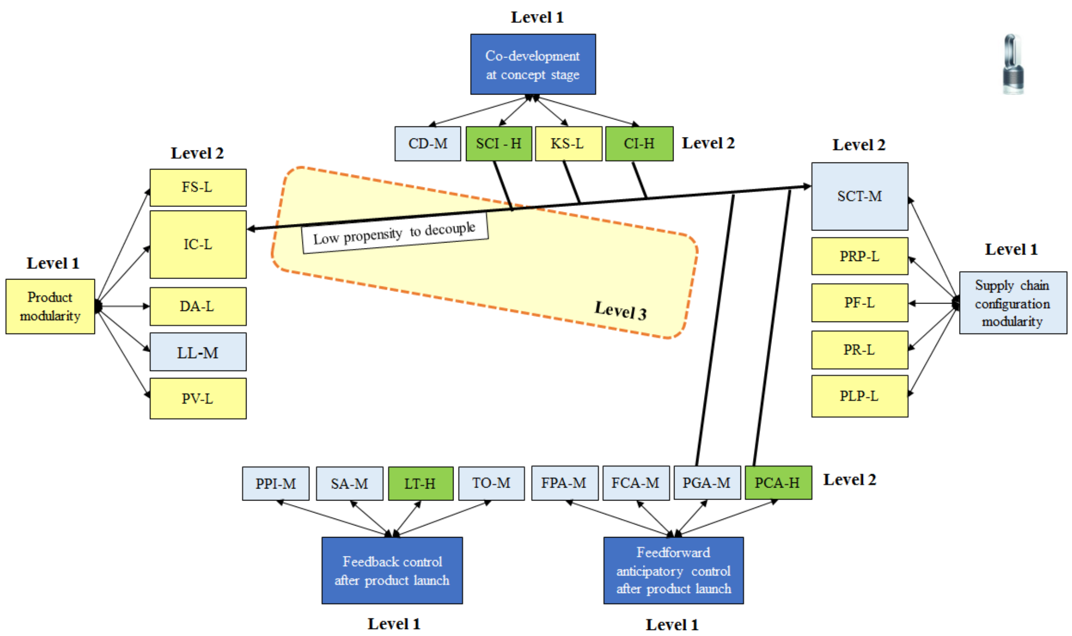


Figure 4-14. Causal relationships and intervening mechanisms - B1

4.5.2.2. Within-case analysis - B2

B2 had high PD, at the concept stage. FAC was used to deliver the PA, shown in Table 4-12. Modular design benefits from FAC involvement, as it requires increased levels of PM and SCCM interface design. This product development team are using digital product design simulation and testing tools. With this UoA there is poor use of CD, and limited use of FC, limited to warranty returns data, shown in Table 4-12 and Figure 4-15. The domestic appliances illustrate tight and medium interface coupling.

Table 4-12. Causal linking relationships - B2

Causal relationships between PM and SCCM for B2					Co-development				Feedback control				Feedforward control			
PM variable	**Causal relationship**	**SCCM variable**	**Explanation of causal relationships**	**Level of mirroring**	Co-development	SCC involvement	Knowledge sharing	Concurrent spec. dev.	Product assessment	SCC assessment	NPI lead-time assessment	Performance assessment	FAC to deliver PA	FCA to deliver SCC	SCC goal achievement	Use of tools for FCA
IC-M (medium coupling)	High propensity to decouple	SCT-M (depth and breadth)	The product is designed for serviceability. Elements of the product are designed for ease of decoupling, including the canister and filter which are separable from the cyclone and digital motor. FAC is used to deliver the medium level of interface coupling, and serviceability.	High												
Overall level of mirroring at product launch			The level of mirroring is high at launch. This product is part of a platform of similar products. The focus is on delivery of quality products at launch, this is achieved by managing input variables and applying FAC to maintain high levels of mirroring.	High												

The SCT for B2 evolved as the product was launched, with a primary sub-assembler tasked with managing the lower supply chain tiers. There was a low level of CD for B2, see Table 4-13. With these products form factor (space) design is an important consideration. *"Sometimes modularity is sacrificed for the sake of the design",* interviewee for UoA B1. There are low levels of customer involvement for B1 and B2.

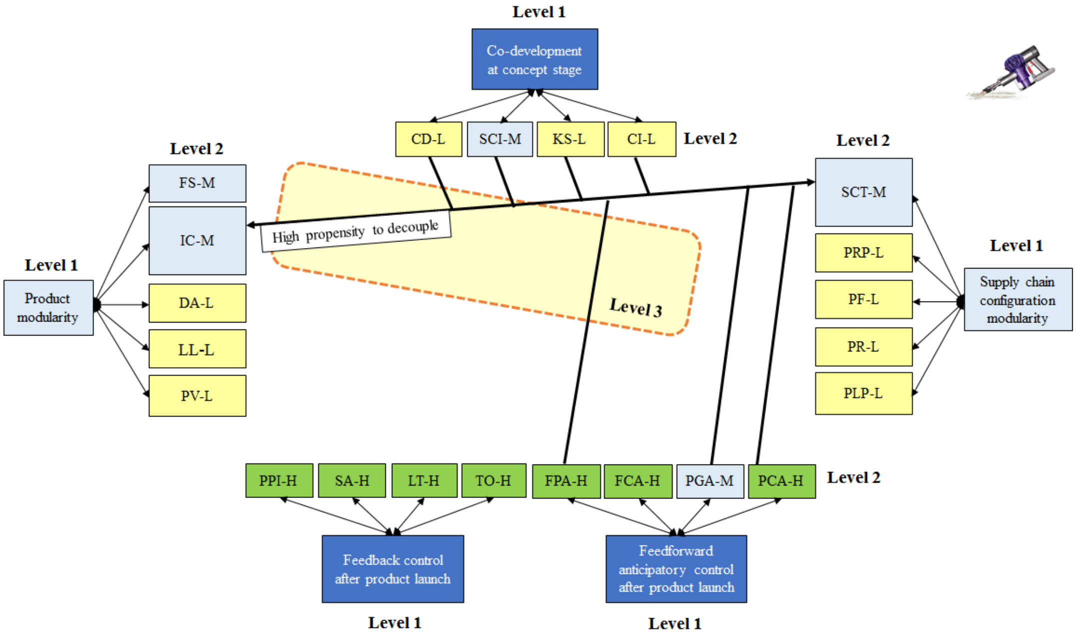


Figure 4-15. Causal relationships and intervening mechanisms - B2

4.5.2.3. Within-case findings - domestic appliances company

There are low levels of customer involvement for B1 and B2. In-house design allows for low PD, and speeds time-to-launch. IC is evolving with these over the NPD cycle for these product from high to low PD.

Table 4-13. Within-case intervening mechanisms – B1 and B2

UoA	PM	Causal link	SCCM	Level of mirroring	Comments
B1	IC-L	Low propensity to decouple	SCT-M (depth and breadth)	Medium	There is limited use of CD in the delivery of the product specification. Suppliers are not involved early, and there is a low level of KS. Suppliers are requested to deliver parts to a defined specification. There is a notable absence of feedback control whilst FAC is used to focus on concurrent development of the product specification.
B2	IC-M			High	

4.5.3. Within-case analysis (automotive products)

The CD, FC and FAC variables for C1 and C2 are shown in Appendices 4-9, Pages 474 – 76.

4.5.3.1. Within-case analysis - C1

Table 4-14. Causal linking relationships - C1

Causal relationships between PM and SCCM for C1					Co-development				Feedback control				Feedforward control			
PM variable	**Causal relationship**	**SCCM variable**	**Explanation of causal relationships**	**Level of mirroring**	Co-development	SCC involvement	Knowledge sharing	Concurrent spec. dev.	Product assessment	SCC assessment	NPI lead-time assessment	Performance assessment	FAC to deliver PA	FCA to deliver SCC	SCC goal achievement	Use of tools for FCA
IC-M (medium coupling)	High propensity to decouple	SCT-H (depth, breadth)	KS and CI at the concept stage are required to support customer variety offering, at the top three levels of the BOM for this UoA. IC-M is required to provide product customisation, upgradeability and serviceability. High customisation is a common feature of the high end SUV market. A high propensity to decouple the product, leads to SCT-H, with high levels of FCA used to deliver the levels decoupling and SCC goal achievement.	Medium												
IC-M (medium coupling)	Knowledge codification	SCT-H (depth, breadth, economic and legal business involvement)	Interface coupling at the top three levels of the BOM is medium. KS is required to link PA and SCC, since seats, navigation, infotainment, heating, lighting and other cross car modules are primarily cross-independent with some inter-dependency where for instance power is required. The top level assembly uses a combination of bus (power and communications interconnect) and slot modularity (mechanical interconnect).The OEM's Product champion co-ordinates this knowledge coding and overall PA. Explicit PA knowledge is shared internally and externally with suppliers of these cross-car modules. This knowledge consists of codified performance, environmental, cost, and interface information. The overall SCT level is high, from a depth, breadth, and economic involvement perspective with the OEM assembling the final product.	Medium												
IC-M (medium coupling)	ESI (Early supplier involvement)	SCT-H (depth, breadth and economic and legal involvement)	Module interface coupling is medium. The OEM requires access to module-specific knowledge at the concept stage for new to market top-hat modules. The OEM requires ESI with lower tier suppliers, who have access to new technology innovation. SCI is required due to the many innovative technologies included in the cross car lines. Component suppliers Bosch and ITT for instance, were the first to introduce the ABS system. ESI leads to a high level of SCT, since suppliers have the required level of economic business involvement, necessary to allow them invest in the required SC processes and capacity.	Medium												
DA-H (data access high)	Life-cycle	SCT-H (depth, breadth)	The OEM uses modularity to integrate external sources of innovation. This UoA accesses performance data at module level, there is a requirement to provide a communication channel to allow access to the servo, and actuator modules. Often these communications technologies are first incorporated into concept vehicles. DA embedment in the product design requires a high level of KS, the cause-effect model however is one-directional from product to SCT.	High												
Overall level of mirroring at product launch			The overall level of mirroring is medium, due to IC-M, and the requirement for the provision of product variety post the product assembly process.	Medium												

There is a notable lack of FC in the case of C1. FC is limited to trade-off analysis associated with design options. These high-end SUV automobiles place a lot of focus on delivering product variety, see Figure 4-16.

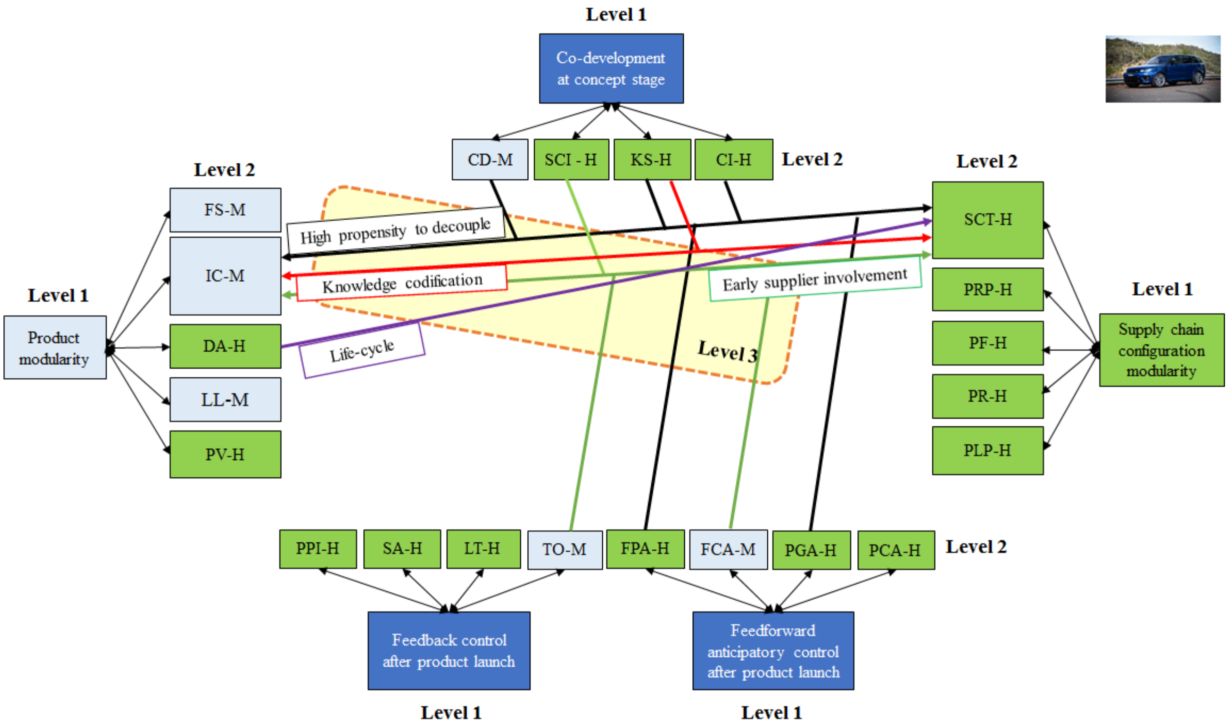


Figure 4-16. Causal relationships and intervening mechanisms - C1

4.5.3.2. Within-case analysis - C2

C2 illustrate similar intervening mechanism values as C1, see Table 4-15 and Figure 4-17

Table 4-15. Causal linking relationships - C2

Causal relationships between PM and SCCM for C2					Co-development				Feedback control				Feedforward control			
PM variable	**Causal relationship**	**SCCM variable**	**Explanation of causal relationships**	**Level of mirroring**	Co-development	SCC involvement	Knowledge sharing	Concurrent spec. dev.	Product assessment	SCC assessment	NPI lead-time assessment	Performance assessment	PAC to deliver PA	PCA to deliver SCC	SCC goal achievement	Use of tools for PCA
IC-M (medium coupling)	High propensity to decouple	SCT-H (depth, breadth)	KS and CI at the concept stage are required to support customer variety offering, at the top three levels of the BOM for this UoA. IC-M is required to provide product customisation, upgradeability and serviceability. High customisation is a common feature of the high end SUV market. A high propensity to decouple the product, leads to SCT-H, with high levels of FCA used to deliver the levels decoupling and SCC goal achievement.	Medium												
IC-M (medium coupling)	Knowledge codification	SCT-H (depth, breadth and economic and legal involvement)	Interface coupling at the top three levels of the BOM is medium. KS is required to link PA and SCC, since seats, navigation, infotainment, heating, lighting and other cross car modules are primarily cross-independent with some inter-dependency where for instance power is required. The top level assembly uses a combination of bus (power and communications interconnect) and slot modularity (mechanical interconnect).The OEM's Product champion co-ordinates this knowledge coding and overall PA. Explicit PA knowledge is shared internally and externally with suppliers of these cross-car modules. This knowledge consists of codified performance, environmental, cost, and interface information. The overall SCT level is high, from a depth, breadth, and economic involvement perspective with the OEM assembling the final product.	Medium												
IC-M (medium coupling)	ESI (Early supplier involvement)	SCT-H (depth, breadth and economic involvement)	Module interface coupling is medium. The OEM requires access to module-specific knowledge at the concept stage for new to market top-hat modules. The OEM requires ESI with lower tier suppliers, who have access to new technology innovation. SCI is required due to the many innovative technologies included in the cross car lines. Component suppliers Bosch and ITT for instance, were the first to introduce the ABS system. ESI leads to a high level of SCT, since suppliers have the required level of economic business involvement, necessary to allow them invest in the required SC processes and capacity.	Medium												
DA-H (data access high)	Life-cycle	SCT-H (depth, breadth)	The OEM uses modularity to integrate external sources of innovation. This UoA accesses performance data at module level, where there is a requirement to provide a communication channel for the servo, and actuator modules. Often these communications technologies are first incorporated into concept vehicles. DA embedment in the product design requires a high level of KS, the cause-effect model however is one-directional from product to SCT.	High												
Overall level of mirroring at product launch			The overall level of mirroring is medium, due to IC-M, and the requirement for the provision of product variety post the product assembly process.	Medium												

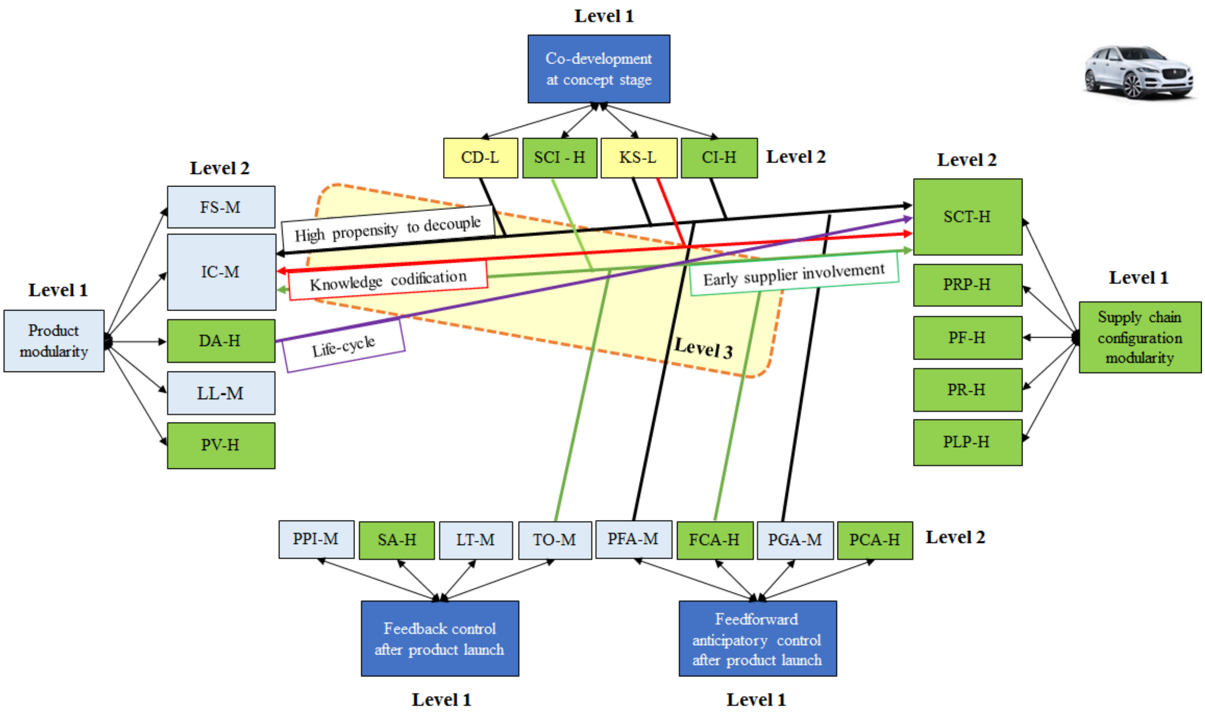


Figure 4-17. Causal relationships and intervening mechanisms - C2

4.5.3.3. Within-case findings – automotive company

The automotive company demonstrates a high level of CD on the concept stage, see Table 4-17. Within-case analysis for C1 and C2 illustrate weak levels of FC and FAC intervening mechanisms. SCT is high with low levels of economic business involvement

Table. 4-16. Within-case intervening mechanisms - C1 and C2.

UoA	PM	Causal link	SCCM	Level of mirroring	Comments
C1	IC-M	Knowledge codification	SCT-H (depth, breadth, low levels of economic business involvement)	Medium	Knowledge codification requires that knowledge is codifiable. It involves making knowledge visible, accessible, and usable for decision making, within the Supply network. This knowledge is codified as a set of rules.
C2					
C1	IC-M	Early supplier involvement		Medium	Companies should consider two major factors when deciding when to integrate the supplier into the product development process: the rate of change of the technology, and the level of supplier expertise in the given technology. Generally speaking, if the technology is undergoing a significant amount of technological change, it should be delayed in the product development cycle. On the other hand, if a supplier's design expertise is significant and its technology experts can provide insights instrumental to crafting the new product, that supplier should be included earlier in the process. This is the situation with the driveline solutions co., who supplies E1 and E2.
C2					
C1	IC-M	High propensity to decouple		Medium	A product being delivered in an ATO fashion has an internal CODP, which makes the internal SCC a mix of MTS and MTO (after Olhager, 2012).
C2					
C1	DA-H	Life-cycle	SCT-H (depth, breadth)	High	Communications is the next frontier of car technology. Increased safety and smarter energy are some of the benefits of Vehicle-to-everything (V2X) technologies. SCT-H is required to allow field testing of these technologies, as they are released over the coming years. With the advent of the software-defined car OEMs, Tier-1 suppliers, and dealers need to have the tools and the platform necessary to enhance security in real time and in a seamless manner.
C2					

4.5.4. Within-case analysis (auto-driveline products)

The CD, FC and FAC variables for D1 and D2 are shown in Appendices 4-10, Pages 477 - 79.

IC is tight for D1, where there is extensive use of CD, and high use of FAC. This tier-one supplier is continuously developing new technologies for the automotive sector, and ESI is a causal link between PM and SCCM.

4.5.4.1. Within-case analysis - D1

Table 4-17. Causal linking relationships - D1

Causal relationships between PM and SCCM for D1					Co-development				Feedback control				Feedforward control			
PM variable	**Causal relationship**	**SCCM variable**	**Explanation of causal relationships**	**Level of mirroring**	Co-development	SCC involvement	Knowledge sharing	Concurrent spec. dev.	Product assessment	SCC assessment	NPI lead-time assessment	Performance assessment	FAC to deliver PA	FCA to deliver SCC	SCC goal achievement	Use of tools for FCA
IC-L (tight coupling)	Low propensity to decouple	SCT-L (economic and legal involvement)	Tight coupling is defined at the concept stage. The modules operate inter-dependently, and are not easily decoupled. Tight coupling is driven by high reliability and performance requirements, with he modules designed to cover the serviceable life of the automobile. The effect of standardising interfaces early is ensure that SCC processes steps are repeatable, this is achieved using high levels of CD and FAC. SCT is focused on efficiently and repeatability delivering the drivetrain platform.	High												
IC-L (tight coupling)	ESI (Early supplier involvement)	SCT-L (economic and legal involvement)	This sub-assembly has tight coupling, modules are application-specific, with their own standards. The selection of modules requires ESI. The specific automobile application determines the torque, capacity and speed of each component, this knowledge is shared amongst suppliers. IC knowledge is shared early with component suppliers, this knowledge consists of torque requirements, electronic and electrical connections, signal bus architecture, and interface tolerances. Often these modules are initially combined and performance tested on concept cars. This tier one supplier has a high level of knowledge sharing with the OEM and provides high levels of design input at the concept stage. There is a low level of SCT and SCCM. This supplier is a leader across the entire range of driveline solutions, and makes a significant contribution at the concept stage, in particular in fuel efficiency, reduced emissions, electrification, weight and space saving idea's. This strategic supplier is the sole source of drivetrains for the OEM, the supplier is a leader in providing many of the technologies contained in the drivetrain.	High												
DA-H (data access high)	Life-cycle	SCT-L (economic and legal involvement)	There is a high level of data access, within the product design. The effect of the arrival of technologies such as radar, lidar, GPS, Odometry, and computer vision, requires product design teams look at means of upgrading these devises across the product life-cycle. Advanced control systems interpret sensory information to identify appropriate navigation paths, as well as obstacles and relevant signage. Data access requires participation by key suppliers, and distribution partners. With the low levels of SCT the access to lower level suppliers may be restricted, resulting in a medium level of mirroring. This risk is managed by the OEM through both relational and modular governance of the supply network. Knowledge is coded to allow the electronic and communications engineers transmit data relating to data access, speed, protocols, standards, security and protection. Data access security is a key consideration.	Medium												
Overall level of mirroring at product launch			Mirroring is high, due to the high level of co-development at the concept stage. Application engineers work closely with their supply chain design counter-parts to build an efficient SCC.	High												

Figure 4-18 illustrates strong use of CD.

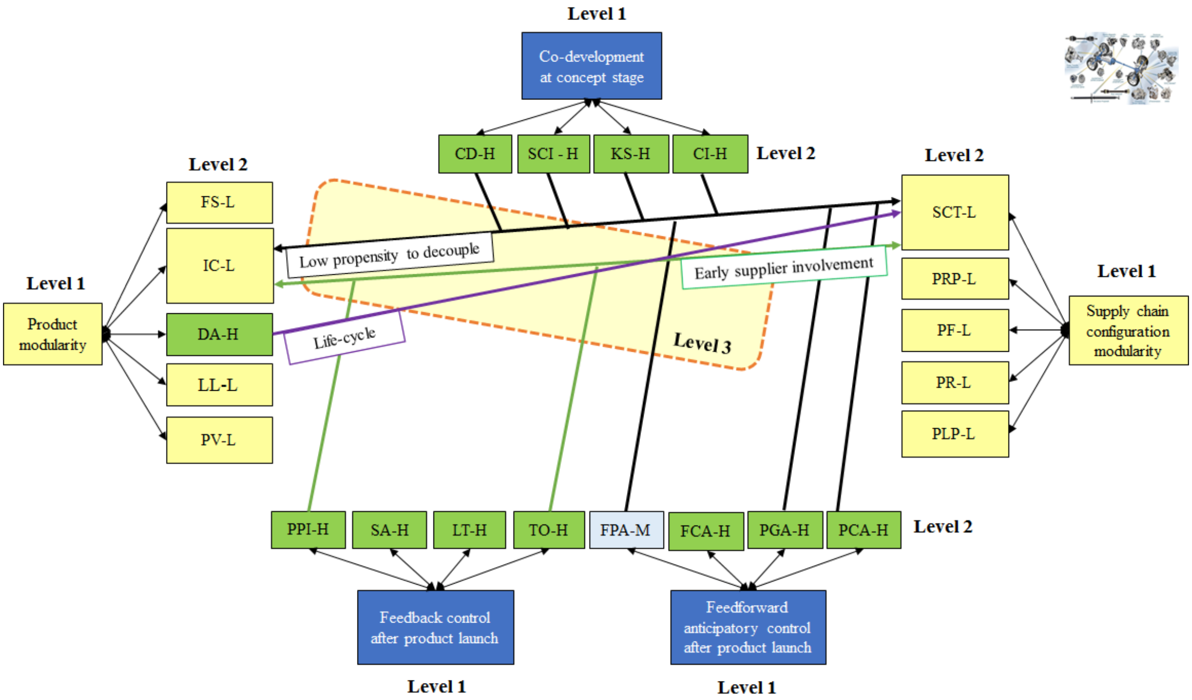


Figure 4-18. Causal relationships and intervening mechanisms - D1

4.5.4.2. Within-case analysis - D2

D2 is produced by the same tier-one supplier as D1. The intervening mechanisms for both UoA are similar.

Table 4-18. Causal linking relationships - D2

Causal relationships between PM and SCCM for D2					Co-development				Feedback control				Feedforward control			
PM variable	**Causal relationship**	**SCCM variable**	**Explanation of causal relationships**	**Level of mirroring**	Co-development	SCC involvement	Knowledge sharing	Concurrent spec. dev.	Product assessment	SCC assessment	NPI lead-time assessment	Performance assessment	FAC to deliver PA	FCA to deliver SCC	SCC goal achievement	Use of tools for FCA
IC-L (tight coupling)	Low propensity to decouple	SCT-L (economic and legal business involvement)	This UoA relies on tight coupling, of standard components. Four-wheel drive systems are generally non-modular, with components being system specific however there are certain components such as the wheel's and non-application specific components which are de-couplable. There are high levels of CD and FAC present at the concept stage.The COEP occurs pre product assembly with the level of process postponement low. COEP at the module interface, leads to high levels of mirroring for this product.	High												
IC-L (tight coupling)	ESI (Early supplier involvement)	SCT-L (economic and legal business involvement)	With thirty per cent of components specific to customer applications there is a requirement for ESI, at the concept stage. IC knowledge is shared with the component suppliers. This sub-assembly ships as a system to the same supplier, for integration in to the drivetrain (D1). ESI is required to ensure product performance specification is achieved at product launch, and component level innovation is supplied at the product concept stage, with PPI and TO occuring at the concept stage.	High												
Overall level of mirroring at product launch			Mirroring is high, due to the high level of co-development at the concept stage. Application engineers work closely with their supply chain design counter-parts in achieving both PA and SCC goals.	High												

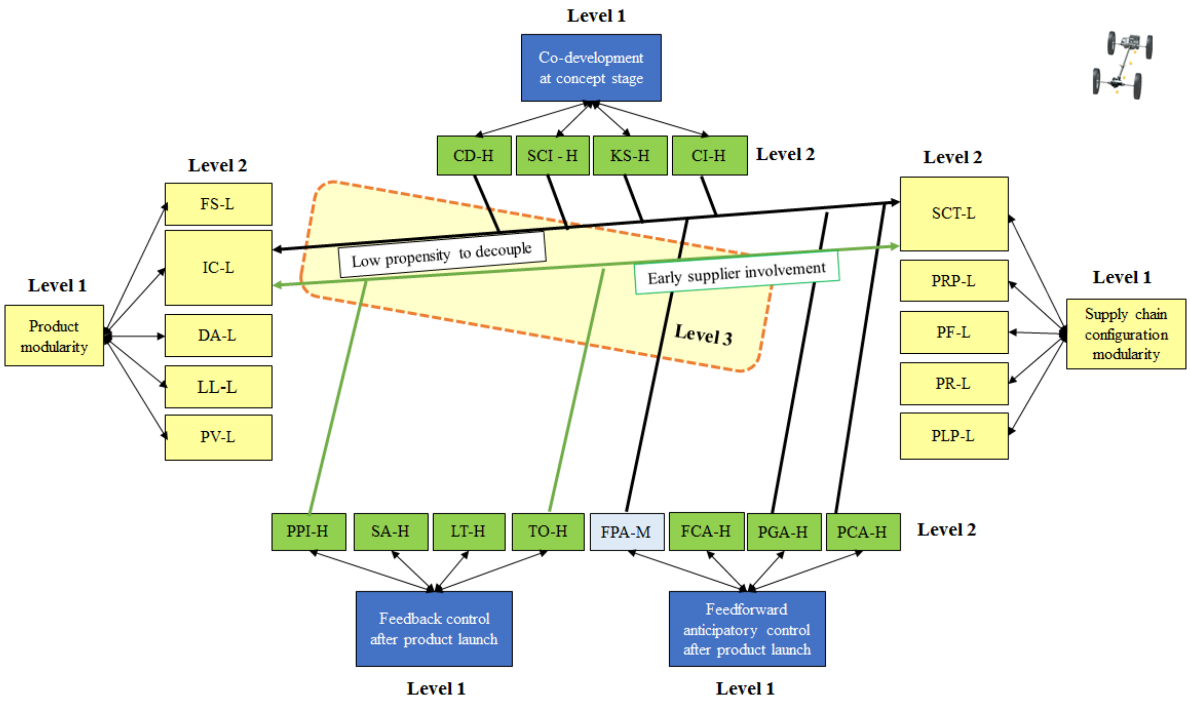


Figure 4-19. Causal relationships and intervening mechanisms - D2

4.5.4.3. Within-case findings (auto-driveline company)

D1 and D2 illustrate a high level of mirroring, and low PD. KC is important between this tier-one supplier and the OEM for C1 and C2.

Table. 4-19 Within-case intervening mechanisms - D1 and D2

UoA	PM	Causal link	SCCM	Level of mirroring	Comments
D1	IC-L	Early supplier involvement	SCT-L (economic and legal involvement)	High	This tier one supplier is involved early at the concept stage with design simulation, because of the companies leadership in drivetrain design. ESI comprises of "integrative strategies including shared education and training and cost information sharing", (after Ragatz *et al.* 1997).
D2	IC-M		SCT-M (economic and legal business involvement)	High	
D1	IC-L	Low propensity to decouple	SCT-L (economic and legal involvement)	High	D2 is MTS, since these are for standard products with predetermined and narrow range and high volume (Berry and Hill 1992). D1 ATO and has an internal CODP, which makes the internal SCC a mix of MTS and MTO, (after Olhager, 2012).
D2	IC-M		SCT-M	High	
D1	DA-H	Life-cycle	SCT-L (economic and legal involvement)	Low	Vehicle connectivity to each other, to the infrastructure and to the cloud requires continuous controls development with increasing access to vehicle drivetrain / powertrains. Memory and computational power is no longer a barrier to optimal powertrain control and calibration. Increased sensor technology development is paving the way for this life-cycle approach, to future automotive technology design.

4.5.5. Within-case analysis (aerospace products)

The CD, FC and FAC variables for E1 and E2 are shown in Appendices 4-11, Pages 480 - 81.

Within-case analysis with E1 illustrates strong use of CD, and strong use of FC and FAC intervening mechanisms, shown below in Table 4-20, and Figure 4-20. This tier-one supplier is a leading supplier of aero-structure assemblies to the aerospace industry, and is focused on product and process innovation.

4.5.5.1. Within-case analysis - E1

Table 4-20. Causal linking relationships - E1

Causal relationships between PM and SCCM for E1					Co-development				Feedback control				Feedforward control			
PM variable	**Causal relationship**	**SCCM variable**	**Explanation of causal relationships**	**Level of mirroring**	Co-development	SCC involvement	Knowledge sharing	Concurrent spec. dev.	Product assessment	SCC assessment	NPI lead-time assessment	Performance assessment	FAC to deliver PA	FCA to deliver SCC	SCC goal achievement	Use of tools for FCA
IC-L (tight coupling)	Low propensity to decouple	SCT-L (economic and legal business involvement)	Coupling is tight, and maintained by a high level of CD. SCT is equally tight with strong economic and legal business involvement by the OEM.	High												
IC-L (tight coupling)	Knowledge codification	SCT-L (economic and legal business involvement)	The tightness of the PM coupling requires KS between this tier one supplier and the OEM. There is less than one millimeter of tolerance along the entire length of the airplane wing. These tight tolerances drive a high level of knowledge codification. The composite carbon material used in the construction of this UoA required extensive R&D involvement during the concept stage by this tier one supplier and the OEM. This captive supplier is linked to the OEM through a low level of SCT. FCA was used to deliver the product specification.	High												
IC-L (tight coupling)	ESI (Early supplier involvement)	SCT-L (economic and legal business involvement)	Interface coupling is tight. This integrated sub-assembly requiring ESI, with the OEM. The tier one supplier provided design, development and productionisation services. ESI SCT is low level since this tier one supplier developed and provided the auto fibre placement and automated assembly processes, for this UoA. ESI using PPI and LT is required to ensure product and process reliability and lead-time delivery assessment. A design and build risk sharing partnership was commited by this supplier, with an investment of $280M over a five year period, with the engineering team assembled and on this program.	High												
Overall level of mirroring at product launch			There is a high level of mirroring due to the extremely close relationship between this supplier and the OEM customer, throughout the process and product R&D phase.	High												

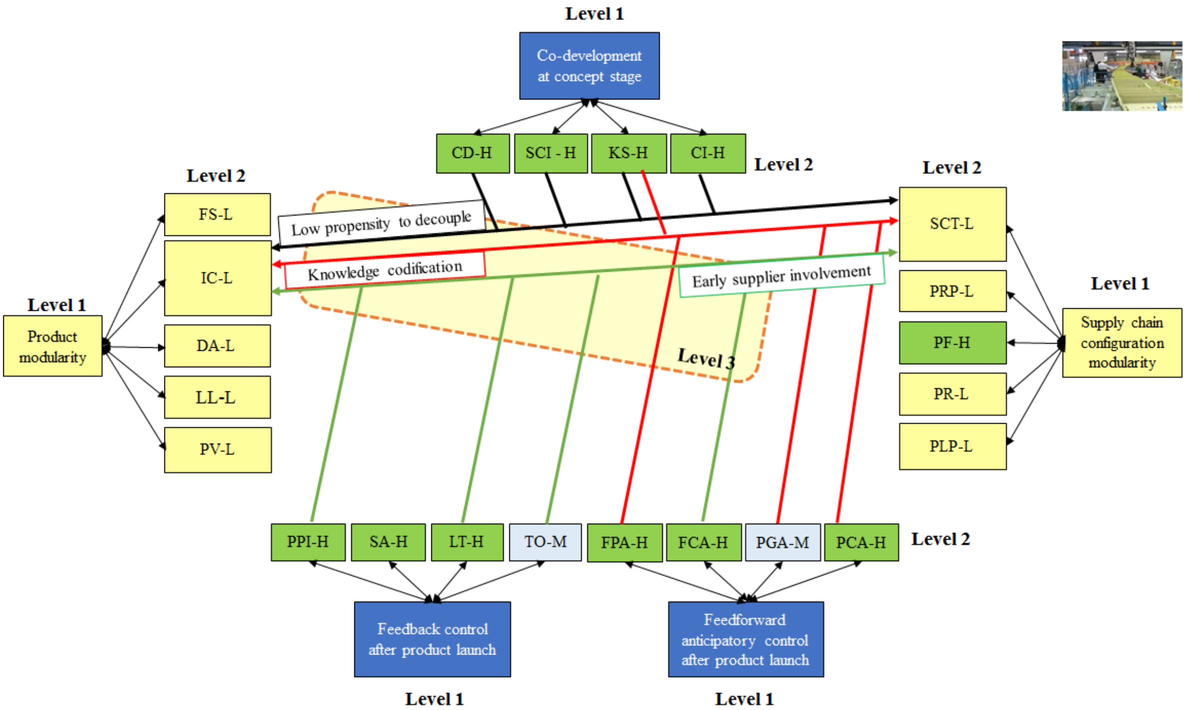


Figure 4-20. Causal relationships and intervening mechanisms - E1

4.5.5.2. Within-case analysis - E2

Within-case analysis of E2 shows high used of CD and high use of knowledge sharing, and FC, as shown below in Table 4-21, and Figure 4-21.

Table 4-21. Causal linking relationships - E2

Causal relationships between PM and SCCM for E2					Co-development				Feedback control				Feedforward control			
PM variable	**Causal relationship**	**SCCM variable**	**Explanation of causal relationships**	**Level of mirroring**	Co-development	SCC involvement	Knowledge sharing	Concurrent spec. dev.	Product assessment	SCC assessment	NPI lead-time assessment	Performance assessment	FAC to deliver PA	FCA to deliver SCC	SCC goal achievement	Use of tools for FCA
IC-L (tight coupling)	Low propensity to decouple	SCT-H (economic and legal business involvement)	Interface coupling is tight. There is a low propensity to decouple at the top three levels of the BOM, with high levels of CD and FAC used. Given the high required reliability, system integration, high levels of redundancy, and input/output monitoring of an airplane there is a requirement for this low decoupling.	Low												
IC-L (tight coupling)	Knowledge codification	SCT-H (depth, breadth, economic and legal business involvement)	Tight interface coupling requires KS, with a high level of knowledge codification between the OEM and module suppliers. The relatively low level of KS across the tiers, is an industry concern, in this sector. There have been examples of product launch delays, and cost over-runs as an example of this medium level of KS. This company experienced a $6B cost over-run and a three year delay with a previous product launch due to inconsistent KS, this has led to a high focus level on NPD leadtime goal assessment.	Medium												
IC-L (tight coupling)	ESI (Early supplier involvement)	SCT-H (economic and legal business involvement)	Technology advances require ESI. New avionics controls for example are often tried and tested on business jets first, prior to integration in commercial airplanes. ESI is required to establish the manageable span of the supply network, and the levels of economic and legal business involvement required with tier one and sub-tier suppliers. There is a high level of economic and legal involvement by the OEM, with tier one suppliers, in some instances the OEM has taken legal control of the tier one supplier based on schedule, quality and cost over-run risks.	Medium												
DA-H (data access high)	Life-cycle	SCT-H (economic and legal business involvement)	Controller Pilot data link communications, in-flight entertainment, remote data monitoring are examples of DA-H. Data access levels require extensive knowledge sharing between the OEM, distribution and service channel partners and regulatory agencies, over the life-cylce of the product. With SCT-H there is a requirement from a regulatory, standards and company perspective for high levels of KS, over the life-cycle. This is driven from the DA perspective, the relationship is one-directional.	High												
Overall level of mirroring at product launch			The overall level of mirroring is medium, due to IC-L, and the requirement for the decoupling of certain systems at the top-level assembly.	Medium												

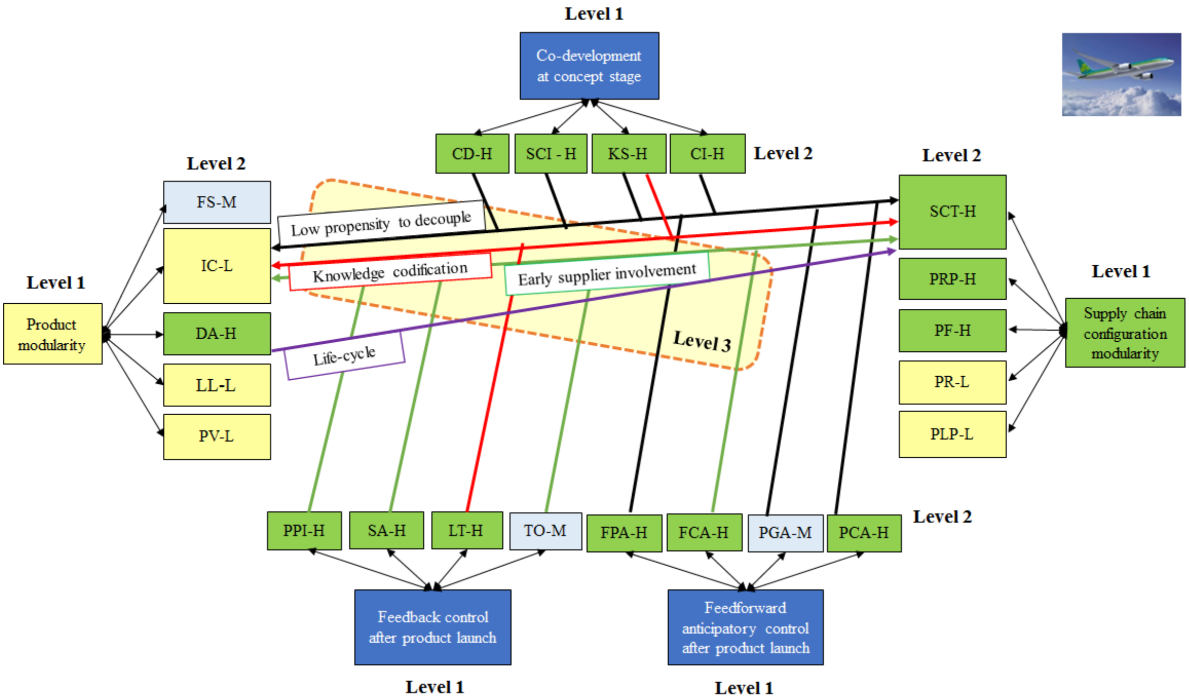


Figure 4-21. Causal relationships and intervening mechanisms - E2

4.5.5.3. Within-case findings - aerospace companies

In the case of the aerospace companies UoA, E1 and E2, all CD variables demonstrate high levels, see Table 4-22. Within-case analysis of E1 and E2 illustrates strong mirroring at the sub-assembly level and medium mirroring at the top-level-assembly. CD is used extensively, together with FC and FAC mechanisms, see Table 4-22.

Table. 4-22 Within-case intervening mechanisms E1 and E2.

UoA	PM	Causal link	SCCM	Level of mirroring	Comments
E1	IC-L	Knowledge codification	SCT-L (economic and legal business involvement)	High	Knowledge codification (KC) involves making knowledge visible, accessible, and usable for decision making, within the supply network. This knowledge is codified as a set of rules. With the airplane supply network internal and external knowledge-based linkages are required across the entire depth and breadth of the network. The OEM is dependent on technological innovation from and between suppliers.
E2			SCT-H (depth, breadth, economic and legal business involvement)	Medium	
E1	IC-L	Early supplier involvement	SCT-L (economic and legal business involvement)	High	E1 engaged for over ten years in primary research on composite materials technology development, working alongside the OEM E2, this was followed by twenty years engagement in product development. The OEM and tier one supplier have developed an Aerospace Joint Venture where both companies work on improving together the airplane design.
E2		Early supplier involvement	SCT-H (economic and legal business involvement)	Medium	
E1	IC-L	Low propensity to decouple	SCT-L (economic and legal business involvement)	High	E1 is manufactured to order. Interface coupling is tight, and there is a strong economic and legal business involvement by the OEM, through a Joint Venture alliance.
E2	IC-L	High propensity to decouple	SCT-H (economic and legal business involvement)	Medium	E2 is a built to the customer order. There is a high level of economic and legal involvement by the OEM, with the supply network, through a Joint Venture alliance.
E2	DA-H	Life-cycle	SCT-H (economic and legal business involvement)	High	Satellite communications allows direct access to airplanes, with enhancements in sensor technology more functions of an airplane can be monitored from the ground. There is paramount focus on data security. In some instance for example in-flight entertainment airlines have taken back control from suppliers, standards are rigorous in managing this data control.

4.5.6. Cross-case analysis

This empirical research in project three found no link between place postponement and life cycle, in the mirroring of PM with SCCM. This supports the research in project two. There is a medium to high level of use of intervening mechanisms across all ten UoA, see

Table 4-23. The numbers in the table illustrate the number of UoA using each intervening mechanism.

The PD (low and high) causal link appears to have the highest level of associated intervention, followed by knowledge sharing and ESI. CD is the overall strongest intervening mechanism, followed by FAC, with weak FC overall. This could be attributable to these being new-to-market products, though this hypothesis was not investigated. A detailed cross-case review of the levels of these intervening mechanisms is also provided in Appendices 4-11, 4-12 and 4-13, Pages 480-485.

Table 4-23. Causal relationships between PM and SCCM

Causal relationships between PM and SCCM					Co-development				Feedback control				Feedforward control			
PM variable	**Causal relationship**	**SCCM variable**	**Explanation of causal relationships**	**Level of mirroring**	Co-development	SCC involvement	Knowledge sharing	Concurrent spec. dev.	Product assessment	SCC assessment	NPI leadtime assessment	Performance assessment	FAC to deliver PA	FCA to deliver SCC	SCC goal achievement	Use of tools for FCA
IC	High propensity to decouple	SCT	A1 and A2 are influenced by CD, KS and CI. A1 is influenced by FPA, PGA and PCA. B2 is influenced by FPA and PCA.	High	2		2	2					2		1	2
IC	Low propensity to decouple	SCT	D1, D2 and E1 are influenced by CD, SCI, KS and CI. D1 and D2 are influenced by PGA and PCA.	High	3	3	3	3							2	2
IC	Knowledge codification	SCT	A1, A2 and E1 are influenced by KS. A2 is influenced by SA and LT. E1 is influenced by FPA and PCA.	High			3			1	1		1			1
IC	ESI (Early supplier involvement)	SCT	A1 is influenced by SCI. D1, D2 and E1 and influenced by PPI. E1 is influenced by PPI, LT and FCA. D1 and D2 are influenced by TO.	High		1			3		1	2		1		
IC	High propensity to decouple	PRP	High propensity to decouple is not influenced by any intervening mechanisms.	High												
IC	Low propensity to decouple	PRP	Low propensity to decouple is not influenced by any intervening mechanisms.	High												
DA	Life-cycle	SCT	Life-cycle perspective of design is not influenced by any intervening mechanisms.	High												

Knowledge codification relates to tight to medium IC across the three levels of SCT. In all cases there is a strong focus on technology innovation, and its incorporation in NPD. These companies established inter-company alliances with their supply network that are not fully defined either by formal contracts or by ownership. These companies established substantial collaboration with their suppliers, often by pooling of their resources and activities. Brusconi *et al.* (2001) research into aero engines and other complex production systems identifies the critical importance of overlaps between partners' knowledge bases, where the company acts as overall knowledge integrator.

The need for knowledge duplication between alliance partners means that a key issue for the efficiency of alliances, relative to individual companies, is the amount of common knowledge required for effective knowledge integration (Grant and Baden-Fuller, 2004). Knowledge codification provides PM mirroring with SCCM for A1 and E1; in both cases KC is required to reduce the complexity of the knowledge exchanged between the OEMs and the supply network, shown below in Table 4-24.

Table 4-24. Knowledge codification

UoA	PM	Causal link	SCCM	Level of mirroring	Comments
A1	IC-M	SCT-M (depth and breadth)	Knowledge codification	High	Knowledge codification involves making knowledge visible, accessible, and usable for decision making, within the supply network. This knowledge is codified as a set of rules.
C1	IC-M	SCT-H (depth, breadth, economic and legal business involvement)		Medium	Knowledge codification involves making knowledge visible, accessible, and usable for decision making, within the supply network. This knowledge is codified as a set of rules.
C2					
E1	IC-L	SCT-L (economic and legal business involvement)		High	Knowledge codification (KC) involves making knowledge visible, accessible, and usable for decision making, within the supply network. This knowledge is codified as a set of rules. With the airplane supply network, internal and external knowledge-based linkages are required across the entire depth and breadth of the network. The OEM is dependent on technological innovation from and between suppliers.
E2		SCT-H (depth, breadth, economic and legal business involvement)		Medium	

All products, except for B1 and B2 require ESI. The rate of change of the technology, the level of supplier expertise in each technology and the requirement for early process validation are the primary reasons for ESI. In the case of B1 and B2, the product is designed by the OEM, and most of the components and sub-assemblies are designed by the OEM, including the digital motor, and cyclone technology. In the case of the medical device suppliers they are involved early in the product design and process validation. The automotive suppliers were involved in drivetrain technology development while the aerospace supplier was involved early in the process development of composite materials for airplanes.

ESI provides PM mirroring with SCCM for A1, A2, D1, D2 and E1. ESI is required where IC is tight to medium, to ensure interface tolerances are developed across the supply network. Supplier embeddedness at the concept stage depends on supplier competence and relational links with the OEM, shown below in Table 4-25.

Table 4-25. Early supplier involvement

UoA	PM	Causal link	SCCM	Level of mirroring	Comments
A1	IC-M	SCT-M (depth and breadth)	Early supplier involvement	High	With the changes to the rule on good manufacturing practice (GMP) in 1996, the FDA have placed increasing emphasis on medical OEM's placing controls on their component suppliers to ensure that components are safe and effective for the use for which they are designed. As a result, many OEMs are requiring their suppliers to implement GMP-compliant quality systems, including process validation. With injection molding, manufacturers are demanding that suppliers validate their plastics molding and component assembly processes. These device firms require evidence to present to FDA that the components in their devices have been verified or manufactured using validated processes. The trend in the medical device market for polymer-based products specifically is toward an increased number of alliances (SCT-M) between medical companies, molders, and raw material suppliers.
A2		SCT-M (economic and legal business involvement)			
C1	IC-M	SCT-H (depth, breadth and economic and legal involvement)		Medium	Companies should consider two major factors when deciding when to integrate the supplier into the product development process: the rate of change of the technology, and the level of supplier expertise in the given technology. If technology is undergoing a significant amount of technological change, it should if feasible be delayed in the product development cycle.
C2					
D1	IC-L	SCT-L (economic and legal involvement)		High	This tier one supplier is involved early at the concept stage with design simulation, because of the companies leadership in drivetrain design. ESI comprises of "integrative strategies including shared education, training and cost information sharing", (after Ragatz *et al.* 1997).
D2	IC-M	SCT-M (economic and legal business involvement)		High	
E1	IC-L	SCT-L (economic and legal business involvement)		High	E1 engaged for over ten years in primary research on composite materials technology development, working alongside the OEM E2, this was followed by twenty years engagement in product development. The OEM and tier one supplier have developed an Aerospace Joint Venture where both companies work on improving together the airplane design. If a supplier's design expertise is significant and its technology experts can provide insights instrumental to crafting the new product, that supplier should be included earlier in the process. This is the situation with the driveline solutions co., who supplies E1 and E2.
E2		SCT-H (economic and legal business involvement)		Medium	

Where there is low PD interface, coupling is tight to medium, and SCT is low to medium level. Low PD illustrates mirroring between PM and SCCM except for B1. In the case of B1 IC is tight, whilst there is a medium level of SCT shown below in Table 2-26.

Table 4-26. Low propensity to decouple

UoA	PM	Causal link	SCCM	Level of mirroring	Comments
A1	IC-M	SCT-M (economic and legal business involvement)	Low propensity to decouple	High	A components' separability and recombinability represent the basic conceptual features of product modularity, that reduce product architecture complexity (after Simon, 1962). A product being delivered in an ATO fashion has an internal CODP, which makes the internal SCC a mix of MTS and MTO (after Olhager, 2012).
A2		SCT-M (breadth)			
B1	IC-L	SCT-M (depth and breadth)		Medium	A components' separability and recombinability represent the basic conceptual features of product modularity, that reduce product architecture complexity (after Simon, 1962). A product being delivered in an ATO fashion has an internal CODP, which makes the internal SCC a mix of MTS and MTO (after Olhager, 2012).
B2	IC-M			High	
D1	IC-L	SCT-L (economic and legal involvement)		High	D1 ATO and has an internal CODP, which makes the internal SCC a mix of MTS and MTO, (after Olhager, 2012).
D2	IC-M	SCT-M		High	D2 is MTS, since these are for standard products with predetermined and narrow range and high volume (Berry and Hill 1992).
E1	IC-L	SCT-L (economic and legal business involvement)		High	E1 is manufactured to order. Interface coupling is tight, and there is a strong economic and legal business involvement by the OEM, through a Joint Venture alliance.

C1 and C2 have a medium level of IC (medium IC modularity) and high PD due to many different systems in the car, from heating, to electrical, navigation, infotainment, seating, etc. E2 has a high level of IC (low IC modularity) and high PD due to the many different systems in the fuselage, cockpit and airplane wings, shown below in Table 2-27.

Table 4-27. High propensity to decouple

UoA	PM	Causal link	SCCM	Level of mirroring	Comments
C1	IC-M	SCT-H (depth, breadth)	High propensity to decouple	Medium	A product being delivered in an ATO fashion has an internal CODP, which makes the internal SCC a mix of MTS and MTO (after Olhager, 2012).
C2					
E2	IC-L	SCT-H (economic and legal business involvement)			E2 is a built to the customer order. There is a high level of economic and legal involvement by the OEM, with the supply network, through a Joint Venture alliance.

Rapid advances in sensor and communications technologies are requiring designers to take a life cycle perspective on product and SCC design. Many new-to-market products do not have data access, at the time of launch, however the ability to add increasing data access during the product life cycle is a key consideration for the automotive and aerospace sectors. C1, C2 and E2 illustrate a high level of mirroring between PM and SCCM, with the life cycle perspective as the linking mechanism, shown below in Table 2-28.

Table 4-28. Life cycle perspective

UoA	PM	Causal link	SCCM	Level of mirroring	Comments
C1	DA-H	SCT-H (depth, breadth)	Life-cycle	High	Communications is the next frontier of car technology. Increased safety and smarter energy are some of the benefits of Vehicle-to-everything (V2X) technologies. SCT-H is required to allow field testing of these technologies, as they are released over the coming years. With the advent of the software-defined car OEMs, Tier-1 suppliers, and dealers need to have the tools and the platform necessary to enhance security in real time and in a seamless manner.
C2					
D1	DA-H	SCT-L (economic and legal involvement)		Low	Vehicle connectivity to each other, to the infrastructure and to the cloud requires continuous controls development with increasing access to vehicle drivetrain / powertrains. Memory and computational power is no longer a barrier to optimal powertrain control and calibration. Increased sensor technology development is paving the way for this life cycle approach, to future automotive technology design.
E2	DA-H	SCT-H (economic and legal business involvement)		High	Satellite communications allows direct access to airplanes, with enhancements in sensor technology more functions of an airplane can be monitored from the ground. There is paramount focus on data security. In some instance for example in-flight entertainment airlines have taken back control from suppliers, standards are rigorous in managing this data control.

4.6. CONTRIBUTIONS

Project three addresses the mirroring of PM with SCCM, and the benefit of using intervening mechanisms, at the concept stage, to strengthen this mirroring. This empirical research has developed an improved understanding of three intervening mechanisms which were developed using GST. This research was developed to better understand how product designers take SCC into new product design at the concept stage. The increased understanding contributes to both academic research and design practice. These two areas of contribution are discussed in the following sections.

4.6.1. Contributions to research

There are five contributions to the literature: 1) identification of mirroring mechanisms induced from the empirical research in project two; 2) assessment of the strength of CD; 3) assessment of the strength of FC; 4) assessment of the strength of FAC, and 5) assessment of the support provided by PM mirroring with SCCM, to product platform design.

The first contribution, is the identification of knowledge codification and knowledge hiding as a means of protecting IP. This contributes to research by Ragatz *et al.* (1997) who advocate the benefits of ESI in NPD, whilst managing IP risk. IP risk was deduced from the empirical research in project two. This contribution also highlights the importance of leveraging innovation capabilities within the supply network.

The second contribution, identifies the support of CD for H2. CD is based on three core principles: 1) knowledge integration which advocates the co-development of PM and SCCM. There is a high-level of knowledge sharing between product and SCC experts, supporting knowledge integration; 2) parallelism and the continuous review of product and SCC designs. There is a high level of concurrent PM development, except for one UoA, and 3) continuous development. Since CD seeks to adjust company scope to extract specialization gains from suppliers, this can only be achieved with focused and coordinated CD of the product and SCC. Many prospector companies limit the role of CD at the concept stage, to a focus on technology innovation, and integration. These prospector companies focus on the parallelism and continuous development principles with follow-on platform designs, as evidenced with the domestic appliance company. This research supports H2, and contributes to the work of Chu, Chang, and Cheng (2006), who state that “The main goal of CD is to integrate and leverage knowledge, technologies, and resources among all the collaborators, usually geographically distant, to quickly respond to the market and fulfill customer needs”.

The third contribution, identifies partial support of FC for hypothesis three. H3 is based on two core principles: 1) integrated knowledge sharing. There is a high-level of knowledge sharing between product and SCC experts, except for three UoA. There is limited used of FC for first generation products, and 2) closed loop information flow. These flows can be represented as single- or double-loop. Assessment of SCC at the concept stage was high except for to UoA which illustrate weak PM mirroring with SCCM.

The forth contribution, identifies support for hypothesis four. H4 is based on two core principles: 1) integration which advocates the co-development of PM and SCCM. There is a high-level of product level FAC used to deliver nine of the ten UoA. The exception is a highly regulated and complex product, which demonstrates a low to medium-level on all four FAC variables. Whilst the product is under-going intense competitive cost pressure, the focus is more on technology-development than cost reduction. Technology development requires materials and components supplier participation. The leading indicators are therefore focused more on the entire product eco-system than on the product, and 2) open loop information flow. These flows start and finish with the input goals that the system is seeking to accomplish. Evaluation of prospective market outcomes, cost, quality and schedule were assessed using FAC, by Baker and Bourne (2014). FAC can be accomplished using techniques such as visioneering and pre-mortems (Klein, 2007). There can be multiple attempts to mirror PM and SCCM using

FAC. Modularizations create new module boundaries with low transaction costs' (Baldwin, 2008, p.175). The evidence of the empirical research in project three supports this hypothesis.

The fifth contribution, is the assessment of the support provided by PM mirroring with SCCM, to product platform design. Most new to market products migrate to platforms, to provide increased product variety. This drive towards platforms increases PM mirroring with SCCM since it leads to higher levels of PM (loose interface coupling) and an increased spread of SCT (higher breadth and depth) with lower economic and legal business involvement (financial autonomy).

4.6.2. Contributions to practice

Project three re-enforces the contributions to practice in project two. PA and SCA designers must keep in mind that there may not be a shared understanding of each respective domain. The findings of this study reinforce the previous research that the NPD process is often constrained by the Stage Gate® process, and to a lesser extent by the Technology Release (TRL) process®. New to market product managers should not assume that both PA and SCA design are using similar measures of success. Product managers need to proactively negotiate and set the success criteria for each new product investment at the concept stage of the design. They must also manage and monitor the realisation of those benefits to overcome barriers that might exist to successful product launch. The evidence of project three supports the use of the three intervening mechanisms and their contribution to enabling PM mirroring with SCCM.

This modularity framework can be applied in many ways. For new to market products it can help identify the mirroring approach that can best serve the companies modular strategy. This framework provides a method by which product and SCC designers can share knowledge around the operational implications of alternative product designs. Finally, this framework can help to improve product and SCC design compatibility decisions, trough tacit coordination of the NPD process.

4.7. RECOMMENDATIONS FOR FURTHER RESEARCH

There are opportunities to build upon this research. Firstly, there is a need for further development of the SCCM construct. Secondly, there is a need for further development of the PM interface attribute. Thirdly, there is a need for further investigation of the causal linkages between PM and SCCM. Fourthly, this research would benefit from a longitudinal study; and finally, there is a need to enlarge the UoA sample, to include service companies, and small-medium sized enterprises.

Further development of the SCCM construct, requires further empirical evidence on the relationships between the five contingent factors: 1) the complexity of the product architecture; 2) clear customer requirements definition at the concept stage; 3) SCC performance assessment at the concept stage for closed-loop SCC; 4) the level of SCC process capability within the supply network, 5) FAC at the product concept stage, and the mirroring hypothesis. 'Further research should test if the mirroring hypothesis holds in contexts that vary in terms of these five contingent factors', following a recommendation by Sorkun and Furlan (2016).

Development of the SCCM construct should consider the possible omission or under-development of important optional SCCM attributes. SCC attributes are complex and multi-dimensional concepts, and difficult to grasp (Gupta and Buzacott, 1996).

The product architecture and SC network relationship is complex because of the levels of SCT and IC attributes that link these two domains. The PM attributes are closely aligned with product bus architecture possessing different mechanical, power transmission, and data transmission characteristics allowing component upgrade, replacement, variety, elimination, adjustment, data access, refurbishment and repair.

Different levels of the PA hierarchy were investigated. "A modular product design utilises open standard (or closed standard) interfaces that permit a range of components to be recombined and to function and interact without undesired or uncontrolled effects. Standard interfaces are ex ante designed, well known, and of repeated use" (Sosa *et al.,* 2003, p. 104), and thus allow companies to know a priori how components will interact. This research would benefit from further research of open- and closed-standard interfaces, at different levels of the PA hierarchy, and assessment of the degree of ESI in product innovation.

Further development of the causal linkages between PM and SCCM is recommended, expanding on the intervening mechanisms.

Further research should test the moderating effect of each intervening mechanism on the relationship between PM and SCCM. An attempt was made to test the mirroring hypothesis across industries with different complexity of PA in the domestic appliance, medical device, automotive and aerospace industries. This research could be continued in to other product sectors.

The PM mirroring with SCCM would benefit from a longitudinal study within a OEM and its supply network. Being able to study the dynamics periodically over an extended period would provide a higher level of robustness, building on Fine's double-helix model which illustrates how industry and product structures evolve from vertical/integral to horizontal/modular and back (Fine, 1995, p. 63).

Whilst the research focused on multi-national and transnational companies, a study of small and medium enterprises would be beneficial to understand the relationship between PM and SCCM in these smaller scale organisations.

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APPENDICES

Appendix 1-1. Product modularity attribute levels

<--- Scale of product modularity attribute --->

Construct		Attribute	High	Medium	Low	Literature
			Measures			
Product modularity	Mandatory	Function sharing (FS)	Low	Medium	High	Ulrich (1995); Fine et al.(2005); Cabigiosu et al. (2013).
		Definition: Function sharing is the phenomenon of a single component implementing several functional elements	There is one functional element to one module, for example a car radio (slot) or office partition (sectional).	There are many functional elements to a small number of modules, and components, for example the iPhone.	There are many functional elements to one module, for example the wing of an airplane. Products tend to have components that perform parts of multiple functions and functions/performance dimensions delivered by multiple subsystems. Systems are also closed, meaning that the interfaces between components are protected intellectual property that is closely held by the patent holder. In closed systems, only licensees of the relevant technology are permitted to develop subsystems for the product.	
		Interface coupling (IC)	Loose	Medium	Tight	Baldwin and Clark (1997); Fine et al. (2005); Suh (2005); Hölttä-Otto et al. (2012).
		Definition: Interface coupling covers the way that components connect. Two components are coupled if a change made to one component requires a change to the other component in order for the overall product to work correctly.	Module functions are independent of each another, with loose interconnects, for example a razor blade or ink cartridge, Modules can be easily disconnected. The information axiom applies, minimizing the information content of the design. The systems are normally open, and not protected by Intellectual property, which is closely held by the patent owner.	Modules are independent of each another, with more tightly defined interconnects, for example Wi-Fi or Bluetooth module. The interfaces can impose certain constraints on these modules according to the product's architecture, as these modules are generally designed by different design team members.	Modules are dependent on one another, with tightly defined interconnects, for example the wing of an aircraft. Modules have high design dependencies on other modules or components in the product. Interfaces tend to be complex, non-standard, and designed and built (or at least customized) explicitly for a particular product.	
	Optional	Data access (DA)	High	Medium	Low	Arnheiter and Harren (2005); Porter and Hellelman (2014); Borgia (2014).
		Definition: Data access denotes the level of data or electronic access to product modules.	Data is directly accessible, in real-time, for example machine to machine modules. Modules contain sensor and actuator components, and communicate with each other, in many cases using low frequency WI-FI, ZigBee, low power Bluetooth or standard Bluetooth protocols.	Data are remotely accessible, for example radio frequency or near field communication modules.	Data is not directly or indirectly accessible, for example using flash memory modules.	
		Limited life (LL)	High	Medium	Low	Boothroyd and Atling (1992); Mewcombe et al. (2003); Arnheiter and Harren (2005); Sundin et al. (2009), and Arnette (2014)
		Definition: Limited life implies the use of disposable modules having distinct characteristics. Limited life modules must be easily replaceable. Interfaces have to be well defined and the connection points of the interchangeable modules must be accessible.	Modules with low mean time to failure, for example a non-rechargeable direct current power battery. These limited life components for example batteries tend to be standardised, with interchangeable options.	An example of a module with medium mean time to failure, is the electric light bulb.	Most electronic modules have a high mean time to failure.	
		Product variety, in use (PV)	High	Medium	Low	Gerwin (1987); Ulrich and Tung (1991); Koufteros et al. (2001), and Arnheiter and Harren (2005).
		Definition: Product variety in use implies the use of modules to facilitate product customisation by the user.	Features that can be easily added to a product by the end-consumer, for example bicycle or printer (add-on). Extensibility is a measure of a product's ability to be extended either through adding functionality or upgrading existing functionality.	Features that can be easily added to a product at the end of the manufacturing process, or in the downstream supply chain, for example software.	Features cannot be easily added to a product at the end of the manufacturing process, or in the downstream supply chain, for example a storage disk drive.	

Appendix 1-2. Supply chain configuration modularity attribute levels

<----- **Scale of supply chain configuration attribute** ----->

	High	Medium	Low

Construct		Attribute	Measures: High	Measures: Medium	Measures: Low	Literature
Supply chain configuration modularity	Mandatory	**Supply chain tiering (SCT)** **Definition:** Supply chain tiering relates to the depth, breadth, geographic spread of the supply chain network and the economic and legal business involvement of the case company with suppliers.	More than 5 value adding tiers, more than 5 suppliers in a tier, regional or global geographic spread of the network, and economic and legal business involvement by the case company with the supply network. High level of economic and legal involvement by the OEM, or focal company.	3 - 5 value adding tiers, 3 - 5 suppliers in a tier, national geographic spread of the network, and economic and legal business involvement by the case company with the supply network. Medium level of economic and legal involvement by the OEM, or focal company.	1 - 2 value adding tiers, 1 - 2 suppliers in a tier, local geographic spread of the network, and economic and legal business involvement by the case company with the supply network. Low level of economic and legal involvement by the OEM, or focal company.	Fine (1995, 2005); van Hoek and Weken (1998); O'Grady (1999); Schilling and Steensma (2001); Takeishi and Fujimoto (2001); Hieber (2002); Sturgeon (2002); Takeishi and Fujimoto (2003); Graves and Willems (2003), and Fleury and Fleury (2007).
	Mandatory	**Process postponement (PRP)** **Definition:** The extent of process postponement is defined by the location of the COEP in the process, i.e. where the product is linked to the customer order.	The final product assembly is postponed until either a customer order, or more accurate demand information, is received, i.e. the COEP is just before final assembly.		Either the whole manufacturing process is conducted to a customer order, that is the COEP is at the beginning of manufacturing, or the whole manufacturing process is conducted to forecast, that is the COEP is at the end of manufacturing.	Lee and Tang (1997); Twede et al. (2000); Tu et al. (2004); Mikkola and Skjøtt-Larsen (2004); Fredriksson and Gadde (2005); Agard and Penz (2009); Gualandris and Kalchschmidt (2013); Wu et al., (2013), and Agard and Bassetto (2013).
	Optional	**Process flexibility (PF)** **Definition:** Process flexibility is the ability to cope with changing circumstances or instability caused by the environment	Flexibility is assessed in terms of a processes ability to be reconfigurable and extensible with respect to process architecture.	Repeatable operations, e.g. laser cutting, CNC drilling and textile dyeing.	Projects (customised tasks).	Gupta and Somers (1992); Hoogeweegen et al. (1999); Teece (2002); Arnheiter and Harren (2004); Agard and Bassetto (2013).
	Optional	**Process re-sequencing (PR)** **Definition:** Re-order the sub processes so that standard sub processes occur first while customization sub-processes occur last.	Ability to re-sequence or re-order the process's, e.g. software defined networks, where the hardware is pre-assembled.		Hard tooled processes e.g. parts which require forging prior to grinding and polishing.	Dapiran (1992); Ulrich (1995); Pine (1993); Feitzinger and Lee (1997); Steensma (2001); Tu et al. (2004); Fine et al. (2005); Erlicher and Massone (2005); Voordijk et al. (2006).
	Optional	**Place postponement (PLP)** **Definition:** Postponing customization or high variety sub processes at a location close to COEP, to achieve maximum time flexibility. This requires strategic inventory positioning.	The COEP is located in many locations, close to market.		The COEP occurs in central location. Direct order fulfilment from production location to customer.	van Hoek (2001); Graves & Willems (2005); Wickner and Rudberg (2005); Dekkers (2006); Wang et al. (2010); Amini and Li (2011).

Appendix 1-3. Concurrent development variable levels

<------------ **Levels of concurrent development** ------->

		High	Medium	Low
Concurrent Development (CD)	Level of concurrent product and SCC development, at the product concept stage	Concurrent development is a core practice at concept stage..	Concurrent development is reliant on knowledge sharing processes and tools; there is lack of engagement at concept stage.	Concurrent development does not occur at product concept stage, but later in the NPD process.
	SCC involvement in multi-funtional team at the product concept stage	Multi-disciplinary Supply chain configuration (SCC) functions, such as channel network design, vendor selection, logistics, customs and trade compliance, SC operations, SC finance and SC information technology are involved at the product concept stage. The more SCC functions involved the better.	The SCC functions involved are limited to for example supplier selection, and/or packaging design. Focus is primarily on plan, source and make, with limited or no focus on deliver and service (SCOR framework).	There is no SCC involvement in CD at the product concept development stage.
	Level of knowledge sharing between SCC and product architecture development	There is both an internal and external SCC focus at the NPD concept stage.User requirements and or core product technology is understood. Communication is taking place with SCC subject matter experts and/or knowledge brokers, through for example experience workshops.	There is primarily only internal SCC focus at the NPD concept stage.User requirements and/or core product technology are not clearly understood until later in the more detailed product development stage.	There is a level of concurrent product and SCC development. SCC is seen as a set of activities that take place post product concept development.
	Customer involvement in concurrent development of product specification	Customer requirements are translated into functional product specifications during the product concept development stage. SCC requirements are defined at the concept phase exit. Company may possibly be using digital product mock-up (DMU) and SCC process simulation.	Customer requirements are evolving during the concept stage; rapid prototyping may not be possible due also to rapid technology change. The new product business case may still be unproven during this stage. The product architecture design is unfrozen at concept stage exit.	Customer requirements are evolving during the concept stage; rapid prototyping is not possible due to rapid technology changes. The product architecture design is not defined at concept stage exit.

Appendix 1-4. Feedback control variable levels

<-------------- **Levels of feedback control** ------->

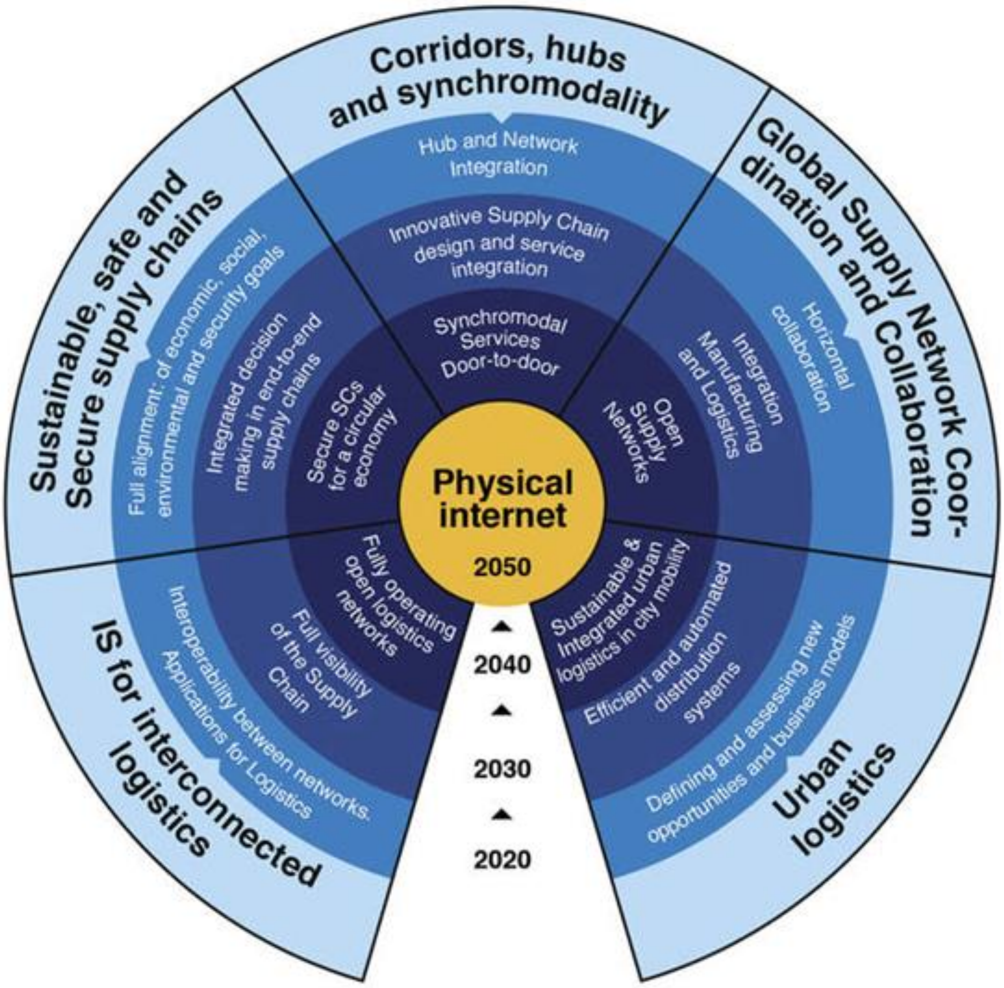
		High	Medium	Low
Feedback control	Level of product performance assessment at NPD stage gates	Key outputs are measured, including the new product introduction rate, component and module cost, quality and reliability. Focus is pro-active.	Focus is limited to engineering change control. Focus is reactive.	There is limited focus on analytic product performance data, during the concept design stage, of NPD.
	Level of SCC assessment at concept stage	Key outputs are measured, including SCC process and technology evaluation. This is often performed using the technology release process.	Focus is limited to manufacturing process capability and variability control (CpK).	There is limited focus on descriptive SCC performance, during the concept design stage, of NPD.
	NPD lead-time goal achievement	Focus is on product concept development time, using feedback control to improve this cycle time.	Focus is on product concept to product launch cycle time, using feedback control to improve this cycle time.	There is limited use of feedback control data, focusing on NPIR cycle time improvement.
	Product versus SCC process performance trade-off analysis at product concept development	Using scenario or contingency planning to assess relative importance of product and SCC features.	Focus limited to SKU management.	Limited or no use made of feedback control to improve product and SCC performance simultaneously.

Appendix 1-5. Feedforward anticipatory control variable levels

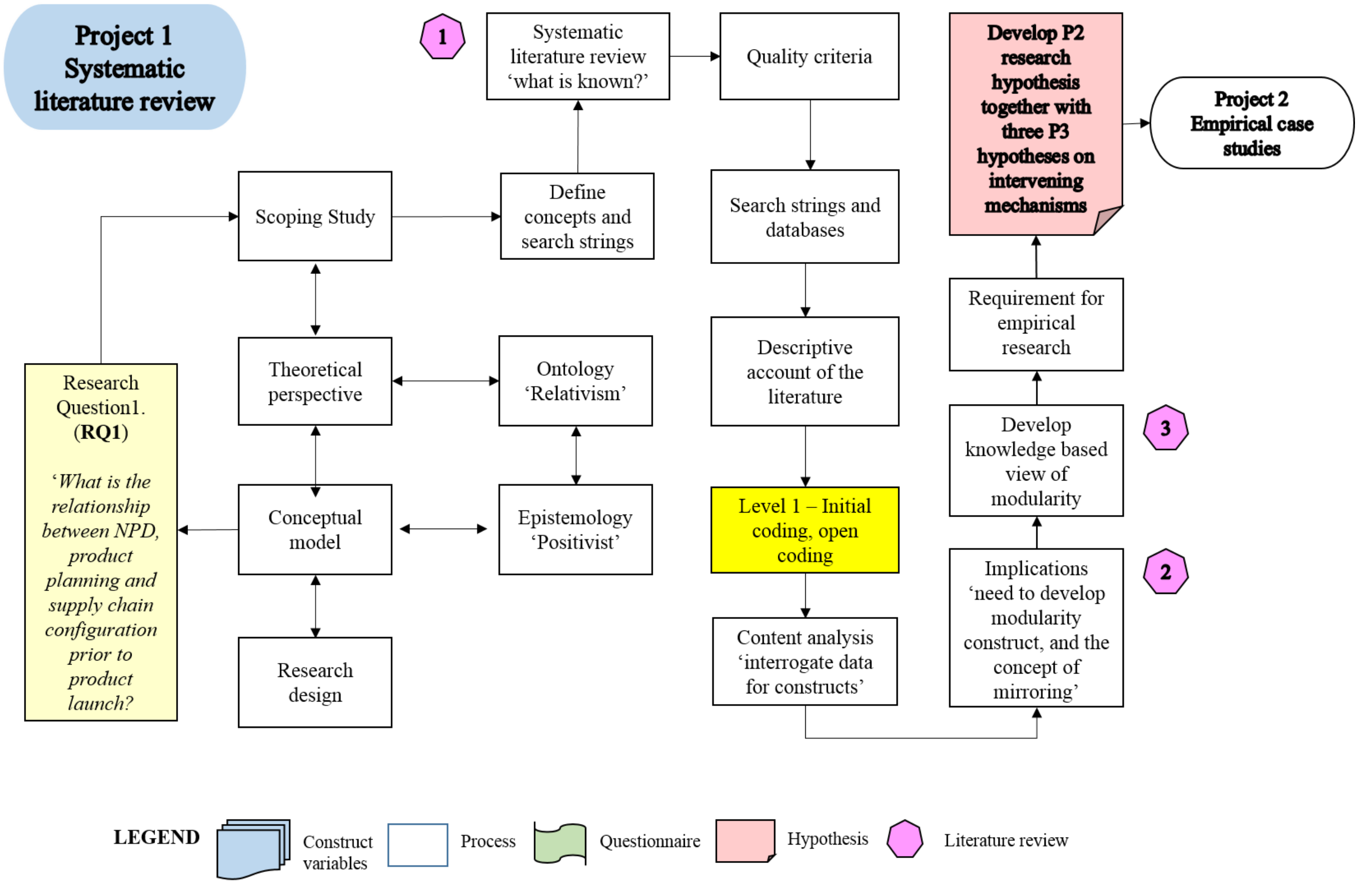
<------------ **Levels of feedforward anticipatory control** ------>

		High	Medium	Low
Feedforward anticipatory control (FAC)	Level of feedforward anticipatory control (FAC) to deliver the product concept	The process is driven by the unique selling proposition (USP) or product claim. The process can also be initiated by assessing customer requirements.	The process is driven by market assessment. This can be supported by regulatory constraints mapping.	There is limited focus on predictive NPD process performance results, during the concept design stage of NPD.
	Level of feedforward anticipatory control (FAC) to deliver the SCC requirements, at concept stage	The company is pro-active in defining SCC goals. This may involve the use of scenario planning, SCC process planning, simulation and application of foresight.	The focus is primarily on product constraints, for example shelf-life, and on complexity management, for example SKU optimisation.	There is limited focus on predictive SCC process performance results, during the concept design stage of NPD.
	SCC goal achievement	SCC impact on cost, quality, schedule are mapped and modelled simultaneously with product architecture	There is limited focus on SCC goal achievement, for example process automation available at product launch	There is limited focus on predictive SCC goals achievement, during the concept design stage of NPD.
	Level of use of Product and SCC architectural tools and models	The company is continuously evaluating modular process requirements.	The focus is limited to design for supply chain and inventory optimisation.	There is limited focus on predictive analysis on tools that are becoming increasing available to analyse NPD and SCC performance data.

Appendix 1-6. Physical internet



Appendix 2-1. Project one research process



Appendix 2-2a. Assessment criteria for conceptual papers

Assessment Criteria - Conceptual papers				
	Quality Level			
Element	**0 Absence**	**1 Low**	**2 Medium**	**3 High**
1. Does the paper inform or improve our understanding of prior theory?	The paper does not provide enough information to assess this criterion	The paper does not make an important contribution. It is not clear the advance it makes.	Although using others' ideas, the paper builds upon the existing theory.	The paper further develops existing knowledge, expanding the way the issue was explained so far.
2. Are the paper's theoretical underpinnings clearly stated?	The paper does not provide enough information to assess this criterion	The paper shows poor awareness of existing literature and debates.	Basic understanding of the issues around the topic being discussed.	Deep and broad knowledge of relevant literature and theory relevant for addressing the research.
3. Are all constructs clearly defined?	The paper does not provide enough information to assess this criterion	One or more constructs has not been defined.	Each construct has been defined, but more information is needed.	All constructs have been defined clearly.
4. Are all claims appropriately warranted?	The paper does not provide enough information to assess this criterion	Under- or over-referenced.	Claims are appropriately referenced, but the source of the reference is questionable.	Claims are appropriately referenced by respected sources.
5. Is the paper well organized and clearly written?	The paper does not provide enough information to assess this criterion	The paper is poorly structured and the argument is difficult to follow.	The paper is clearly written, but the argument is poorly constructed.	The paper is well written and the argument is clearly structured.

Appendix 2-2b. Assessment criteria for quantitative papers

Assessment Criteria - Quantitative papers				
	Quality Level			
Element	**0 Absence**	**1 Low**	**2 Medium**	**3 High**
1. Does the paper inform or improve our understanding of prior theory?	The paper does not provide enough information to assess this criterion	Does not make an important contribution. It is not clear the advance it makes.	Although using others' ideas, builds upon the existing theory.	Further develops existing knowledge, expanding the way the issue was explained so far.
2. Is the conceptual framework clearly articulated?	The paper does not provide enough information to assess this criterion	There is little reference made to theory or the motivation for the research is unclear. One or more hypotheses are absent.	The motivation for the research is clearly stated and all hypotheses are present.	The motivation for the research is clearly stated and the findings are related back to theory.
3. Does the data support the claims?	The paper does not provide enough information to assess this criterion	One or more claims are unsupported by the data.	The claim is too strongly worded to be supported by the data collected.	There is ample data to support the claims.
4. Is the methodology clearly described?	The paper does not provide enough information to assess this criterion	Data inaccuracy and not related to theory. Flawed research design or insufficient description of methodology.	Data are related to the arguments, though there are some gaps. Research design may be improved.	Data strongly supports arguments. Besides, the research design is robust: sampling, data gathering, data analysis is rigorous
5. Is the paper well organized and clearly written?	The paper does not provide enough information to assess this criterion	The paper is poorly structured and the argument is difficult to follow.	The paper is clearly written, but the argument is poorly constructed.	The paper is well written and the argument is clearly structured.
6. Are the results related to practice?	The paper does not provide enough information to assess this criterion	Very difficult to implement the concepts and ideas presented. Not relevant for practitioners or professionals.	There is a potential for implementing the proposed ideas, with minor revisions or adjustments	Significant benefit may be obtained in the ideas being discussed are put into practice
7. Generalizability	The paper does not provide enough information to assess this criterion	Only to the population studied	Generalizable to organizations of similar characteristics	High level of generalizability

Appendix 2-2c. Assessment criteria for qualitative papers

Assessment Criteria - Qualitative papers				
	Quality Level			
Element	**0 Absence**	**1 Low**	**2 Medium**	**3 High**
1. Does the paper inform or improve our understanding of prior theory?	The paper does not provide enough information to assess this criterion	Does not make an important contribution. It is not clear the advance it makes.	Although using others' ideas, builds upon the existing theory.	Further develops existing knowledge, expanding the way the issue was explained so far.
2. Is the conceptual framework clearly articulated?	The paper does not provide enough information to assess this criterion	There is little reference made to theory or the motivation for the research is unclear.	The motivation for the research is clearly stated.	The motivation for the research is clearly stated and the findings are related back to theory.
3. Does the data support the claims?	The paper does not provide enough information to assess this criterion	One or more claims are unsupported by the data.	The claim is too strongly worded to be supported by the data collected.	There is ample data to support the claims.
4. Is the methodology clearly described?	The paper does not provide enough information to assess this criterion	Data inaccuracy and not related to theory. Flawed research design or insufficient description of methodology.	Data are related to the arguments, though there are some gaps. Research design may be improved.	Data strongly supports arguments. Besides, the research design is robust: sampling, data gathering, data analysis is rigorous
5. Is the paper well organized and clearly written?	The paper does not provide enough information to assess this criterion	The paper is poorly structured and the argument is difficult to follow.	The paper is clearly written, but the argument is poorly constructed.	The paper is well written and the argument is clearly structured.
6. Are the results related to practice?	The paper does not provide enough information to assess this criterion	Very difficult to implement the concepts and ideas presented. Not relevant for practitioners or professionals.	There is a potential for implementing the proposed ideas, with minor revisions or adjustments	Significant benefit may be obtained in the ideas being discussed are

Appendix 2-2d. Quality assessment criteria

Level 1 - Quality Assessment Criteria					
	Quality Level				
Element	**0 Absence**	**1 Low**	**2 Medium**	**3 High**	**Not applicable**
1. Theory Robustness	The paper does not provide enough information to assess this criterion	Poor awareness of existing literature and debates, Under- or over-referenced. Low validity of theory	Basic understanding of the issues around the topic being discussed. The theory is weakly related to data	Deep and broad knowledge of relevant literature and theory relevant for addressing the research. Good relation theory-data	This element is not applicable to the document or study
2. Implication for practice	The paper does not provide enough information to assess this criterion	Very difficult to implement the concepts and ideas presented. Not relevant for practitioners or professionals	There is a potential for implementing the proposed ideas, with minor revisions or adjustments	Significant benefit may be obtained if the ideas being discussed are put into practice	This element is not applicable to the document of study
3. Methodology, data supporting arguments	The paper does not provide enough information to assess this criterion	Data inaccuracy and not related to theory. Flawed research design	Data are related to the arguments, though there are some gaps. Research design may be improved	Data strongly supports arguments. Besides, the research design is robust; sampling, data gathering, data analysis is rigorous	This element is not applicable to the document or study
4. Generalisability	The paper does not provide enough information to assess this criterion	Only to the population studied	Generalizable to organizations of similar characteristics	High level of gerneralizability	This element is not applicable to the document of study
5. Contribution plus a short statement summarizing the article's contribution	The paper does not provide enough information to assess this criterion	Does not make an important contribution. It is not clear the advances it makes	Although using others' ideas, builds upon the existing theory	Further develops existing knowledge, expanding the way the issue was explained so far	This element is not applicable to the document or study

Appendix 2-3a. Fifty-nine academic papers selected

	Domains	NPD mirroring with SCC	Paper Title	Authors
1	New Product Development and Supply chain	Product platform requirements	Sourcing by Design: Product Complexity and the Supply Chain	Sharon Novak, Steven D. Eppinger
2	Product life-cycle and Supply chain	Order Winner requirements at each stage in the product lifecycle	The impact of product life cycle on supply chain strategy	James Aitken, Paul Childerhouse, Denis Towill
3	Product design, Supply chain, and Manufacturing Process	Cost of product delivery to customer, and delivery lead-time to customer	Connecting product design, process and supply chain decisions to strengthen global supply chain capabilities	Erika Marsillac, James Jungbae Roh
4	New Product Development and Supply Chain Management	Customer orders	Aligning supply chain management and new product development: a theoretical framework	Margherita Pero, Andrea Sianesi
5	Supply chain integration and Product design	Product modules	Supply chain product co-development, product modularity and product performance	Antonio K.W. Lau, Richard C.M. Yam, and Esther P.Y. Tang
6	Product nature and supply chain strategy	Product lifecycle stages	An empirical investigation of the relationship between product nature and supply chain strategy	Sonia M. Lo and Damien Power
7	Product Design and Supply chain design	Product modules	Concurrent Product - Supply Chain Design: A Conceptual Framework & Literature Review	Thiam-Soon Gan and Martin Grunow
8	Product modularity and Supply chain integration	Product and Supply chain knowledge	Factors influencing the relationship between product modularity and supply chain integration	Antonio K.W. Lau, Richard C.M. Yam, Esther P.Y. Tang and H.Y. Sun.
9	Supply chain operations reference model and supply chain performance	Planning function	Linking SCOR planning practices to supply chain performance	Archie Lockamy, Kevin McCormack
10	New Product Development and supply chain design	Product building blocks	Making supply chain design the rational differentiating characteristic of the OEMs	H. Noori, D. Georgescu
11	Product development and supply chain configuration		Product Development: Past Research, Present Findings, and future directions	Shona L. Brown, Kathleen M. Eisenhardt
12	Supply integration and New Product Development	Project team effectiveness	Supplier integration into new product development: coordinating product, process and supply chain design	Kenneth J. Petersen, Robert B. Handfield, Gary L. Ragatz
13	New Product Development and Supplier involvement	Top management commitment and internal cross-functional coordination	Supplier involvement in new product development and innovation: Taking stock and looking to the future	Thomas E. Johnsen
14	Supply chain, Product and Process design	Product features	Achieving agility in supply chain through simultaneous "design of" and "design for" supply chain	H. Sharifi, H.S. Ismail and I. Reid
15	New Product Development and supply chain design	Product building blocks	Modeling tradeoffs in three-dimensional concurrent engineering: a goal programming approach	Charles H. Fine, Boaz Golany, Hussein Naseraldin

Appendix 2-3b. Fifty-nine academic papers selected

16	New Product Development and Supply chain alignment	Product innovativeness, modularity and variety	A framework for the alignment of new product development and supply chains	Margherita Pero, Nizar Abdelkafi, Andrea Sianesi, Thorsten Blecker
17	New Product Development and Supply Chain Management	Theoretical links	Complementary theories of supply chain management	Arni Halldorsson, Herbert Kotzab, Juliana H. Mikkola, Tage Skjott-Larsen
18	Product Postponement	Customer order coupling points	Postponement: an inter-organizational perspective	Biao Yang, Ying Yang, Jacob Wijngaard
19	New Product Development and Supply chain design	Product characteristics e.g. Number of components, Component complexity, Component commonality, Product platforms, Product modularity, Loosely coupled interfaces	Product architecture assessment: a tool to link product, process, and supply chain design decisions	Sebastian K. Fixson
20	NPD and supply chain co-development	Co-design processes	Supply chain product co-development, product modularity and product performance	Antonio K.W. Lau, Richard C.M. Yam, Esther P.Y. Tang
21	Product Architecture and supply chain design	Supply chain nodes	Matching product architecture with supply chain design	Bimal Nepal, Leslie Monplaisir, Oluwafemi Famuyiwa
22	Supply chain configuration and new product development	Safety Stock	Optimizing the Supply Chain Configuration for New Products	Stephen C. Graves, Sean P. Willems
23	Engineering Design and Operations Management	NPD decision clusters	Product Development Decisions: A Review of the Literature	V. Krishnan, Karl T. Ulrich
24	Design for Supply chain and centralized versus decentralized supply chains	Product module features	An investigation on Centralized and Decentralized Supply chain scenarios at the Product Design Stage to increase performance	Ming-Chuan Chiu, Gul E. Okudan Kremer
25	Supply chain configuration and new product development	Product components	Supply chain configuration model for new product development: A multi-objective approach	Bimal Nepal, Leslie Monplaisir, Femi Famuyiwa
26	Modular and Integral Products	Product modules	Clockspeed-based strategies for supply chain design	Charles H. Fine
27	Planning levels and Supply chain configuration decisions	Hierarchical planning decisions	A hierarchical product development planning framework	Edward G. Anderson Jr, Nitin R. Joglekar
28	Product Design and Supply chain design	Products modules	Product universality and design for supply chain management	Hau L. Lee, Margherita Sasser
29	Suppliers and New Product Development	Assets	Success factors for integrating suppliers into new product development	Gary L. Ragatz, Robert B. Handfield, Thomas V. Scannell
30	Supply chain management and Advanced planning	Process planning functions	Supply chain management and advanced planning - basics, overview and challenges	Hartmut Stadler

Appendix 2-3c. Fifty-nine academic papers selected

31	Concurrent engineering and new product development	Project phase, Design and Product concurrency	A tutorial on implementing concurrent engineering in new product development programs	Morgan L. Swink
32	Engineer to Order supply chain and new product development	Customer Orders	Engineer-to-order supply chain management: A literature review and research agenda	Jonathan Gosling, Mohamed M. Naim
33	Supply chain architecture	Network stakeholders	Emerging trends in supply chain architecture	W.T. Walker
34	Product family and platform based product development	Cost	Product family design and platform-based product development: a state-of-the-art review	Jianxin (Roger) Jiao, Timothy Simpson, Zahed Siddique
35	New Product and Supply Chain	Safety stock	New Product Supply Chain Configuration with Fuzzy parameters	Jihui Zhang, Guijuan Chang, Junqin Xu
36	Industry Clockspeed and the pace of New Product Development	Clockspeed	Industry clockspeed and the pace of new product development	Janice E. Carrillo
37	Supplier integration and New Product Development	Quality	An exploratory study of the effects of supplier relationships on new product development outcomes	Marcos A.M. Primo, Susan D. Amundson
38	Product Standardization and Supply chain design	Supply chain costs	Mutual impacts of product standardization and supply chain design	Bertrand Baud-Lavigne, Bruno Agard, Bernard Penz
39	Platform products and manufacturing supply chains	Supplier flexibility	Simultaneous configuration of platform products and manufacturing supply chains	Xinyan Zhang, George Q. Huang, M. Johnny Rungtusanatham
40	Supply chain configuration and new products	Structural, Managerial and Financial Compatibility, and transaction costs	A multi-objective supply chain configuration model for new products	Bimal Nepal, Leslie Monplaisir, Oluwafemi Famuyiwa
41	Concurrent engineering	Logistics movements of products	A modeling approach to logistics in concurrent engineering	Shad Dowlatshahi
42	Supply Chain and Supply Chain Management research	Change management process steps	A review and analysis of supply chain operations reference (SCOR) model	Samuel H. Huan, Sunil K. Sheoran, Ge Wang
43	Supply Chain and Product uncertainties	Product nature, functional vs. Innovative vs. Hybrid	Aligning Supply Chain Strategies with Product Uncertainties	Hau L. Lee
44	Supply Chain and New Product Development	Change elements	From tinkering around the edge to enhancing revenue growth: supply chain-new product development	Remko van Hoek, Paul Chapman
45	Supply chain and New product development	Change elements	How to move supply chain beyond cleaning up after new product development	Remko van Hoek, Paul Chapman

Appendix 2-3d. Fifty-nine academic papers selected

46	Supplier involvement in New product development	Core capabilities, and knowledge	Involving Suppliers in New Product Development	Robert B. Handfield, Gary L. Ragatz, Kenneth J. Petersen, Robert M. Monczka
47	Product platform and supply chain management	Relationships with outsource partners	Platform management: Implication for new product development and supply chain management	Juliana H. Mikkola, Tage Skjott-Larsen
48	New product development and Supply chain management	Demand and Supply processes must be viewed as complementary	Coordinating new product development with supply chain management	Per Hilletofth, David Eriksson
49	Supply chain configuration	Nodes in four networks, Strategic, Virtual, Regional and Operational (Wiendahl et al. 1998)	Supply Chain Configuration Revisited - Challenges and Strategic Roles for Western Manufacturers	Brian Vejrum Waehrens, Jens Ove Riis, John Johansen
50	Production information and supply chain dynamics	SC structure link (serial, divergent, dyadic, convergent and network)	Impacts of Sharing Production Information on Supply Chain dynamics: A review of the literature	George Q. Huang, Jason S.K. Lau, K.L. Mak
51	Supplier involvement and New product development	Identifies barriers to successful ESI	Supplier involvement in product development in the electronics industry: A case study	Ronan McIvor, Paul Humphreys, Trevor Cadden
52	Supply chain involvement and better product development performance	SCI involvement timing, innovation strategy, and business environment	Supply chain involvement for better product development performance	Taiwen Feng, Dan Wang
53	Sustainable Product and Supply chain design	Product module interfaces	Integrating Sustainable Product and Supply Chain Design: Modeling Issues and Challenges	Haritha Metta, Fazleena Badurdeen
54	Product module structure and global supply chain configuration	3D CE links	Concurrent Design of Product Modules Structure and Global Supply Chain configuration	H.A. ElMaraghy, N. Mahoudi
55	Fast Fashion design and Supply chain configuration	Segmented supply chains	ZARA: Fast Fashion	Pankaj Ghemawat, Jose Luis Nueno
56	Modular products and modular organizations	System integrators who divide the design and manufacturing process in to appropriate modular sub-task, and design the interface between them	Do modular products lead to modular organizations	Glenn Hoetker
57	Supply chain management and product life cycle	Variable and Fixed costs throughout the supply chain	A general model for extended strategic supply chain management with emphasis on product life cycles including development and recycling	G. Fandel and M. Stammen
58	Supply chain management and product recovery	Value creation tasks	Green supply-chain management: A state-of-the-art literature review	Samir K. Srivastava
59	Product Design and Supply chain design and supply chain	Product design for Supply chain responsiveness and resilience	Aligning product design with the supply chain: a case study	Omera Khan, Martin Christopher, Alessandro Craezza

Appendix 2-4a. Linking codes deduced from the systematic literature review

	Codes	Authors		
1	Modularity	1. Novak & Eppinger (2001)	1. Noori & Georgescu (2008)	1. Halldorsson, et al. (2007)
		2. Lau, Yam, Tang (2007)	1. Fine, Golany, Naseraldin (2005)	2. Yang, Yang & Wijngaard (2007)
		1. Lau, Yam, Tang & Sun (2010)	2. Pero, Adelkafi, Sianesi, Blecker (2010)	1. Fixson (2005)
		2. Lau, Yam, Tang (2011)	2. Nepal, Monplaisir & Famuyiwa (2012)	1. Krishnan & Ulrich (2001)
		2. Chiu & Kremer (2014)	2. Fine (2000)	1. Lee & Sasser (1995)
		1. Jiao, Simpson & Siddique (2007)	1. Mikkola & Skott-Larsen (2006)	2. ElMaraghy & Mahoudi (2008)
		1. Hoetker (2006)		
2	Integrality (low modularity)	1. Novak & Eppinger (2001)	2. Pero, Adelkafi, Sianesi, Blecker (2010)	1. Jiao, Simpson & Siddique (2007)
		1. Pero & Sianesi (2009)	2. Yang, Yang & Wijngaard (2007)	
3	Early supplier involvement	2. Lau, Yam & Tang (2007)	1. Halldorsson, et al. (2007)	1. Krishnan & Ulrich (2001)
		2. Petersen, Handfield & Ragatz (2005)	2. Yang, Yang & Wijngaard (2007)	2. Ragatz, Handfield & Scannell (1997)
		2. Johnsen (2009)	2. Graves & Willems (2005)	2. Swink (1998)
		1. Baud-Lavigne, Agard & Penz (2012)	4. Lee (2002)	2. van Hoek & Chapman (2007)
		2. Handfield, Ragatz, Petersen & Monczka (1998)	2. Hilltofth & Eriksson (2010)	2. Feng & Wang (2012)
4	Internal co-development	2. Marsillac & Roh (2014)	2. Johnsen (2009)	2. Swink (1998)
		2. Lau, Yam, Tang (2007)	2. Yang, Yang & Wijngaard (2007)	1. Baud-Lavigne, Agard & Penz (2012)
		2. Gan & Grunow (2013)	1. Krishnan & Ulrich (2001)	2. Ghemawat & Nueno (2006)
		1. Hoetker (2006)		
5	Customer co-development	2. Marsillac & Roh (2014)	2. Stadtler (2005)	
		2. Lau, Yam &Tang (2007)	1. Baud-Lavigne, Agard & Penz (2012)	
		2. Yang, Yang & Wijngaard (2007)	2. Zhang, Huang & Rungtusanatham (2008)	
6	Major product characteristics	3, 4 Aitken, Childerhouse & Towill (2003)	2. Pero, Adelkafi, Sianesi, Blecker (2010)	1. Mikkola & Skott-Larsen (2006)
		1. Pero & Sianesi (2009)	1. Lee & Sasser (1995)	2. Hilltofth & Eriksson (2010)
		3. Lo & Power (2010)	1. Baud-Lavigne, Agard & Penz (2012)	2. Metta & Badurdeen (2013)
7	Order Winner	3, 4 Aitken, Childerhouse & Towill (2003)		
		2. Gosling & Naim (2009)		
		1. Zhang, Chang & Xu (2008)		
8	Market Qualifier	3, 4 Aitken, Childerhouse & Towill (2003)		
		2. Handfield, Ragatz, Petersen & Monczka (1998)		
9	Product concept	3, 4 Aitken, Childerhouse & Towill (2003)	2. Gan & Grunow (2013)	1. Fine, Golany, Naseraldin (2005)
		1. Pero & Sianesi (2009)	2. Petersen, Handfield & Ragatz (2005)	2. Lau, Yam, Tang (2011)
		3. Lo & Power (2010)	4. Sharifi, Ismail & Reid (2006)	1. Krishnan & Ulrich (2001)
		2. Chiu & Kremer (2014)	1. Lee & Sasser (1995)	2. Gosling & Naim (2009)
		2. Primo & Amundson (2002)	2. Zhang, Huang & Rungtusanatham (2008)	2. van Hoek & Chapman (2006)
		2. van Hoek & Chapman (2007)	1. Mikkola & Skott-Larsen (2006)	2. Metta & Badurdeen (2013)
10	Product development	2. Marsillac & Roh (2014)	2. Pero, Adelkafi, Sianesi, Blecker (2010)	2. Nepal, Monplaisir & Famuyiwa (2012)
		4. Brown & Eisenhardt (1995)	1. Halldorsson, et al. (2007)	2. Nepal, Monplaisir & Famuyiwa (2010)
		4. Ludema (2008)	2. Graves & Willems (2005)	4. Carrillo (2005)
11	Product Launch & Ramp	1. Zhang, Chang & Xu (2008)		
12	Product recycle	1. Lee & Sasser (1995)		
		2. Metta & Badurdeen (2013)		
13	Product complexity	1. Novak & Eppinger (2011)	1. Lee & Sasser (1995)	
		1. Fine, Golany, Naseraldn (2005)	1. Jiao, Simpson & Siddique (2007)	
		2. Fine (2000)		
14	SCOR framework	1. Lockamy & McCormack (2004)	2. Gosling & Naim (2009)	
		1. Anderson & Joglekar (2005)	2. Huan, Sheoran & Wang (2004)	
		2. Stadtler (2005)	2. van Hoek & Chapman (2006)	
15	Make versus buy	1. Novak & Eppinger (2011)	2. Nepal, Monplaisir & Famuyiwa (2010)	2. Walker (2005)
		2. Pero, Adelkafi, Sianesi, Blecker (2010)	2. Fine (2000)	2. Zhang, Huang & Rungtusanatham (2008)
		1. Krishnan & Ulrich (2001)	2. Ragatz, Handfield & Scannell (1997)	2. Ghemawat & Nueno (2006)
16	Supplier selection	2. Johnsen (2009)	2. McIvor, Humphreys & Cadden (2006)	
		1. Fine, Golany, Naseraldin (2005)	2. Metta & Badurdeen (2013)	
		2. Nepal, Monplaisir & Famuyiwa (2010)		
17	Supplier integration	2. Lau, Yam & Tang (2007)	2. Nepal, Monplaisir & Famuyiwa (2012)	2. Primo & Amundson (2002)
		1. Lau, Yam, Tang & Sun (2010)	1. Anderson & Joglekar (2005)	2. van Hoek & Chapman (2007)
		2. Petersen, Handfield & Ragatz (2005)	2. Walker (2005)	2. Handfield, *et al.* (1998)
		1. Mikkola & Skott-Larsen (2006)	2. McIvor, Humphreys & Cadden (2006)	2. Ghemawat & Nueno (2006)
18	Fast clockspeed	1. Noori & Georgescu (2008)	2. Fine (2000)	2. Ghemawat & Nueno (2006)
		4. Sharifi, Ismail & Reid (2006)	4. Carrillo (2005)	
		1. Fixson (2005)	2. van Hoek & Chapman (2007)	
19	Slow clockspeed	4. Carrillo (2005)		

Appendix 2-4b. Linking codes deduced from the systematic literature review

	Codes	Authors		
20	Vertical integration	1. Novak & Eppinger (2011)	2. Ghemawat & Nueno (2006)	
		2. Fine (2000)		
		1. Mikkola & Skott-Larsen (2006)		
21	Horizontal integration	2. Fine (2000)	2. Gosling & Naim (2009)	
		2. Ragatz, Handfield & Scannell (1997)	2. Walker (2005)	
		2. Stadtler (2005)		
22	New to market products	2. Marsillac & Roh (2014)	2. Ragatz, Handfield & Scannell (1997)	2. Ghemawat & Nueno (2006)
		1. Pero & Sianesi (2009)	2. Dowlatshahi (1999)	
		1. Lee & Sasser (1995)	2. Hilltofth & Eriksson (2010)	
23	Supply chain planning	3. Lo & Power (2010)	2. Stadtler (2005)	2. Feng & Wang (2012)
		1. Fine, Golany, Naseraldin (2005)	2. Nepal, Monplaisir & Famuyiwa (2010)	
		1. Anderson & Joglekar (2005)	4. Lee (2002)	
24	Supply chain collaboration	2. Pero, Adelkafi, Sianesi, Blecker (2010)	2. Stadtler (2005)	2. Nepal, Monplaisir & Famuyiwa (2010)
		2. Yang, Yang & Wijngaard (2007)	2. Swink (1998)	2. Dowlatshahi (1999)
		2. Ragatz, Handfield & Scannell (1997)	2. Zhang, Huang & Rungtusanatham (2008)	4. Lee (2002)
		2. van Hoek & Chapman (2007)	2. Handfield, Ragatz, Petersen & Monczka (1998)	2. Feng & Wang (2012)
25	Supply chain network	1. Halldorsson, et al. (2007)	2. Ragatz, Handfield & Scannell (1997)	2. Waehrens, Riis & Johansen (2008)
		2. Nepal, Monplaisir & Famuyiwa (2012)	2. Stadtler (2005)	2. Huang, Lau & Mak (2003)
		1. Lee & Sasser (1995)	2. Dowlatshahi (1999)	2. Feng & Wang (2012)
26	Lean (efficient) supply chain	3. Lo & Power (2010)		
		2. Chiu & Kremer (2014)		
		2. Gosling & Naim (2009)		
27	Agile (responsive) supply chain	3. Lo & Power (2010)	2. Gosling & Naim (2009)	
		4. Sharifi, Ismail & Reid (2006)		
		2. Chiu & Kremer (2014)		
28	Fast fashion sector	2. Yang, Yang & Wijngaard (2007)		
		2. Ghemawat & Nueno (2006)		
29	Automotive sector	1. Novak & Eppinger (2011)	2. Fine (2000)	
		1. Noori & Georgescu (2008)	1. Anderson & Joglekar (2005)	
		1. Fine, Golany, Naseraldin (2005)	2. Handfield, Ragatz, Petersen & Monczka (1998)	
30	Consumer electronics sector	2. Graves & Willems (2005)		
		2. Fine (2000)		
		1. Lee & Sasser (1995)		
31	Industry Sector (other than fast fashion, automotive and consumer)	3, 4 Aitken, Childerhouse & Towill (2003)		
32	Intellectual assets (IP protection)	2. Ragatz, Handfield & Scannell (1997)		
		2. Huang, Lau & Mak (2003)		
		2. ElMaraghy & Mahoudi (2008)		
33	Quality Function Deployment	4. Sharifi, Ismail & Reid (2006)		
		2. Stadtler (2005)		
		2. Primo & Amundson (2002)		
34	Distribution network design	4. Ludema (2008)	2. Dowlatshahi (1999)	
		2. Stadtler (2005)	2. Waehrens, Riis & Johansen (2008)	
		1. Zhang, Chang & Xu (2008)		
35	Transportation network	3, 4 Aitken, Childerhouse & Towill (2003)	2. Walker (2005)	
		4. Ludema (2008)	1. Zhang, Chang & Xu (2008)	
		2. Stadtler (2005)	2. Dowlatshahi (1999)	
36	Safety stock	2. Graves & Willems (2005)	2. Nepal, Monplaisir & Famuyiwa (2010)	
		2. Nepal, Monplaisir & Famuyiwa (2010)		
		1. Zhang, Chang & Xu (2008)		
37	Single-tier supply chain	2. Gan & Grunow (2013)		
		2. Graves & Willems (2005)		
		2. Chiu & Kremer (2014)		
38	Multi-tier supply chain	2. Gan & Grunow (2013)	1. Zhang, Chang & Xu (2008)	
		2. Nepal, Monplaisir & Famuyiwa (2012)	2. Nepal, Monplaisir & Famuyiwa (2010)	
		2. Zhang, Huang & Rungtusanatham (2008)	2. ElMaraghy & Mahoudi (2008)	

Appendix 2-5a. Data extraction sheets

	Domains	In Final list?	Source	Paper Title	Authors	Journal	Year of Publication	Theoretical Foundation	Citations (June 11, 2014)	Geographic base	Industry base	Research Method	Unit of Analysis	Contribution	Underlying theory	Implication for Business Practice	Sample size (companies)	Longitudinal Study (time period)	Data supporting arguments	Linking mechanisms
1	Product design, Supply chain, and Manufacturing Process	Yes	EBSCO / ProQuest	Connecting product design, process and supply chain decisions to strengthen global supply chain capabilities	Erika Marsillac, James Jungbae Roh	International Journal of Production Economics	2014	Concurrent integration of product design in to process and supply chain design, 3DCE. Fine (1998, 2000)	1	US	Flooring, IT products, bedding and athletic clothing	Case studies	Country	Uses a 3D-CE lens to examine the influences of Supply Chain Configuration on New Product Development	Product process matrix, to illustrate how product design can determine and stimulate process design (Hayes & Wheelwright 1979) and 3D-CE Theory base	Product design changes exist on a continuum. There are potential dual direction correlations	4	Not applicable	Four case studies	Cost of product delivery to customer, and delivery lead-time to customer
2	Design for Supply chain and centralized versus decentralized supply chains	Yes	EBSCO	An investigation on Centralized and Decentralized Supply chain scenarios at the Product Design Stage to increase performance	Ming-Chuan Chiu, Gul E. Okudan Kremer	IEEE Transactions on Engineering Management	2014	Supply chain design function comprises of a theory-based transition matrix. Product architecture is the foundation of the proposed model.	0	Taiwan	Bicycle	Case Studies	Company	Product Architecture is the key to integrating product design decisions and supply chain configuration. An MIP model is used to optimize a centralized supply chain, and a bi-level model is used to optimize a decentralized supply chain	Decentralized supply chains are advantageous for time performance, whereas the centralized supply chain demonstrates superiority on cost performance	Different product architectures shape various supply chain networks	5	Not applicable	Literature Review and five case studies, proposed a fuzzy logic-based goal programming model to both minimize total supply chain cost and maximize supply chain compatibility	Product modules or Integral product design features
3	Product Design and Supply chain design	Yes	EBSCO / ProQuest	Concurrent Product - Supply Chain Design: A Conceptual Framework & Literature Review	Thiam-Soon Gan and Martin Grunow	46th CIRP Conference on Manufacturing Systems 2013	2013	Design trade-off methodology Tomiyama et al (2009) provide a comprehensive review of Product Development methodologies and theories. Simchi-Levi (2008), Fine (1998) and Graves & Willems (2008) provide theoretical perspectives on Supply Chain design	1	Global	Multiple	Theory Building	Company	Develops a Framework (Concurrent Design Attribute - Trade off Pyramid (CDA-TOP)) based on concurrent product and supply chain design	Concurrent Product and Supply chain design	Proposes a methodology for CE	17	Not applicable	Trade-off design attributes and their trade-off methodologies	Product modules and common components
4	Sustainable Product and Supply chain design	Yes	EBSCO	Integrating Sustainable Product and Supply Chain Design: Modeling Issues and Challenges	Haritha Metta, Fazleena Badurdeen	IEEE Transactions on Engineering Management	2013	Closed loop systems with growing awareness of sustainability. Industry led discussion Wal-Mart, P&G, Exxon Mobile, IBM, HP etc. Importance of co-ordinating SSC and Product design. Paper describes the six 'R''s.	24	USA	None	Case Studies	Network	Sustainable supply chain management requires a focus on all four product life-cycle stages	Closed loop materials flow	Sustainable supply chains compliance	2	Not applicable	Mixed Integer Programming Model, and Literature review	Product module interfaces
5	Product Architecture and supply chain design	Yes	Cross Reference	Matching product architecture with supply chain design	Bimal Nepal, Leslie Monplaisir, Oluwafemi Famuyiwa	European Journal of Operational Research	2012	Extends the Supply chain configuration work of Graves and Willems (2005). Huang et al. (2007) employed a game theoretic approach to configure both the product family and the supply chain for mass customization.	19	USA	Earth moving equipment and automotive climate control system	Case Studies	Company	Propose a framework which matches product architecture (PA) with supply chain design, taking the form of three steps (1) Selection of PA (2) Evaluation of potential suppliers (3) optimal configuration of supply chain	Modularization	Comparison of supply chain performance between modular and integral product structures. The optimal supply chain configuration minimizes the sum of three relevant costs: COGS, safety stock cost, and pipeline stock cost.	2	Not applicable	Goal programming model tested on two case studies. This paper extends the works of Graves and Willems (2003, 2005) on supply chain configuration by integrating product architectural design with supply chain design	Supply chain nodes
6	Product Standardization and Supply chain design	Yes	EBSCO	Mutual impacts of product standardization and supply chain design	Bertrand Baud-Lavigne, Bruno Agard, Bernard Penz	International Journal of Production Economics	2012	It is well established that product design has a great impact on manufacturing and logistics, Dowlatshahi (1996). However, the opposite link has to be highlighted. Design for Logistics, and supply chain are under researched area's. Mass customization involves a set of concepts that can be used at the product design stage: modular design, scalability and commonality. Modular design, Kusiak and Huang (1996) consists to assemble the product from functional modules. Scalability allows easy changes to the product, while, commonality, Fixson (2007) reuses components or sub-assemblies of other existing products.	15	France	None	Case studies	Industry	Use of Mixed integer Programming Model (MILP) to model the simultaneously product standardization and product allocation	Supply chain network optimization	Simultaneous optimization of product and supply chain design is difficult	2	Not applicable	Literature review, and two case studies	Fixed, Labor and Transport costs
7	Supply chain involvement and better product development performance	Yes	EBSCO	Supply chain involvement for better product development performance	Taiwen Feng, Dan Wang	Industrial Management & Data Systems	2012	Stakeholder involvement in product development is important. Despite its importance, SCI is only a recent entry on the agenda of researchers. There are no commonly accepted sub-dimensions of SCI, and the relationships between different SCI dimensions are inconsistently described in previous studies Singh and Power (2009) Lau (2011).	5	China	Multiple	Case studies	Company	Besides the significant influence of Supply Chain integration on NPD performance, the effectiveness of SCI may be contingent on involvement timing, innovation strategy and business environment	SCI	SCI with Chinese companies has enormous practical implications	214	Not applicable	Study of 214 Chinese manufacturing companies	SCI involvement timing, innovation strategy, and business environment
8	Product Design and Supply chain design and supply chain	Yes	Cross Reference	Aligning product design with the supply chain: a case study	Omera Khan, Martin Christopher, Alessandro Creazza	Supply Chain Management: An International Journal	2012	Lack of in depth cases on alignment of product design with supply chain		UK	Fast fashion	Case study	Industry	The speed of product flow is citically important in time sensitive markets	Supply Chain alignment	There are positive relationships in terms of responsiveness and resilience from aligning new product design and supply chain	1	Not applicable	Literature review	Product design for Supply chain responsiveness and resilience
9	Supply chain configuration and new products	Yes	EBSCO / ProQuest	A multi-objective supply chain configuration model for new products	Bimal Nepal, Leslie Monplaisir, Oluwafemi Famuyiwa	International Journal of Production Research	2011	The objectives of the model are to minimise the total costs of the supply chain (TCSC) and to maximise the total supply chain compatibility index (SCCI) among the supply chain members.	1	USA	None	Case Study	Network	Supply chain configuration decisions which involve deciding on what options to deploy at each node, depend on factors including lead time, cost, and relationship	Strategic alliance, based on either transaction cost or resources.	Total Cost of Ownership	1	Not applicable	Total cost of ownership model	Structural, Managerial and Financial Compatibility, and transaction costs
10	Product nature and supply chain strategy	Yes	EBSCO	An empirical investigation of the relationship between product nature and supply chain strategy	Sonia M. Lo and Damien Power	Supply Chain Management: An International Journal	2010	Supply chain uncertainty, Fisher (1997) only covers demand uncertainty. Fisher suggests matching supply chain with the product structure	40	Australia	Multiple	Survey	Company	Combining competitive strategies within a Hybrid Supply Chain configuration, is key to pursuing product efficiency and supply chain responsiveness	Proposed extensions to Fishers (1997) model, provides more comprehensive understanding of the influence of product nature on the choice of supply chain strategy	The model does not consider supply, or supply chain uncertainty. Supply chain structure and characteristics of supply chain partners should be considered	107	Not applicable	107 completed questionnaires in Australia	Product lifecycle stage
11	Product modularity and Supply chain integration	Yes	EBSCO	Factors influencing the relationship between product modularity and supply chain integration	Antonio K.W. Lau, Richard C.M. Yam, Esther P.Y. Tang and H.Y. Sun	International Journal of Operations & Production Management	2010	Literature about the relationship between Product modularity and Supply chain integration is in its infancy. Value-transfer theory, Doran et al (2007) argues that manufacturers transfer value-adding activities to suppliers. The Double Helix Model, Fine (2000) is a good framework from which to progress this research	9	Hong Kong, The Netherlands and USA	Electronics and Rubber	Case Studies	Network	Explores the relationship between Product Modularity (loose coupling of components) and Supply chain integration, and value-transfer theory. IP protection becomes key.	Value-transfer theory	Knowledgeable lead customers are key	5	Not applicable	5 case studies, 4 Electronics companies, 1 Rubber company	Knowledge
12	New Product Development and Supply chain alignment	Yes	EBSCO / ProQuest	A framework for the alignment of new product development and supply chains	Margherita Pero, Nizar Abdelkafi, Andrea Sianesi, Thorsten Blecker	Supply Chain Management: An International Journal	2010	Supply chain performance	52	Italy	Electronics	Case studies	Company	Transaction costs theory and studies on client-supplier relationships provide guidance to firms on how to define the right level of vertical integration	Supply Chain alignment	Supply chain performance depends on matching NPD and supply chain design, planning and management	4	Not applicable	Literature Review and five case studies	Product innovativeness, modularity and variety
13	Supply chain configuration and new product development	Yes	Cross Reference	Supply chain configuration model for new product development: A multi-objective approach	Bimal Nepal, Leslie Monplaisir, Femi Famuyiwa	POMS 21st Annual Conference Proceedings	2010	Inventory positioning. Interaction between product architecture characteristics decisions in product, process and supply chain domains, is adapted from Fixson (2005).	19	USA	Bulldozer	Case Study	Company	Multi-objective optimization modeling taking both hard and soft variables in to consideration, can lead to enhanced supply chain stability	Graves and Willems single-objective supply chain configuration model is a robust model, with empirical backing, and delivers higher compatibility than multi-objective models	Each stage in a multi-echelon supply chain seeks to optimise their output. However for the end stage, the output service time can be given by the customer or determined by the optimization model	1	Not applicable	Developed a multi-objective optimization model for supply chain configuration, during product development. Graves and Willems showed the benefits of this approach.	Product components
14	New product development and Supply chain management	Yes	ProQuest	Coordinating new product development with supply chain management	Per Hilletofth, David Eriksson	Industrial Management & Data Systems	2010	Supply chain innovation is required. It may be argued that the NPD process not only enables management to coordinate the flow of new products efficiently, but also to assist in the ramp-up of supply processes and other related activities (e.g. marketing and sales), that support the commercialization of the product, Carillo and Franza (2006).	29	Sweden	Furniture	Case study	Company	Supply chain configuration must take in to consideration how consumer-desired products are made innovative, customized and affordable	Consumer oriented supply chains	Strong focus on the demand side (NPD)	1	Not applicable	Literature review, and case study	Demand and Supply processes must be viewed as complementary
15	New Product Development and Supply Chain Management	Yes	Cranfield Library Request	Aligning supply chain management and new product development: a theoretical framework	Margherita Pero, Andrea Sianesi	International Journal of Electronic Customer Relationship Management	2009	Integral and modular product architecture, is central to decision making in product, process and supply chain design, Krishnan & Ulrich (2001). Product novelty is the degree of newness of a product for the firm of for the market Garcia and Calantone (2002). Novelty appears to be only addressed in SCM-oriented literature	6	Europe	Electronics MNC	Case study	Network	Explores NPD based on 'constraints anticipation' concept, and SCM-orientation concerned with design, planning and management of supply chain, based on characteristics of new product	NPD-SCM alignment measurement	External and Internal product variety and product novelty are the main product features to be considered to align Supply chain decisions to NPD	1	Not applicable	Product features and SCM related decisions are analysed. Product architecture plays a pivotal role	Customer orders

Appendix 2-5b. Data extraction sheets

	Domains	In Final list?	Source	Paper Title	Authors	Journal	Year of Publication	Theoretical Foundation	Citations (June 11, 2014)	Geographic base	Industry base	Research Method	Unit of Analysis	Contribution	Underlying theory	Implication for Business Practice	Sample size (companies)	Longitudinal Study (time period)	Data supporting arguments	Linking mechanisms
16	New Product Development and Supplier involvement	Yes	EBSCO	Supplier involvement in new product development and innovation: Taking stock and looking to the future	Thomas E. Johnsen	Journal of Purchasing and Supply Management	2009	Transaction cost economics concept of asset specificity	83	US, Japan, Europe	Strong roots in Japanese Automotive Industry	Empirical Research	Industry	Suppliers to be engaged early in NPD represent high value and complexity, either taking on a full black-box or grey-box responsibility. Applying Transaction Cost Economics concept of asset specificity shows the positive impact of supplier involvement.	Innovative capability of suppliers and complementary	Requirement for internal coordination, advanced supplier selection, and long term relationship adaptation.	Multiple	Not applicable	Literature Review	Top management commitment and internal cross-functional coordination
17	Engineer to Order supply chain and new product development	Yes	Cross Reference	Engineer-to-order supply chain management: A literature review and research agenda	Jonathan Gosling, Mohamed M. Naim	International Journal of Production Economics	2009	Many of the frameworks for thinking about matching supply chains to the marketplace have been organised around the concept of the 'decoupling point'. The customer order decoupling point (CODP) is a stock holding point.	69	UK	Multiple	Observation	Network	ETO is represented by decoupled point at the design stage. There is little empirical research to align the agile approach with the ETO model	Dominance of conceptual and case study approaches	ETO, BTO, MTO, ATO, MTS, STS etc., it is all about understanding benefits of decoupling points	n/a	Not applicable	Literature review related to ETO	Customer Orders
18	New Product Development and supply chain design	Yes	EBSCO	Making supply chain design the rational differentiating characteristic of the OEMs	H. Noori, D. Georgescu	International Journal of Production Research	2008	Value chain integration, Porter (1980,1985)	1	USA	Automotive	Case Study	Industry	Successful outsourced manufacturing leads to synchronized supply chain control, leveraging Fine's 3D-CE framework	3C-CE framework (linking architecture, technology and focus)	High clockspeed leads to increased levels of supplier integration, outsourcing modular design	1	Not applicable	Formulation of SC design for Commodity, Critical Styling and Essential components, through the NPD process	Product Building blocks
19	New Product and Supply Chain	Yes	EBSCO	New Product Supply Chain Configuration with Fuzzy parameters	Jihui Zhang, Guijuan Chang, Jungin Xu	IEEE Transactions on Engineering Management	2008	Inventory optimization, continuation of Graves & Willems (2005)	0	China	Computing	Case Study	Company	The supply chain configuration problem chooses a sourcing option for each stage of the supply chain so as to minimize the sum of these costs and maximize the whole chain reliability	Decision modeling	The SC configuration problem chooses a sourcing option for each stage of the supply chain	1	Not applicable	Literature review	Safety stock
20	Platform products and manufacturing supply chains	Yes	EBSCO	Simultaneous configuration of platform products and manufacturing supply chains	Xinyan Zhang, George Q. Huang, M. Johnny Rungtusanatham	International Journal of Production Research	2008	Simultaneous configuration of product and supply chain is advantageous. Focus with platform strtegy is on profitability	28	China	None	Observation	Network	Although supply chain configuration and product line/family design for mass customization are closely interrelated they have been rarely studied as an integrated, systematic and comprehensive manner	Concurrent Engineering for Mass customization	Key challenge is to strike a balance between platform commonality and modularity. Platform benefits decline as volume increases	n/a	Not applicable	Mixed Integer Programming Model. Manufacturers and suppliers (two-echelons) were studied, this should be extended further	Supplier flexibility
21	Supply chain configuration	Yes	Cross Reference	Supply Chain Configuration Revisited - Challenges and Strategic Roles for Western Manufacturers	Brian Vejrum Waehrens, Jens Ove Riis, John Johansen	Intechopen.com	2008	Competitive advantage, leveraging the global value chain	3	Denmark	Toys, Industrial solutions, Fast fashion, Designer furniture	Case studies	Network	Logistics management perspective dominates supply chain theory, focusing on links between nodes, as opposed to focusing on the nodes. Three archetypal companies are proposed: focused, networking and integrating firms	Network theory. Supply chain networks are integrated rather than aggregated(Rudberg & olhager, 2003)	Shift in focus from value chain to value web	4	Not applicable	Knowledge development and sharing within the supply network is key	Nodes in four networks, Strategic, Virtual, Regional and Operational (Wiendahl et al. 1998)
22	Product module structure and global supply chain configuration	Yes	EBSCO	Concurrent Design of Product Modules Structure and Global Supply Chain configuration	H.A. ElMaraghy, N. Mahoudi	intelhweb.com	2008	Intellectual property and trade-secrets protection, is key to global supply chain configuration.	26	Canada	None	Theory Building	Network	Developed a decision support model to assess total supply chain cost	Concurrent Engineering	Design for Supply chain	n/a	Not applicable	Optimization based decision model and case study	3D CE links
23	Supply chain integration and Product design	Yes	EBSCO	Supply chain product co-development, product modularity and product performance	Antonio K.W. Lau, Richard C.M. Yam, and Esther P.Y. Tang	Industrial Management & Data Systems	2007	Supply chain integration includes suppliers, customers and internal functional units, Vickery (2003)	50	Hong Kong and China	Electronics, Plastics and Toy Manufacturers in Hong Kong	Survey	Company	Supply chain integration (co-development) with product development, examining supplier, customer and internal co-development processes	Resource based view (Verona, 1999)	There is a positive relationship between SCI and modular product designs	251	Not applicable	251 completed questionnaires	Product modules (building blocks)
24	New Product Development and Supply Chain Management	Yes	EBSCO / ProQuest	Complementary theories of supply chain management	Arni Halldorsson, Herbert Kotzab, Juliana H. Mikkola, Tage Skjott-Larsen	Supply Chain Management: An International Journal	2007	Different dominant theories apply under different circumstances. Principal agent and network are two such theories. Alderson's functionalist theory, Alderson (1957) has many similarities with SCM theories.	127	Global	None	Theory building	Network	Four theories are discussed (1) the principal-agent theory (2) transaction cost analysis (3) the network theory; and (4) the resource-based view	Interorganizational phenomena (1) the principal-agent theory (2) transaction cost analysis (3) the network theory; and (4) the resource-based view	Transactional cost analysis, and the principal-agent theory are especially valuable with respect to supply chain structuring	n/a	Not applicable	Research framework is applied to 3rd party logistics and NPD, within SCM	Theoretical links
25	Product Postponement	Yes	EBSCO	Postponement: an inter-organizational perspective	Biao Yang, Ying Yang, Jacob Wijngaard	International Journal of Production Research	2007	Networks of relationships Harland (1996), in the areas of logistics, producton, purchasing and product development postponement	32	USA	Clothing	Conceptual	Network	Significant difficulties in postponement implementation relate to how a company configure and manage its external networks	Postponement theory (Logistics, Production, Purchasing, Product development)	Studies postponement with an inter-organizational perspective	n/a	Not applicable	Postponement is relevant to a networked and modular organizational form (Van Hoek et al. 1998)	Customer order coupling points
26	NPD and supply chain co-development	Yes	EBSCO	Supply chain product co-development, product modularity and product performance	Antonio K.W. Lau, Richard C.M. Yam, Esther P.Y. Tang	Industrial Management & Data Systems	2007	Supply chain integration. This hypothesized model is largely based on the resource-based theory which is widely used in both product development, Verona (1999) and supply chain literature.	50	Hong Kong	Plastics, Electronics and Toys	Empirical	Company	Develop a theoretical framework based on Supply Chain Product co-development elements, supplier, internal and customer co-development, and review of product and supply chain performance	Supply chain integration business processes	Product co-development effect product performance both directly and indirectly	285	Not applicable	Questionnaire survey, with 285 firms responding	Co-design processes
27	Product family and platform based product development	Yes	EBSCO	Product family design and platform-based product development: a state-of-the-art review	Jianxin (Roger) Jiao, Timothy Simpson, Zahed Siddique	Journal of Intelligent Manufacturing	2007	End customer preferences should be the basis for configuring supply chains Lee and Sasser (1995). There are statistically significant relationships between supply chain structures and product architecture for luxury and high-performance vehicles, Novak and Eppinger (2001)	317	USA	None	Theory Building	Network	Demand chain management advocate that end customers should be the basis for configuring supply chains. Customers are central to value creation	Constraint networks	Product families are recognized as an effective means to achieve economies of scale	n/a	Not applicable	Literature review	Cost
28	Supply chain and New product development	Yes	EBSCO	How to move supply chain beyond cleaning up after new product development	Remko van Hoek, Paul Chapman	Supply Chain Management: An International Journal	2007	Focus on Internal Alignment, Mentzer (2004) and role of R&D in Supply Chain Management, Zacharia (2000)	32	USA	None	Survey	Industry	Internal alignment is probably the most fundamental starting point for NPD success	Supply Chain alignment	Co-maker ship and co-design partnerships	n/a	Not applicable	Survey	Change elements
29	Supply chain management and product recovery	Yes	Cross Reference	Green supply-chain management: A state-of-the-art literature review	Samir K. Srivastava	International Journal of Management Reviews	2007	Multiple Utility theory, approach by Kainuma & Tawara (2006)	1060	Global	Cross section of industries	Theory Building	Network	development and recycling costs, capacities and the process integration into an extended supply chain	Various theories including Environmentally conscious design and manufacturing, Zhang et al. (1997)	Regulatory and market forces are driving firms to take this are of operations more seriously	n/a	Not applicable	Literature review	Value creation tasks
30	Supply chain, Product and Process design	Yes	EBSCO	Achieving agility in supply chain through simultaneous "design of" and "design for" supply chain	H. Sharifi, H.S. Ismail and I. Reid	Journal of Manufacturing Technology Management	2006	Quality Function deployment Hauser and Clausing (1988)	59	UK	Sports, Eyebath and Shower, Information kiosk and Ultrasonic cleaning sectors	Case Study	Country	Focus on how supply chains can be configured to ensure sustainable competitiveness, with sufficient levels of agility	Supply Chain Agility, uses Ansoff's extended matrix for growth strategy	It is critical to understand the capabilities of suppliers	4	Not applicable	4 case studies, with 10-90 per cent product outsourced. Demonstrated that many supply chain problems can be avoided	Product features

Appendix 2-5c. Data extraction sheet

	Domains	In Final list?	Source	Paper Title	Authors	Journal	Year of Publication	Theoretical Foundation	Citations (June 11, 2014)	Geographic base	Industry base	Research Method	Unit of Analysis	Contribution	Underlying theory	Implication for Business Practice	Sample size (companies)	Longitudinal Study (time period)	Data supporting arguments	Linking mechanisms
31	Supply Chain and New Product Development	Yes	EBSCO	From tinkering around the edge to enhancing revenue growth: supply chain-new product development	Remko van Hoek, Paul Chapman	Supply Chain Management: An International Journal	2006	Leveraging supply chain in NPD, starts with internal alignment. Appelqvist (2004) highlights that modeling has done little to focus on studying the effect of supply chain on NPD. The mismatch between demand and supply have been the primary areas of focus, with demand uncertainty to the fore. The proposed new focus from NPD perspective is on efficiency, and the focus from SC perspective is on inventory and forecasting	38	UK	None	Observation	Industry	What has been largely missing in research is efforts to leverage supply chain capability as part of the product development team for greater market impact and revenue growth through new product introduction	Supply Chain alignment	Need to ensure product availability at launch	n/a	Not applicable	Literature review	Change elements
32	Product platform and supply chain management	Yes	ProQuest	Platform management: Implication for new product development and supply chain management	Juliana H. Mikkola, Tage Skjott-Larsen	European Business Review	2006	From a theoretical perspective, it would be interesting to investigate how the existing boundaries of the firm are changing with increasing outsourcing activities. In doing so, one has to bridge different academic disciplines such as transaction cost economics, resource-based view of the firm, or network theory, with SCM and NPD, Halldorsson et al. (2005). Vertical cooperation is an important consideration. According to Fine (1998), the ultimate competence in a fast clock speed world is the ability to create and manage new capabilities while growing profits and adjusting to ever-faster clock speeds	24	Denmark	Hearing aids	Case study	Company	Developing a platform strategy involves suppliers, and customers. It is not unusual for firms to own production tools, where outsourcing is practiced	Efficient supply chain	Degree of supplier involvement in NPD relates to the platform design	1	Not applicable	Efficiency is delivered through ESI, VMI and Quick response programs	Relationships with outsource partners
33	Supplier involvement and New product development	Yes	EBSCO	Supplier involvement in product development in the electronics industry: A case study	Ronan McIvor, Paul Humphreys, Trevor Cadden	Journal of Engineering and Technology Management	2006	Early Supplier integration has focused on three key strategic dimensions; extent of supplier involvement, buyer–supplier relationships and information exchange.	54	UK	Electronics	Case Study	Company	Well trained technical liaison staff are key to ESI	Supplier integration	ESI requires a cultural change	1	Not applicable	Case Study	Identifies barriers to successful ESI
34	Fast Fashion design and Supply chain configuration	Yes	Cross Reference	ZARA: Fast Fashion	Pankaj Ghemawat, Jose Luis Nueno	Harvard Business School Case 9-703-497 Dec 21, 2006	2006	Postponement reflects the business strategy for Fast Fashion sector. Quick Response supply chains have become key. Volume commitments replace price reductions in many of these negotiations.	160	Global	Fast fashion	Case study	Industry	Study of Quick Response supply chain configuration, focus on speed	Complexity theory, and continuous innovation	Buyer driven supply chains	1	Not applicable	Case study	Segmented supply chains
35	Modular products and modular organizations	Yes	Cross Reference	Do modular products lead to modular organizations	Glenn Hoetker	Strategic Management Journal	2006	Transaction cost economics, Williamson (1979) and the knowledge-based view of the firm, Grant (1996).	233	USA	Notebook computer	Data Analysis	Network	Empirical evidence on the impact of product modularity on the ease of which firms can reconfigure their organizational design	Transaction cost economics, and knowledge based view of the firm	Creates more flexible company, more capable of outsourcing, and perhaps a virtual company	n/a	Not applicable	Quantitative data	System integrators who divide the design and manufacturing process in to appropriate modular sub-task, and design the interface between them
36	Supply integration and New Product Development	Yes	ProQuest	Supplier integration into new product development: coordinating product, process and supply chain design	Kenneth J. Petersen, Robert B. Handfield, Gary L. Ragatz	Journal of Operations Management	2005	Social process of Supplier integration, and the requirement for collaboration mechanisms	556	Japan an USA	Cross Industry	Case studies	Company	Assumption that supplier integration in to new product development is a social process, as such affected by a variety of behavioral factors. Social problems often occur because of a lack of coordinating mechanisms	Early Supplier Involvement, study of White, Grey and Black box suppliers	Supplier culture is an important consideration	2	Not applicable	134 responses to questionnaire	Project team effectiveness
37	New Product Development and supply chain design	Yes	EBSCO	Modeling tradeoffs in three-dimensional concurrent engineering: a goal programming approach	Charles H. Fine, Boaz Golany, Hussein Naseraldin	Journal of Operations Management	2005	3D CE Fine (1998)	92	US	Automotive (Daimler-Chrysler)	Modeling (Goal programming)	Industry	Weighed Goal Programming simultaneously solves the best combination, per product version, of product design, assembly plan and supply chain design	3D CE	High	1	Not applicable	Integral SC's have high levels of formalization, centralization and complexity	Product building blocks
38	New Product Development and Supply chain design	Yes	EBSCO / ProQuest	Product architecture assessment: a tool to link product, process, and supply chain design decisions	Sebastian K. Fixson	Journal of Operations Management	2005	Product architecture is the link which operationalises 3D CE. Theoretically, every interface can be disconnected. However, modular product architectures have strong interactions within modules and weak ones between them implies that the weakness of these relations can be translated into low efforts to reverse (or disconnect) the interface.	251	USA	None	Conceptual, product architecture mode, mathematical, conceptual and engineering models	Network	Review of Product characteristics constraining and enabling design decisions in supply chain domain. Product characteristics are often described as 'coupled' or 'dependent'	Product architecture	Operationalization of the Product architecture concept	n/a	Not applicable	Uses two product examples to show how product architecture dimensions link decisions across different domains	Product characteristics e.g. Number of components, Component complexity, Component commonality, Product platforms, Product modularity, Loosely coupled interfaces
39	Supply chain configuration and new product development	Yes	EBSCO / ProQuest	Optimizing the Supply Chain Configuration for New Products	Stephen C. Graves, Sean P. Willems	Management Science	2005	Framework developed builds on Multi-echelon inventory theory and network design theories	151	USA	Computing	Case Study	Company	Supply chain configuration benefits increase with multi-echelons, where there is longer lead times at downstream stages, as demand variability increases, and where inventory costs are high relative to the total supply chain costs. The optimization model seeks to minimize total supply chain cost, minimizing COGS, safety stock and pipeline stock cost	Minimization of Total cost	Configuring supply chains where design is already decided. Optimal supply chain configuration minimizes the sum of three relevant costs COGS, safety stock cost and pipeline stock cost	1	Not applicable	Computational experiment to test various hypotheses, and case study.	Safety Stock
40	Planning levels and Supply chain configuration decisions	Yes	EBSCO	A hierarchical product development planning framework	Edward G. Anderson Jr, Nitin R. Joglekar	Production and Operations Management	2005	Product planning models tend to focus on a single dimension of uncertainty in the product development environment. This paper argues for a 4th planning level, the infrastructural level, that re-establishes norms for market projections, technological forecasts, scheduling and requirements as latent uncertainty.	57	USA	Automotive	Case study	Industry	Strong argument for a 4th planning level, the infrastructural. Unlike production or project management, hierarchical planning is key to addressing market, creative and process uncertainty	Path dependency, it characterizes the NPD context because goals, task structures, and boundaries not only evolve during the NPD planning process, the NPD process in fact creates them.	Infrastructure planning represents Level 0, in a 4-level model. At this level we need to develop working assumptions	1	Not applicable	Development of a HPDP (Hierarchical Product Development Planning) framework	Hierarchical planning decisions
41	Supply chain management and Advanced planning	Yes	EBSCO	Supply chain management and advanced planning - basics, overview and challenges	Hartmut Stadler	European Journal of Operational Research	2005	SCM has drawn knowledge and approaches from a number of disciplines like computer science, logistics, marketing, operations research, organizational theory and many more, with Organization theory showing great significance. Advanced planning of Product and Supply chain is required.	506	USA	Multiple	Conceptual	Network	Supply Chain configuration is focused on serving customer needs, however process orientation and advanced planning across company borders is in its infancy	Voice of the customer	Supply chain planning matrices, are element of SC Configuration	n/a	Not applicable	Literature review	Process orientation and advanced planning across companies is still in its infancy
42	Supply chain architecture	Yes	Cross Reference	Emerging trends in supply chain architecture	W.T. Walker	International Journal of Production Research	2005	Collaborative supply chain networks. The 5-V principle point to emerging trends in supply chain architecture are a compelling framework from which to develop 3D CE research	17	USA	None	Theory Building	Network	Recognition that all network stakeholders win if the network works to maximize throughput, while only a few network stakeholders win if the individual trading partners work to minimize cost	Value principle	Five principles of supply chain networks, velocity, variability, vocalize, visualize, value	n/a	Not applicable	Conceptual paper	Network stakeholders
43	Industry Clockspeed and the pace of New Product Development	Yes	EBSCO / ProQuest	Industry clockspeed and the pace of new product development	Janice E. Carrillo	Production and Operations Management	2005	Rate of introduction of new products, Fine (2000). Time pacing new products in particular in fast clockspeed industries, is important Eisenhardt and Brown (1998). Optimal development time and product performance levels are positively related, Bayus (1997).	58	USA	Semiconductor	Empirical	Industry	Managers need to identify the appropriate factors specific to their firm before relying blindly on a strategy of increasing the pace of NPD	Optimal product performance	There is a need to synchronies NPD with the products marketplace Industry clockspeed)	1	Not applicable	Literature review	Clockspeed
44	Supply chain operations reference model and supply chain performance	Yes	EBSCO	Linking SCOR planning practices to supply chain performance	Archie Lockamy, Kevin McCormack	International Journal of Operations & Production Management	2004	SCOR Framework (SCOR). Uses the Theory of constraints. Elgazzar et al. (2012) research illustrated a method to link SC performance metrics to the priorities of company's financial performance	228	USA	Cross Industry	Survey	Company	SCOR provides a framework for characterizing SCM practices, and their resulting performance, extended to NPD	SCOR Model framework is robust model	Competitive advantage	90	Not applicable	55 responses from 90 SCOR Member firms	Planning function
45	Supply Chain and Supply Chain Management research	Yes	EBSCO / ProQuest	A review and analysis of supply chain operations reference (SCOR) model	Samuel H. Huan, Sunil K. Sheoran, Ge Wang	Supply Chain Management: An International Journal	2004	Research on supply chain management can be broadly classified into three categories, namely, operational, design, and strategic. Information sharing is critical area of research. Supply chain configuration falls in to the Strategic decision area, and requires an understanding of the dynamics of supply chain and development of objectives for the whole chain, Gopal (1992). It involves a critical evaluation fo the alternative supply chain configurations and partnerships. SCOR model also incorporate the work of Saaty (1980) on Analytic Hierarchy process	261	USA	None	Theory Building	Network	Design for supply chain focuses on the location of decision spots and the objectives of the chain. Four categories of models are found (1) deterministic analytical (2) stochastic analytical (3) economic (4) simulation	SCOR Model framework is robust model	Research in SCM is operational, design or strategic	n/a	Not applicable	Analytical Hierarchical process behind design of SCOR model. AHP follows three steps (1) problem decomposition and hierarchy construction (2) determine alternatives (3) pair-wise comparison	Change management process steps

Appendix 2-5d. Data extraction sheet

	Domains	In Final list?	Source	Paper Title	Authors	Journal	Year of Publication	Theoretical Foundation	Citations (June 11, 2014)	Geographic base	Industry base	Research Method	Unit of Analysis	Contribution	Underlying theory	Implication for Business Practice	Sample size (companies)	Longitudinal Study (time period)	Data supporting arguments	Linking mechanisms
46	Supply chain management and product life cycle	Yes	Cross Reference	A general model for extended strategic supply chain management with emphasis on product life cycles including development and recycling	G. Fandel and M. Stammen	International Journal of Production Economics	2004	SCM extended to incorporate product development and recycling, Fleischmann et al. (2000)	91	Global	Cross section of industries	Empirical	Network	a linear optimization model is designed that considers the extended supply chain	Strategic planning	The framework permits the evaluation of alternative investments between various projects	None	Not applicable	Supporting Optimisation models	Variable and Fixed costs throughout the supply chain
47	Product (life-cycle) and Supply chain	Yes	ECSCO	The impact of product life cycle on supply chain strategy	James Aitken, Paul Childerhouse, Denis Towill	International Journal of Production Economics	2003	Christopher (1992) highlights the need to bundle delivery, reliability and after-sales support. In practice product families are grouped in to a restricted number of pipelines Fuller et al (1993).Defined Order Winner (OW) and Market Qualifier (MQ) characteristics, Hill (1985). DWV3 (Duration of lifecycle, Window of delivery, volume, variety, variability) mode, to classify demand chain types, Christopher and Towill (2000)	161	UK	Lighting Products	Empirical	Factory	Explores the concept of key order winner (OW) and market qualifier (MQ), and synchronized PDP and PIP, throughout the product lifecycle	Product lifecycle concept, and the use of the DWV3 classification system (Christopher 1992)	Product availability needs and holding costs determine resultant distribution channels	1	4 years	Assessment of the OW for each of four groups of lighting products	Time window for product delivery, and Order Winner requirements at each stage in the product lifecycle
48	Production information and supply chain dynamics	Yes	Cross Reference	Impacts of Sharing Production Information on Supply Chain dynamics: A review of the literature	George Q. Huang, Jason S.K. Lau, K.L. Mak	International Journal of Production Research	2003	Information sharing is critical to success of global supply chains	341	Hong Kong	None	Empirical	Network	Vast majority of literature on Supply chain configuration and NPD takes an analytical and/or simulation approach. Empirical approach has not been widely used.	Network theory	Information sharing reduces the bullwhip effect	n/a	Not applicable	Development of a Supply chain framework	SC structure link (serial, divergent, dyadic, convergent and network)
49	Supplier integration and New Product Development	Yes	EBSCO / ProQuest	An exploratory study of the effects of supplier relationships on new product development outcomes	Marcos A.M. Primo, Susan D. Amundson	Journal of Operations Management	2002	The level of supplier involvement on the NPD project is seen as contingent on the level of technical difficulty of the project.	293	USA	Automotive	Observation	Network	Companies with shorter NPD cycle times involve suppliers to a significantly greater extent in their NPD processes than companies with long cycle times. NPD projects with technical difficulty also involve suppliers earlier	Contingency theory	Supplier quality control is positively correlated with supplier involvement in new product development	38	Not applicable	Literature review, together with a two-stage model	Quality
50	Supply Chain and Product uncertainties	Yes	EBSCO	Aligning Supply Chain Strategies with Product Uncertainties	Hau L. Lee	California Management Review	2002	SCM research is broadly classified into three categories, operational, design and strategic. SCOR primarily covers Demand uncertainty.	788	USA	None	Observation	Network	Demand and Supply uncertainty drive supply chain configuration innovation	Information sharing	Demand uncertainty and supply uncertainty lead to different supply chains	n/a	Not applicable	Literature review	Product nature, functional vs. Innovative vs. Hybrid
51	New Product Development and Supply chain (Product complexity and Vertical Integration-Sourcing)	Yes	Cross Reference	Sourcing by Design: Product Complexity and the Supply Chain	Sharon Novak, Steven D. Eppinger	Management Science	2001	Vertical integration allows bargaining issues to be resolved, employees obey orders, in contrast to suppliers, Williamson (1979). Ulrich & Ellison (1998) argue that splitting design and production of coupled systems should be avoided	418	Japan, US, Europe	Automotive	Longitudinal Study	Industry	Test Hypothesis with a simultaneous equation model	Discusses Transaction Cost theory and the Property Rights approach	Sourcing is not a binary make/buy decision. Sourcing relationships are more complex.	8	1980-1995	Models relationship between product complexity and vertical integration	Product platform requirements, and Sunk costs
52	Engineering Design and Operations Management	Yes	EBSCO	Product Development Decisions: A Review of the Literature	V. Krishnan, Karl T. Ulrich	Management Science	2001	Operations Management perspective	1128	USA	None	Survey	Network	Clustering of product development decisions by functional area, runs the risk that interdependencies amongst development decisions may be ignored. Framing product development research in to the following three clusters is more optimal (1) Product (2) Portfolio, and (3) Architecture	Theory based on product development practice, advocate stronger adherence to scientific method, with empirical validation	Team structure in NPD to ensure interdependencies amongst development decisions are not ignored	n/a	Not applicable	Survey of 50 researchers in the field of product design, together with a literature review	NPD decision clusters (this may be a better way to frame the organization of research)
53	Modular and Integral Products	Yes	EBSCO / Proquest	Clockspeed-based strategies for supply chain design	Charles H. Fine	Production and Operations Management	2000	3D CE concept. Supply chain dynamics along the double helix is important are of research.	248	USA	Computing	Theory Building	Industry	A single product/supply chain decision, by a dominant producer, can trigger a structural shift from vertical/integral structure to horizontal/modular one	Ensure core competencies do not become core rigidities	Ultimate core competency of an organization is "supply chain design". Modular supply chains can be unstable	1	Not applicable	3D-CE modeling (Supply chain development is divided in to the supply chain architecture decisions and logistics/coordination system decisions. Intel are example of benefits of supply chain co-development	Product modules
54	Concurrent engineering	Yes	EBSCO	A modeling approach to logistics in concurrent engineering	Shad Dowlatshahi	European Journal of Operational Research	1999	Design for logistics, and development of theory of Reverse Logistics	62	USA	Automotive	Case study	Company	A Bond Energy Algorithm is used to accomplish the design for logistics concerns	Transaction cost economics	Logistics engineering, design for transport, packaging etc. are important	1	Not applicable	Bond Energy Algorithm looking at design for logistics	Logistics movements of products
55	Supplier involvement in New product development	Yes	EBSCO / ProQuest	Involving Suppliers in New Product Development	Robert B. Handfield, Gary L. Ragatz, Kenneth J. Petersen, Robert M. Monczka	California Management Review	1999	Early Supplier integration	579	USA, CA, Europe, APAC, Aus, South America	Cross section of industries	Observation	Industry	There is a percentage of companies not satisfied with supplier integration process, with increasing expectations from this process	Company dynamic capabilities and resource based view	Supplier involvement has both positive and negative aspects	134	Not applicable	Develop a process model for reaching consensus on suppliers to integrate in to the NPD project, survey	Core capabilities, and knowledge
56	Concurrent engineering and new product development	Yes	Cross Reference	A tutorial on implementing concurrent engineering in new product development programs	Morgan L. Swink	Journal of Operations Management	1998	Organizational breadth, product complexity and the need for a tailored approach all are key factors in takes a concurrent approach to NPD	93	USA	n/a	Theory Building	Network	CE represents cross-functional integration and concurrency. Concurrency takes the form of Project Phase, Design, and Product, and can provide fundamental sources of competitive advantage.	3D CE	Organizational learning and 3D CE can provide fundamental sources of competitive advantage	n/a	Not applicable	Tutorial on three aspect of 3D CE	Three types of concurrency, Project phase, Design and Product
57	Suppliers and New Product Development	Yes	EBSCO	Success factors for integrating suppliers into new product development	Gary L. Ragatz, Robert B. Handfield, Thomas V. Scannell	Journal of Product Innovation Management	1997	(ESI) Supplier membership in NPD team is the single greatest contributor to cycle time minimization, and NPD success	730	USA	Multiple	Survey	Network	Relationship structuring, asset (intellectual, physical and human) allocation is key to successful supplier integration, in NPD and Supply chain design	Relationship structuring, incl. Shared education, training, risk/reward, performance measurement	US companies are more extensively involving suppliers in the NPD process, than European or Asian companies. Supply Chain config. must consider Intellectual, Human and Physical assets	60	Not applicable	Literature review, and survey of 210 GEBN participants, with 83 responses from 60 companies	Assets
58	Product development and supply chain configuration	Yes	EBSCO / ProQuest	Product Development: Past Research, Present Findings, and future directions	Shona L. Brown, Kathleen M. Eisenhardt	Academy of Management Review	1995	Boundary spanning behavior, Ancona & Caldwell (1980). Information and Resource dependence	3197	USA	Cross Industry	Observation	Network	Research can be economics or organization oriented. NPD related research follows three streams (a) rational plan, (b) communication web, and (c) disciplined problem solving, all three streams relate to supply chain configuration design	3 Streams of NPD, as a Rational plan, communication web, and as disciplined problem solving	NPD and Supply chain configuration are both economics oriented and organizations-oriented	n/a	Not applicable	Literature Review	Team effectiveness
59	Product Design and Supply chain design	Yes	EBSCO	Product universality and design for supply chain management	Hau L. Lee, Margherita Sasser	Production Planning and Control	1995	Design for Supply Chain Management, argues for delayed product differentiation, for logistics cost and customer service optimisation	107	USA	Computing	Case Study	Network	Design for supply chain is limited by the basic design of the product	Delayed product differentiation is proven theoretical model	NPD is an increasingly recognized major factor in effective supply chain management	1	Not applicable	Review of HP's rainbow product structure and supply chains, looking at cost-benefit trade-off's incorporating a UPC as a design alternative	Products link modules with Customized products

Appendix 2-6. Primary themes from the SLR

	Theme	Construct
1	**Modularity**	Modular
2	**Early supplier involvement**	Early involvement
3	**Co-development**	Suppliers
		Internal
		Customers
4	**Life-cycle**	Concept
		Development

Appendix 2-7a. Academic papers focused on elements of PM - SCC mirroring

Mirroring concept		
	Author(s)	Year
1	Sharon Novak, Steven D. Eppinger	2001
2	Margherita Pero, Andrea Sianesi	2009
3	Antonio K.W. Lau, Richard C.M. Yam, Esther P.Y. Tang and H.Y. Sun.	2010
4	H. Noori, D. Georgescu	2008
5	Arni Halldorsson, Herbert Kotzab, Juliana H. Mikkola, Tage Skjott-Larse	2007
6	Sebastian K. Fixson	2005
7	V. Krishnan, Karl T. Ulrich	2001
8	Edward G. Anderson Jr, Nitin R. Joglekar	2005
9	Hau L. Lee, Margherita Sasser	1995
10	Jianxin (Roger) Jiao, Timothy Simpson, Zahed Siddique	2007
11	Jihui Zhang, Guijuan Chang, Junqin Xu	2008
12	Bertrand Baud-Lavigne, Bruno Agard, Bernard Penz	2012
13	Juliana H. Mikkola, Tage Skjott-Larsen	2006
14	Glenn Hoetker	2006

Appendix 2-7b. Papers focused on co-development

Co-development		
	Author(s)	Year
1	Erika Marsillac, James Jungbae Roh	2014
2	Antonio K.W. Lau, Richard C.M. Yam, and Esther P.Y. Tang	2007
3	Thiam-Soon Gan and Martin Grunow	2013
4	Kenneth J. Petersen, Robert B. Handfield, Gary L. Ragatz	2005
5	Thomas E. Johnsen	2009
6	Charles H. Fine, Boaz Golany, Hussein Naseraldin	2005
7	Margherita Pero, Nizar Abdelkafi, Andrea Sianesi, Thorsten Blecker	2010
8	Biao Yang, Ying Yang, Jacob Wijngaard	2007
9	Antonio K.W. Lau, Richard C.M. Yam, Esther P.Y. Tang	2007
10	Bimal Nepal, Leslie Monplaisir, Oluwafemi Famuyiwa	2012
11	Stephen C. Graves, Sean P. Willems	2005
12	Ming-Chuan Chiu, Gul E. Okudan Kremer	2014
13	Bimal Nepal, Leslie Monplaisir, Femi Famuyiwa	2010
14	Charles H. Fine	2000
15	Gary L. Ragatz, Robert B. Handfield, Thomas V. Scannell	1997
16	Hartmut Stadler	2005
17	Morgan L. Swink	1998
18	Jonathan Gosling, Mohamed M. Naim	2009
19	W.T. Walker	2005
20	Marcos A.M. Primo, Susan D. Amundson	2002
21	Xinyan Zhang, George Q. Huang, M. Johnny Rungtusanatham	2008
22	Bimal Nepal, Leslie Monplaisir, Oluwafemi Famuyiwa	2011
23	Shad Dowlatshahi	1999
24	Samuel H. Huan, Sunil K. Sheoran, Ge Wang	2004
25	Remko van Hoek, Paul Chapman	2007
26	Robert B. Handfield, Gary L. Ragatz, Kenneth J. Petersen, Robert M. Monczka	1998
27	Per Hilletofth, David Eriksson	2010
28	Brian Vejrum Waehrens, Jens Ove Riis, John Johansen	2008
29	George Q. Huang, Jason S.K. Lau, K.L. Mak	2003
30	Ronan McIvor, Paul Humphreys, Trevor Cadden	2006
31	Taiwen Feng, Dan Wang	2012
32	Haritha Metta, Fazleena Badurdeen	2013
33	H.A. ElMaraghy, N. Mahoudi	2008
34	Pankaj Ghemawat, Jose Luis Nueno	2006
35	G. Fandel and M. Stammen	2004
36	Samir K. Srivastava	2007

Appendix 2-7c. Papers focused on life cycle

Life-cycle perspective		
	Author(s)	Year
1	Archie Lockamy, Kevin McCormack	2004
2	Janice E. Carrillo	2005
3	James Aitken, Paul Childerhouse, Denis Towill	2003
4	Sonia M. Lo and Damien Power	2010
5	Shona L. Brown, Kathleen M. Eisenhardt	1995
6	H. Sharifi, H.S. Ismail and I. Reid	2006
7	Hau L. Lee	2002

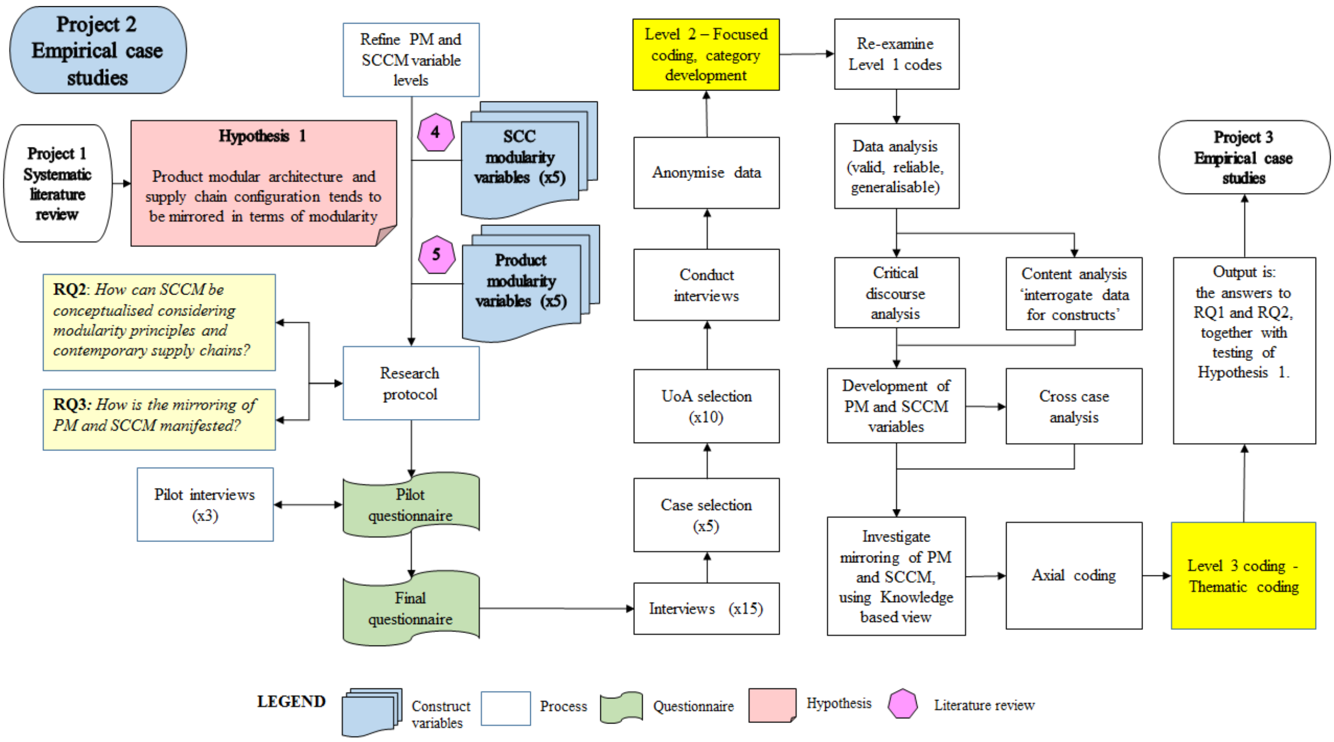
Appendix 2-8. Papers categorised by linking theme

Papers categorised by theme			
(1) Modularity	**(2) Early supplier involvement**	**(3) Co-development (PA and SCC)**	**(4) Product and SCC process life-cycle**
Lee & Sasser (1995) Fine & Whitney (2000) Novak & Eppinger (2001) Krishnan & Ulrich (2001) Fixson (2005) Anderson & Joglekar (2005) Mikkola & Skott-Larsen (2006) Hoetker (2006) Halldorsson, Kotzeb, Mikkola, Skitt-Larsen (2007) Jiao, Simpson & Siddique (2007) Noori & Georgescu (2008) Zhang, Chang & Xu (2008) Pero & Sianesi (2009) Lau, Yam, Tang & Sun (2010) Baud-Lavigne, Agard & Penz (2012) Fine, Golany & Naseraldin (2005) Hoetker (2006) Schilling (1999)	Lau, Yam & Tang (2007) Petersen, Handfield & Ragatz (2005) Johnsen (2009) Baud-Lavigne, Agard & Penz (2012) Handfield, Ragatz, Petersen & Monczka (1998) Halldorsson, et al. (2007) Yang, Yang & Wijngaard (2007) Graves & Willems (2005) Lee (2002) Hilltofth & Eriksson (2010) Krishnan & Ulrich (2001) Ragatz, Handfield & Scannell (1997) Swink (1998) van Hoek & Chapman (2007) Feng & Wang (2012)	Ragatz, Handfield & Scannell (1997) Handfield, Ragatz, Petersen & Monczka (1998) Swink (1998) Dowlatshahi (1999) Fine (2000) Primo & Amundson (2002) Huang, Lau & Mak (2003) Fandel & Stammen (2004) Huan, Sheoran & Wang (2004) Petersen, Handfield & Ragatz (2005) Graves & Willems (2005) Stadler (2005) Walker (2005) McIvor, Humphreys & Cadden (2006) Ghemawat & Nueno (2006) Srivastava (2007) Lau, Yam & Tang (2007) Lau, Yam & Tang (2011) Yang, Yang & Wijngaard (2007) van Hoek & Chapman (2007) ElMaraghy & Mahoudi (2008) Waehrens, Riis & Johansen (2008) Zhang, Huang & Rungtusanatham (2008) Johnsen (2009) Gosling & Naim (2009) Hilltofth & Eriksson (2010) Nepal, Monplaisir & Famuyiwa (2010) Pero, Abdelkafi, Sianesi & Blecker (2010) Nepal, Monplaisir & Famuyiwa (2011) Nepal, Monplaisir & Famuyiwa (2012) Feng & Wang (2012) Metta & Badurdeen (2013) Gan & Grunow (2013) Marsillac & Roh (2014) Chiu & Kremer (2014)	Brown & Eisenhardt (1995) Lee (2002) Aitken & Childerhouse & Towill (2003) Lockamy & McCormack (2004) Carrillo (2005) Sharifi, Ismail & Reid (2006) Ludema (2008) Srivastava (2007)

Appendix 2-9. Academic research areas

	New Products					Supply chain configuration						Multi-stage Supply chain modelling							Methodology				SC performance metrics			
Article	Product Novelty	Product Variety	Product platform	**Product architecture**	Component standardisation	Make-Buy decisions	Early Supplier Selection	**Supply chain configuration**	Long term capacity planning	Business planning	Product life cycle	Deterministic analytical	Statistical	Stochastic analytical	Economic	Simulation	Periodic review	Multi-objective goal programming	Descriptive	Prescriptive	Empirical	Conceptual	Monetary value	Product availability	Knowledge exchange	Response time
Stewart (1997)			X	X		X		X	X	X	X															
Beamon (1998)												X		X	X	X										
Graves and Willems (2005)				X														X								
Croom et al (2000)																			X	X	X	X				
Novak et al. (2001)	X			X		X							X						X		X					
Min & Zhou (2002)												X	X	X		X			X				X	X		X
Huan et al. (2004)			X	X				X	X	X	X							X	X			X	X	X		X
Graves and Willems (2005)				X				X	X			X			X		X		X		X		X			
Goh et al. (2007)										X				X								X	X			
Zhang et al. (2008)			X	X												X			X				X			
ElMaraghy et al. (2008)			X	X				X										X				X	X			
Pero et al. (2009)				X				X										X				X	X			
Nepal et al. (2010)																		X					X			X
Baud-Lavigne et al. (2012)					X			X							X			X			X					
Metta et al. (2013)												X			X						X		X			
Ramezani (2013)								X										X			X		X			X
Chiu et al. (2014)				X			X	X				X									X		X			X
Cigolini et al. (2014)								X								X						X	X			

Appendix 3-1. Project two research process



Appendix 3-2. Project two case study questionnaire

Construct	Variable	Primary Questions	Secondary Questions
Product modularity	Function sharing	To what extent are your products modular and explain how they are modular? **Prompt:** i.e. the extent to which product functionality maps onto the physical components, in a one to one fashion.	Does each module perform a well defined function? If there is function sharing between modules, does this lead to reduced component count?
	Interface coupling	How loosely coupled are the modules and are the interfaces clearly specified? Are the modules easily interchangeable or substitutable? **Prompt:** What type of module interfaces are used? For example, slot, bus and section.	Do you regard modularity as interface standardisation? Please expand on your answer
	Data accessibility	To what extent does your product allow access to component, module and system level data, explain the answer? **Prompt:** e.g. to enable reliability, durability and soft module protection including internet access.	Has your company started to introduce Internet of things (IoT) technologies in to your product and supply chain configuration? What are your company's plans in this area?
	Limited life	To what extent are the modules designed with respect to their useful life and how? i.e. where the useful life is limited are the modules designed in a different way? **Prompt:** e.g. to be accessible, low cost and recyclable?	Are there opportunities for component upgradeability? Are modules designed for re-use, or re-manufacture?
	Variety in use	To what extent is the product customisable by the user and why / how? This refers to the core product and excludes extension of the product via accessories or service contracts. **Prompt:** e.g. to change appearance, durability or ergonomics?	What is your core product? And what areas of end-user customisation are important to your customers?
Supply chain configuration modularity	Supply chain tiering	To what extent does the supply chain configuration provide supply chain process modules? Supply chain is that required to produce the 3 tiers of the product's BOM - this may be outside the company.	Can new SC modules be added quickly in response to changing product requirements?
	Process postponement	To what extent are differentiation/customisation sub processes postponed to the time of receipt of the customer order (or call off or more accurate forecast is received), achieving greater flexibility? How does this happen? How easily can the processes be decoupled by insertion of an Order Entry Point (OEP)?	Do you provide product postponement at the design, fabrication, assembly or user level?
	Process flexibility	To what extent can the processes be broken down into standard sub-processes, that produce standard base units and customisation sub processes that further customise the base units? Explain	Can you provide examples of loosely coupled supply chain configuration processes?
	Process re-sequencing	To what extent can the sub processes be re-ordered so that standard sub processes occur first, while differentiation / customisation sub processes occur last?	Are data analytics used in supply chain configuration re-sequencing?
	Place postponement	To what extent are differentiation/customisation sub processes postponed to the location of the customer order, achieving greater flexibility? How does this happen?	Are certain component and materials purchases postponed until after receipt of customer order?

Appendix 3-3. Pilot interview questionnaire

Date: 13th April, 2015
Interviewee: VP Product Design, Global Electronics Design & Manufacturing co.

Constructs	Variables	Code	Primary questions	Rating	Secondary answers	Ranking
Product modularity	Function sharing	PM1	Does the product provide function sharing, by mapping single functions to single component or modules? (from very high = 7, to very low level = 1)	7	Function sharing leads to lower component count and cost	1
	Interface coupling	PM2	Are component and module interfaces standardised and clearly defined, allowing ease of component substitution? (from very high = 7, to very low level = 1)	6	Since we design and manufacture medical electronic devices we do not want customer replacing components, or modules with alternate parts	2
	Data access	PM3	Does your product offer component, module and system level performance data access? (from very high = 7, to very low level = 1)	5	We are in the early phases of data connectivity, we are still not clear on how to use data	4
	Limited life	PM4	Does your product take into consideration the limited (or useful) life of components? (from very high =7, to very low level = 1)	7	There is limited part substitution and upgradeability, due to regulatory controls	3
	Product variety in use	PM5	Does your product design facilitate user product customisation? (from very high = 7, to very low level =1)	2	User customisation is limited to software customisation and accessories	5
Supply chain configuration modularity	Multi-functional product configuration	SCCM1	Does the supply chain configuration provide varying product configuration options? (from very high = 7, to very low level = 1)	2	Our SCCM processes provide multi-stage configuration to customer order	1
	Process flexibility	SCCM2	Can supply chain configuration deliver both standardised and customised modules and systems? (from very high = 7, to very low level = 1)	5	This process flexibility is limited due to regulatory controls	3
	Process re-sequencing	SCCM3	Can supply chain configuration be re-sequenced so standard subprocesses occur first while customisation or differentiation sub-process occur last? (from very high = 7, to very low level = 1)	2	Re-sequencing is limited to software and add-on module options	4
	Process postponement	SCCM4	Supply chain processes can be rearranged so that product assembly occurs after the COEP? (from very high = 7, to very low level = 1)	2	This process flexibility is limited due to regulatory controls	2
	Place postponement	SCCM5	Can supply chain configuration provide user late stage form postponement (Fp) at a location close to the COEP? (from very high = 7, to very low level = 1)	1	There are options to order software, and colour options at the COEP	5

Appendix 3-4. Quantitative assessment

	Technique	Purpose	Method	Matrix	When to use	Challenge	Interpretation	Questions	Response
1	Rank correlation between Product (PM) and Supply chain modularity (SCCM)	Measure statistical dependence between two variables.	Spearman or Kendall's rank correlation technique (non-parametric tests).	5X5	Appropriate for discrete and continuous variables. Non-parametric tests do not rely on any assumptions about the distributions of X or Y.	Need a population sample of 20 to 30 UoA.	If the p value <0.05 these are significant, negative value means inverse relationship, positive equals close correlation the larger the absolute value means a strong relationship (both +1 and -1).	Are the relationships between PM and SCCM variables significant? Are the relationships statistically dependent?	The relationships between PM and SCCM are not statistically dependent in this research
2	Normality tests	Takes averages of each reading, to compute how likely is it for a random variable to be normally distributed.	Parametric statistics.	1X1	To determine if the data set is modelled by a normal distribution, and are there any random variables.	It might not be appropriate to take average of all variables within a construct.	Requires further semantic analysis of how appropriateit is to aggregate the data by construct.	Are the relationships between the PM and SCCM significant?	The relationships between PM and SCCM are not significant in this research.
3	The t-test	Check if the means of two normally distributed populations are equal.		5X12	To determine if two sets of data are significantly different from each other.	Is it correct to aggregate the scores? This is a question of semantics.	Check the equality of two median sets of attribute data.	Are PM and SCCM with intervening control mechanisms?	Not applicable.
4	Mann-Whitney U Test	It is used to compare differences between two independent groups when the variables are not normally distributed. It can be used to the test equality of two medians when the data sets are not normally distributed.	Mann-Whitney is a non-parametric test.		This test has greater efficiency than t-test on non-normal distributions.		There is a need to carefully assess the relationships between these two populations of attribute data.	Am I comparing PM and SCCM with control techniques?	Not applicable.
5	ANOVA test	Analyse the difference between group means (PM versus intervention techniques).	ANOVA		Generalises the t-test to more than two groups.		Is it possible to measure the combined effectiveness of PM and SCCM on the new product introduction rates (NPIR) using this technique?	What is the effectiveness of the intervention techniques on NPIR?	Not applicable.
6	Chi-square test	Can be used to check the independency of two qualitative variables.	Chi-square test.		Are there differences between the expected and observed values due to sampling variation?				Not applicable
7	Mood's Median Test	Non- parametric tests can be used to test that the medians of two of more populations are identical.	Mood's Median Test.					Are there differences between the expected and observed values due to sampling variation?	Not applicable.

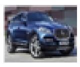
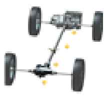
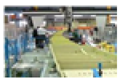
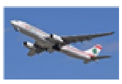
Appendix 3-5. Project two pattern codes and code descriptions

Key constructs - pattern descriptions		
Code	**Description**	**Pattern type**
TYPE1	Mirroring of the mandatory PM variables	Typology
TYPE2	Mirroring of the mandatory SCCM variables	Typology
TYPE3	Mirroring of the optional PM variables	Typology
TYPE4	Mirroring of the optional SCCM variables	Typology
FS	Function sharing related to interface coupling	Thematic
FS	Function sharing related to level of module in BOM	Thematic
IC	Interface coupling related to function sharing	Thematic
IC	Interface coupling related to bus modularity	Thematic
IC	Interface coupling related to supply chain tiering	Thematic
DA	Data access related to network communications	Thematic
DA	Data access related to interdiciplinary systems engineering	Thematic
LL	Limited life related to mean-time-to-failure (MTTF)	Thematic
LL	Limited life related to mean-time-between-failure (MTBF)	Thematic
LL	Limited life related to component failure in time (FIT) rates	Thematic
PV	Product variety related to customer variety	Thematic
PV	Product variety related to customer order entry point (COEP)	Thematic
SCT	Supply chain tiering related to depth of supply network	Thematic
SCT	Supply chain tiering related to breadth of supply network	Thematic
SCT	Supply chain tiering related to geographic spread of the supply network	Thematic
SCT	Supply chain tiering related to economic and legal involvement of OEM	Thematic
PRP	Process postponement related to time of customer order entry	Thematic
PRP	Process postponement related to buffer inventory levels	Thematic
PRP	Process postponement related to process agility	Thematic
PF	Process flexibility	Thematic
PR	Process resequencing	Thematic
PLP	Place postponement	Thematic
KC	Knowledge codification between PM and SCCM - low level	Relationships
KC	Knowledge codification between PM and SCCM - medium level	Relationships
KC	Knowledge codification between PM and SCCM - high level	Relationships
ESI	Early supplier involvement in PM and SCCM - low level	Relationships
ESI	Early supplier involvement in PM and SCCM - medium level	Relationships
ESI	Early supplier involvement in PM and SCCM - high level	Relationships
LC	Life-cycle applied to PM and SCCM - low level	Relationships
LC	Life-cycle applied to PM and SCCM - medium level	Relationships
LC	Life-cycle applied to PM and SCCM - high level	Relationships
PD	Propensity to decouple - low	Relationships
PD	Propensity to decouple - high	Relationships

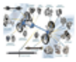
Appendix 3-6. Project two pattern codes and pattern types

First Level code	Second Level code	Pattern code	Pattern description	Pattern Type
PM	FS	FS-L	Low	Thematic
PM	FS	FS-M	Medium	Thematic
PM	FS	FS-H	High	Thematic
PM	IC	IC-L	Low	Thematic
PM	IC	IC-M	Medium	Thematic
PM	IC	IC-H	High	Thematic
PM	DA	DA-L	Low	Thematic
PM	DA	DA-M	Medium	Thematic
PM	DA	DA-H	High	Thematic
PM	LL	LL-L	Low	Thematic
PM	LL	LL-M	Medium	Thematic
PM	LL	LL-H	High	Thematic
PM	PV	PV-L	Low	Thematic
PM	PV	PV-M	Medium	Thematic
PM	PV	PV-H	High	Thematic
SCCM	SCT	SCT-L	Low	Thematic
SCCM	SCT	SCT-M	Medium	Thematic
SCCM	SCT	SCT-H	High	Thematic
SCCM	PRP	PRP-L	Low	Thematic
SCCM	PRP	PRP-M	Medium	Thematic
SCCM	PRP	PRP-H	High	Thematic
SCCM	PF	PF-L	Low	Thematic
SCCM	PF	PF-M	Medium	Thematic
SCCM	PF	PF-H	High	Thematic
SCCM	PR	PR-L	Low	Thematic
SCCM	PR	PR-M	Medium	Thematic
SCCM	PR	PR-H	High	Thematic
SCCM	PLP	PLP-L	Low	Thematic
SCCM	PLP	PLP-M	Medium	Thematic
SCCM	PLP	PLP-H	High	Thematic
	KC	KC-L	Low	Relationship
	KC	KC-M	Medium	Relationship
	KC	KC-H	High	Relationship
	ESI	ESI-L	Low	Relationship
	ESI	ESI-M	Medium	Relationship
	ESI	ESI-H	High	Relationship
	LC	LC-L	Low	Relationship
	LC	LC-M	Medium	Relationship
	LC	LC-H	High	Relationship
	PD	PD-L	Low	Relationship
	PD	PD-H	High	Relationship

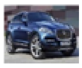
Appendix 3-7. Bus architecture typologies

Case Co.	UoA			Bus-type architecture	Description
Medical device company		A1	Non-invasive surgical cartridge	Mechanical bus	Staple is a mechanical structure which holds wire staples, and is assembled varying diameters and lengths
		A2	Verio blood glucose measurement meter	Electronic and DC power buses	Based on amperometric electrochemical biosensor technology with corresponding reagent test strips
Domestic appliance company		B1	Air Purifier	Mechanical and DC power buses	The DC motor forms the primary bus, the electrical circuit connects to main components
		B2	Cordless vacuum cleaner	Mechanical and DC power buses	The DC motor forms the primary bus, the cyclones and head motor are connected to this bus
Automotive company		C1	Sports Utility Vehicle (SUV)	Powertrain, electrical, and mechanical buses	Driveline solutions are integrated into the drivetrain, and powertrain
		C2	Crossover Utility Vehicle (CUV)		
Auto-driveline company		D1	Driveline	Drivetrain, electronic, and power buses	The servo-technology, and electronics are integrated on to the driveline platform
		D2	Driveshaft assembly	Front and rear sideshafts and central propshaft buses	This All-wheel drive (AWD) systsem is comprised of a power transfer unit, prop shafts, AWD couplings, the final drive unit and disconnects.
Aerostructure company		E1	Trailing-edge wing structure for A350	Mechanical bus	Fixed trailing edge composite aircraft wing structure
Aerospace company		E2	A330 airplane	Mechanical, electrical, electroinc communications and DC power buses	Centre fuselage is the core of the airplane, avionics are centred in the cockpit

Appendix 3-8. Additional product and SCC data

Case	Sector	UoA		Platform product currently	Product release frequency	Core Intellectual Property	Future platform opportunities
1	Medical device		A1	N	Single design released to market to date	Materials, and process automation	Modular in-line stapling machine, that can assemble staples to specific patient requirement.
			A2	Y	3-4 per year	Materials, enzymes (biologics), and algorithm for measuring blood glucose levels, and process automation	Wi-Fi and Bluetooth connectivity, together with non-invasive measurement and insulin delivery capabilities.
2	Domestic appliance		B1	N	Single design released to market to date	Air filtering process technology, digital motor technology	1st release of this product which will be part of a platform. Future models will have Wi-Fi and Bluetooth connectivity, together with alternate sensor and air quality filter technologies.
			B2	Y	1 per year, per category	DC motor, battery technology	Future models will have Wi-Fi and Bluetooth connectivity, together with alternate sensor and filter technologies.
3 - 4	Automotive		C1	Y	1 per every 3-5 years	Module interface and process development	Incorporate technologies proven on C-X75 concept car.
			C2	Y			
			D1	Y	1 per year	SCC process design	
			D2	Y	1 per every 3-5 years	Product performance specification	
5	Aerospace		E1	Y	1 every 20 years	Materials science and carbon fibre materials processing technology	Increased usage of lighter, lower erosion carbon fibre materials.
			E2	Y	2 every 20 years	Engine, avionics, power technologies	New engine options to reduce fuel burn.

Appendix 3-9. Economic and legal business involvement by OEM

Economic and legal business involvement by OEM										
Company	Med device co.		Domestic appliance co.		Auto co.		Auto driveline co.		Aerostructure co.	Airplane co.
UoA	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
										
Economic and legal business involvement by OEM	Medium involvement	Medium involvement	Medium involvement	Medium involvement	Low involvement	Low involvement	High involvement	High involvement	High involvement	Low involvement
SCT modularity	Medium	Medium	Medium	Medium	High	High	Low	Low	Low	High

Appendix 3-10. Primary themes deduced from projects one and two

	Theme	Construct	Developed during
1	**Modularity**	Product Modularity	P1
		Supply Chain Configuration Modularity	P1
2	**Co-development**	Downstream suppliers	P1
		Internal and External product development	P1
		Upstream distribution process development	P1
3	**Supplier capability**	Early Supplier Involvement	P1
4	**Life-cycle perspective**	at Product Concept stage	P1
5	**Knowledge Codification**	at PM-SCCM interface	P2
6	**Propensity to decouple**	at PM-SCCM interface	P2

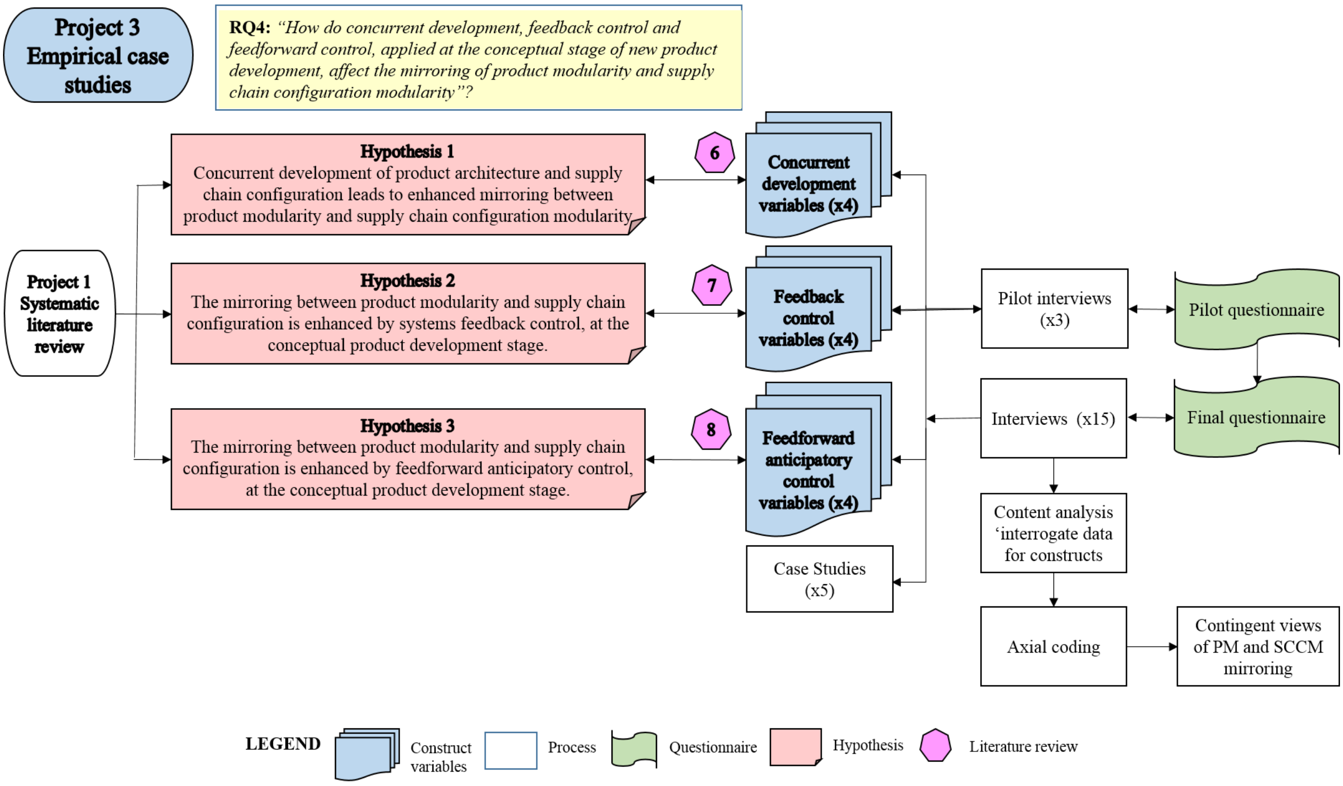
Appendix 3-11. SCC knowledge innovation areas

	Academic research	Author(s)	SCC topic of discussion	SCC innovation knowledge area
Knowledge based research on Supply chain configuration	Supply chain configuration innovation	Mandal *et al.* (unpublished)	Uses the RBV and dynamic capabilities perspectives, to formulate a conceptual model consisting of several capability based antecedents and outcomes	Resource based view
	Concept of decisiveness is important in comparing the cost of coordination between a modular design strategy and an integral design strategy receptively.	Foss, 1999	Discussion on targeting optimal product architecture designs	Cost control
	Improved knowledge sharing during the early design stages may decrease the number of last-minute changes	Wynstra *et al.* 2001	Reviews aspects of SCC alignment with product architecture design.	Concurrent development
	Digital distribution and structures of e-supply chain	van Hoek, 2001	Discusses the digital re-imaging of supply chains	e-supply chain
	Supply chain configuration modelling	Arora and Kumar, 2002	Reviews how product designers make SCC decisions, focus on enterprise integration.	SCC re-engineering
	Decision support tool	Blackhurst *et al.* 2005	Which features of supply chain configuration add most value to product designs	SCC influence on NPD
	Optimizing the Supply Chain Configuration for New Products	Graves and Willems 2005	The optimal SCC moves from the minimum Unit Manufacturing Cost solution to the minimum lead-time solution, as a function of the holding cost.	SCC optomisation
	Green supply-chain management: A state-ofthe-art literature review	Srivastava, 2007	Systematic literature review on green supply-chain management	Sustainability
	Cloud based supply chain	Lindner *et al.* 2010	Discusses the impact of Cloud and Pervasive computing	Cloud computing
	Design for Supply chain configuration	Ülkü and Schmidt, 2011	Discuss on mapping from product architecture to supply chain structure is not always a one-to-one relationship.	SCC influence on NPD
	Intelligent supply chain	Borgia, 2014	Discusses the impact of IoT (Intelligence of Things) on supply chains.	Cloud computing
	Self discovering of entities and services	Borgia, 2014	Assesses the impact of big data analytics.	Cloud computing
	Smart objects	Borgia, 2015	Reviews the impact of social media on supply chains.	Social media
	Low carbon supply chain configuration for a new product	Brandenburg, 2015	A goal programming approach is suggested to deterministically assess trade-offs between environmental and economic criteria.	Sustainability
	Reliable Supply Chain Network Design	Yildiz *et al.* 2016 Forthcoming in Decision Sciences	Attempt to model the impact of upstream supply chain's reliability on the reliability of the downstream entities through three different compounding mechanisms.	Network reliability

Appendix 3-12. Literature focused on intervening mechanisms

	Author(s)	**Horizontal tier**					**Intervening mechanism**			**Units of Analysis**				
		Plan	Source	Make	Deliver	Service	CD	FC	FAC	Electronic products	Auto	Aero	Medical devices	Domestic appliances
1	Ameri and McArthur (2013)		X	X						X				
2	Amaral and Kuettner (2008)			X	X					X				
3	Amin and Zhang (2012)		X	X						X				
4	Baud-Lavigne (2014)		X				X							
5	Chiu and Okudan (2011)		X	X										X
6	Choi and Hong (2002)			X							X			
7	Cohen and Fine (2000)						X							
8	Corominas (2015)				X									
9	Feitzinger and Lee (1997)		X	X	X		X			X				
10	Gan and Grunow (2013)						X							
11	Graves and Willems (2005)		X	X	X		X							
12	Khan *et al.* (2012)				X						X			
13	Li and Womer (2008)									X				
14	Magretta (1998)		X	X	X		X			X				
15	Marsillac and Roh (2014)													
16	Medini and Rabenasolo (2014)				X									
17	Metters and Walton (2007)		X		X					X				X
18	Nepal et al. (2010)						X							
19	Osman and Demirli		X									X		
20	Pero, Abdelkafi et al. (2010)						X							
21	Pero and Sianesi (2009)			X			X							X
22	Randall and Ulrich (2001)		X	X										X
23	Shahzad and Hadj-Hamou (2013)									X				
24	Swink (2000)						X							
25	Ulku & Schmidt (2011)		X	X			X							
26	Vanteddu *et al.* (2011)		X								X			
27	Verdouw *et al.* (2011)			X	X									X
28	Woolsey (1994)		X	X	X		X							
29	Yan *et al.* (2015)						X							
30	Zhang *et al.* (2008)		X	X			X			X				

Appendix 4-1. Project three research process



Appendix 4-2. Updated literature review, focus on intervening mechanisms

	Author(s)	**Horizontal tier**					**Intervening mechanism**			**Units of Analysis**				
		Plan	Source	Make	Deliver	Service	CD	FC	FAC	Electronic products	Auto	Aero	Medical devices	Domestic appliances
1	Ameri and McArthur (2013)		X	X						X				
2	Amaral and Kuettner (2008)			X	X					X				
3	Amin and Zhang (2012)		X	X						X				
4	Baud-Lavigne (2014)		X				X							
5	Chiu and Okudan (2011)		X	X										X
6	Choi and Hong (2002)			X							X			
7	Cohen and Fine (2000)						X							
8	Corominas (2015)				X									
9	Feitzinger and Lee (1997)		X	X	X		X			X				
10	Gan and Grunow (2013)						X							
11	Graves and Willems (2005)		X	X	X		X							
12	Khan *et al.* (2012)				X						X			
13	Li and Womer (2008)									X				
14	Magretta (1998)		X	X	X		X			X				
15	Marsillac and Roh (2014)													
16	Medini and Rabenasolo (2014)				X									
17	Metters and Walton (2007)		X		X					X				X
18	Nepal et al. (2010)						X							
19	Osman and Demirli		X									X		
20	Pero, Abdelkafi et al. (2010)						X							
21	Pero and Sianesi (2009)			X			X							X
22	Randall and Ulrich (2001)		X	X										X
23	Shahzad and Hadj-Hamou (2013)									X				
24	Swink (2000)						X							
25	Ulku & Schmidt (2011)		X	X			X							
26	Vanteddu *et al.* (2011)		X								X			
27	Verdouw *et al.* (2011)			X	X									X
28	Woolsey (1994)		X	X	X		X							
29	Yan *et al.* (2015)						X							
30	Zhang *et al.* (2008)		X	X			X			X				

Appendix 4-3. Project three questionnaire

Constructs	Variables	Opening Questions	Secondary Questions
Co- development	Level of concurrent development at concept stage **(CD)**	At your company to what extent is concurrent development used for product concept development? **Note:** CD involves the concurrent design of product, manufacturing and supply chain (procurement)	Is concurrent development used for generating ideas before product concepts are developed?
	What SCC functions are involved in the concurrent development team **(SCI)**	Which functions are involved at the concept stage of development? Is a product development team used?	Are customer product requirements fuzzy (emerging) or pre-defined?
	Level of knowledge sharing and concurrency between Product architecture and SCC **(KS)**	How much supply chain configuration design is done concurrently with product design?	Does your design process support engineering cooperation across the product development chain?
	Level of concurrent development of product specification **(CI)**	Does your company use formal techniques, to translate customer requirements in to product and supply chain parameters, at product concept design stage?	Does your company utilise design evaluation systems such as customer design for supply chain, reusability, serviceability and disposability?
Feedback control	Product assess at each stage gate exit **(PPI)**	Does your company employ systems thinking and feedback control to improve product design? Explain feedback control	Is your product designed from an open- or closed-loop perspective?
	SCC performance assessment after concept stage **(SA)**	Does your company employ systems thinking and feedback control to improve supply chain configuration? Explain supply chain configuration (SCC)	Is your supply chain configuration open- or closed-loop?
	NPD lead-time goal assessment **(LT)**	How do product complexity and the amount of product change vary from previous product releases impact on development lead-time?	Does you design take in to consideration the parameters which require time to launch measurement?
	Product architecture versus SCC performance trade-off analysis **(TO)**	Does your company maintain a balanced scorecard for managing supply chain configuration and product design trade-offs?	Does your new product constitute a significant improvement on the previous product, involving supply chain configuration considerations?
Feedforward anticipatory control	Level of FAC to deliver the product architecture **(FPA)**	Are input variables measured in terms of their relationship to the NPD introduction rate?	Does your company employ feedforward control measures in NPD?
	Level of FAC to deliver the SCC requirements **(FCA)**	Does your company select input variables that make a material difference in improving the NPD introduction rate?	Does your company employ feedforward control measures in supply chain configuration?
	SCC goal achievement **(PGA)**	Is data collected, to establish SCC goals?	Is this data gathered dynamically?
	Use of product and SCC architectural tools **(PCA)**	Do management look for new influences both within and outside the control system, which require new input variable controls?	Does you company benchmark "best practices", for the purposes of continuous NPD process improvement?

Appendix 4-4. Intervening mechanism codes

Code	Level	Description
CD	1	Concurrent development
SI-L	2	Supplier involvement - low level
SI-M	2	Supplier involvement - medium level
SI-H	2	Supplier involvement - high level
II-L	2	Internal team involvement - low level
II-M	2	Internal team involvement - medium level
II-H	2	Internal team involvement - high level
CI-L	2	Customer involvement - low level
CI-M	2	Customer involvement - medium level
CI-H	2	Customer involvement - high level
CD-L	2	Level of co-development - low level
CD-M	2	Level of co-development - medium level
CD-H	2	Level of co-development - high level
FC	1	Feedback control
SC-L	2	Level of assessment of SCC - low level
SC-M	2	Level of assessment of SCC - medium level
SC-H	2	Level of assessment of SCC - high level
LT-L	2	Use of leading product performance indicators - low level
LT-M	2	Use of leading product performance indicators - medium level
LT-H	2	Use of leading product performance indicators - high level
TO-L	2	Use of SCC and PA trade-off analysis - low level
TO-M	2	Use of SCC and PA trade-off analysis - medium level
TO-H	2	Use of SCC and PA trade-off analysis - high level
FC-L	2	Level of feedback design review - low level
FC-M	2	Level of feedback design review - medium level
FC-H	2	Level of feedback design review - high level
FAC	1	Feedforward anticipatory control
SAC-L	2	Level of FAC to deliver SCC requirements - low level
SAC-M	2	Level of FAC to deliver SCC requirements - medium level
SAC-H	2	Level of FAC to deliver SCC requirements - high level
LPI-L	2	Use of leading product performance indicators - low level
LPI-M	2	Use of leading product performance indicators - medium level
LPI-H	2	Use of leading product performance indicators - high level
AA-L	2	Level of PA and SCA assessment - low level
AA-M	2	Level of PA and SCA assessment - medium level
AA-H	2	Level of PA and SCA assessment - high level
FAC-L	2	Level of feedforward design review - low level
FAC-M	2	Level of feedforward design review - medium level
FAC-H	2	Level of feedforward design review - high level
SC	3	Supplier capabilities
CI	3	Complexity of information exchanged
CO	3	Codifiability of PM and SCCM information
COEP	3	Customer order entry point

Appendix 4-5. Intervening mechanism pattern descriptions

Intervening mechanism codes		
Code	**Description**	**Type**
TYPE1	Intervening mechanism - Co-development	Construct
TYPE2	Intervening mechanism - Feedback control	Construct
TYPE3	Intervening mechanism - Feedforward anticipatory control	Construct
CD	Co-development of NPD and SCC	Relationship
FC	Feedback control of NPD and SCC performance knowledge	Relationship
FAC	Feedforward anticipatory control of NPD and SCC performance knowledge	Relationship
SC	Supplier capabilities	Axial theme
CIE	Complexity of information exchanged	Axial theme
CO	Codifiability of PM and SCCM information	Axial theme
COEP	Customer order entry point	Axial theme

Appendix 4-6a Co-development for medical devices

		A (Med device co.)				
		A1		A2		
Construct	**Variable**	**Level**	 High	**Level**	 High	
Concurrent Development (CD) at concept stage	Overall level of Co-development at the product concept stage **(CD)**		CD is a core practice, with patients, doctors, nurses and the entire system. For this product SCC was excluded from the concept stage.		CD is a core practice. This company use the standard stage gate process, and Technology Release Levels.	CD focuses on discovering new product requirements, materials with a focus on experimentation. These products have a relatively long life-cycle, requiring a more open approach to design thinking.
	SCC function involvement at the concept stage **(SCI)**		SCC involvement, was late in the NPD process, primarily post the concept stage.		SCC involvement was late, however this practice is changing.QA and supplier quality are key considerations at the concept stage.	SCC is a traditional area of lean thinking. Whilst there are opportunities for improvements in SCC, SCC knowledge needs to be refined and communicated.
	Knowledge sharing and concurrency between PA and SCC **(KS)**		Knowledge sharing is medium level. Geometric tolerancing and dimensioning are critical. Supplier selection and core materials capabilities are key focus.		Materials handling considerations are the main SCC knowledge exchanges, at the concept stage.	Tacit Product and SCC knowledge is a valuable resource for this medical company. Distributing this knowledge at the concept stage is key to building sustainable advantage.
	Co-development of product specification **(CI)**		Practitioners are actively involved in product design. Education and re-education are key.		These is customer involvement through patient study groups, and customer focus groups.	Customer involvement is high, and leads to increasing levels of product customisation.

Appendix 4-6b Feedback control for medical devices

		A (Med device co.)				
		A1		A2		
Construct	**Measure**	**Level**	 Medium	**Level**	 High	
Feedback control (stage gate)	Product assessment at stage-gate exist **(PPI)**		Strong verbal communications with surgeons. There are approximately 100 expert practitioners globally.		There is strong customer experience feedback monitoring. Proving there is equivalence on dual sourced materials is a key regulatory requirement.	Material Science plays a key role in the concept development of this companies medical products. Customer feedback is important to product development teams.
	SCC performance after concept stage **(SA)**		Focus is also on manufacturing process capability (Cpk) and yield improvement. Focus is on SCC process cost, flexibility and quality.		Process capability (Cpk) is a key SCC variability measure. Device serialisation is introduced at concept stage to provide improved product traceability.	SCC process capability is prioritised. Other SCC variables include product traceability, Importantly design knowledge should be captured at the concept stage.
	NPD lead-time goal assessment **(LT)**		NPD assessment at stage gates		New product introduction rate (NPIR) is a key measure.	System design waste prevention involves the movement of information, products and customers through the futures system. This company are focused on process cycle efficiency.
	Product - SCC process performance trade-off analysis at product concept development **(TO)**		Process automation changes are not purely technical decisions.		Product specification, is built from a marketing requirements document. A trace matrix is used to balance product and manufacturing process decisions.	The company evaluate the trade-offs between inventory 'waste' and SCC process time 'waste'. Inventory availability are key considerations, in both product instances.

Appendix 4-6c Feedforward anticipatory control for medical devices

		A (Med device co.)				
		A1		A2		
Construct	**Measure**	**Level**	 High	**Level**	 Medium	
Feedforward anticipatory control (FAC)	Level of FAC to deliver product architecture **(FPA)**		FAC is not about selling opportunities internally. There is a desire to innovate the product design from a process perspective.		There was a need to evaluate materials and process capability (Cpk), in particular for the strips, and where material equivalence is required.	Future PA requirements were fed downstream to key suppliers.
	Level of FAC to deliver the SCC requirements **(FCA)**		In process yield is a key process variable. This is linked to known product constraints.		This company tends to stick with processes that work. There is a desire to innovate the product design from a process perspective.	Early PA information permits this company to reduce any randomness in their SCC process.
	SCC goal achievement **(PGA)**		Cost, in process yield and repeatable quality are the critical KPI's. Company rarely meets on time launch goals. Challenges exist around market definition and regulatory constraints.		Automation at launch for the strip is required to meet cost, and yield targets.	The long time-horizon goal is to introduce further automation to improve SCA goal achievement.
	Use of product and SCC architectural tools **(PCA)**		Generally there is poor manufacturing strategy early in the product design process. Design for automation is key.		There is a focus on the 'whole' customer experience. There are continuous glucose monitoring, non-invasive meters coming to market. There are cell phone-enhanced meters and combined meter and insulin delivery devices coming to market.	New technologies are allowing this company to evaluate closed loop SCC systems, where the medical practitioner, and patient are included in the system, real-time. This is opening up opportunities for multiple control loops, and improved patient experience.

Appendix 4-7a Co-development for domestic appliances

		B (Domestic appliance co.)				
		B1		B2		
Construct	**Variable**	**Level**	 Medium	**Level**	 Medium	
Concurrent Development (CD) at concept stage	Overall level of Co-development at the product concept stage **(CD)**		CD is a core practice. There was no tangible SCC involvement with CD at the product concept stage. R&D are focused on problem resolution, and the unique product selling proposition 'market claim'.		There was no tangible SCC involvement with CD at the concept stage. R&D focus was on further exploitation of the company's core product technologies.	This company's focus in the concept stage is on innovative product design. They are constantly exploiting core technology from previous products. The company use basic prototypes to avoid excessive tooling investments prior to detailed design.
	SCC function involvement at the concept stage **(SCI)**		Late SCC involvement, post phase gate zero. There was limited supplier involvement, with the exception of the supplier of the HEPA filter.		Late SCC involvement, post phase gate zero. There was limited supplier involvement.	This company consider the commercial potential of their invention before attempting to develop it. The company consider the price of a radically new product to assess if it can be set sufficiently high to be a viable proposition.
	Knowledge sharing and concurrency between PA and SCC **(KS)**		SCC is involved late in the design concept, with the exception of plastics tooling.		SCC is involved late in the design concept, with the exception of plastics tooling, and manufacturing process.	The company's products focus on finite problems, within specific area's of knowledge. The company make excessive use of CAD, there is room for further use of SCC knowledge.
	Co-development of product specification **(CI)**		Customer experience workshops and user surveys were used in the concept stage.		Customer experience workshops and user surveys were used in the concept stage.	Customer involvement is high, the voice of the customer is preserved, which leads to strong brand loyalty.

Appendix 4-7b Feedback control for domestic appliances

		B (Domestic appliance co.)				
		B1		B2		
Construct	Measure	Level	 Medium	Level	 High	
Feedback control (stage gate)	Product assessment at stage-gate exist **(PPI)**		Product performance is measured at phase gate. Non-conformances are recorded. A post launch milestone is completed six months after launch.		There was a strong adherence to the phase gate process.	There was poor use of prior product warranty data. Certain components are re-usable from prior designs.
	SCC performance after concept stage **(SA)**		Process Cpk (variability control), Tooling evaluation is completed during the concept stage.		Acknowledgement that the company could gain more value by evaluating product returns.	The company manage supplier power through in-house design and SCC knowledge.
	NPD lead-time goal assessment **(LT)**		Concept to launch time, is a key measure		Concept to launch time, is a key measure	Premium pricing places high pressure on time to launch targets being achieved. This requires strong IP protection, to maximise specialisation gains.
	Product - SCC process performance trade-off analysis at product concept development **(TO)**		There are four scorecards for time, cost, quality and reliability. It is ten times more difficult when you launch new product, and new technology in a new market.		SKU management at product level is key.	Strong property rights enables this company to operate a disaggregated supply chain.

Appendix 4-7c Feedforward anticipatory control for domestic appliances

		B (Domestic appliance co.)				
		B1		B2		
Construct	Measure	Level	 Medium	Level	 High	
Feedforward anticipatory control (FAC)	Level of FAC to deliver product architecture **(FPA)**		Product USP, or marketing claim, was key driver. Performance usually has a direct correlation to a market claim. Focus is on product categories e.g. environmental control.		The product's USP, was a key driver. Since this is a platform product there was prior information on user expectations, this led to more focused product marketing.	Company successfully establish product claim at concept stage. Everything including the marketing of the products is related to this product claim.
	Level of FAC to deliver the SCC requirements **(FCA)**		Company pro-actively established these SCA goals.		This is a challenging task. Company is discussing the use of Nett Promoter score to measure the contributions of SCC persons to the concept design.	There is an onus on SCC experts to increasingly communicate tacit and explicit SCC knowledge to NPD team, and establish credibility within the team.
	SCC goal achievement **(PGA)**		NPIR was not critical. Product performance testing, and validation is more critical than meeting strict product launch timelines.		NPIR was not critical. Company spent fifteen years on a new digital motor design.	SCA goals relate to repeatable delivery of product quality, and reliability.
	Use of product and SCC architectural tools **(PCA)**		Focus is on the 'whole' customer experience. Fulfilling the product marketing claim is a primary focus.		Modular process development is being used increasingly to reduce product complexity, supply chain risk and protect I.P.	Product modularity is a primary FAC tool, focused on mapping of product requirements, functionality, interface standardisation and I.P. protection. These environmental products contain four basic modules, for power generation, power transmission, carrying load, housing and protecting the motor.

Appendix 4-8a Co-development for automobile

			C (Auto co.)			
			C1		C2	
Construct	Variable	Level	 High	Level	 Medium	
Concurrent Development (CD) at concept stage	Overall level of Co-development at the product concept stage **(CD)**		CD is a core practice. Module teams are involved from the commencement of the concept design. With 3D simulation tools a concept car can be built and electronically performance tested.		CD is a core practice. Module teams are involved from the commencement of the concept design. Virtual build capabilities have existed for five years.	Procurement, quality and manufacturing engineering are involved in concept design.
	SCC function involvement at the concept stage **(SCI)**		Rapid prototyping, Digital simulation and 3D additive manufacturing techniques are applied at the concept stage. SCC is heavily involved in working with distribution channel at concept stage.		Five to ten key suppliers, were involved at concept stage.	As company becomes more globally focused there will be more focus on local sourcing decisions.
	Knowledge sharing and concurrency between PA and SCC **(KS)**		Suppliers might be requested to contribute design solutions prior to selection. Localised production brings challenges to further integrate suppliers.		Strategic Suppliers are involved early. The process for building product cost is structured.	Concurrent modular teams play a significant role. On the horizontal axis there are the modules, on the vertical axis there are the platforms.
	Co-development of product specification **(CI)**		The company use VOC techniques. The company build a physical life size model of the car, at the concept stage.		Customer experience workshops and user surveys were used in the concept stage	VOC plays a significant role, in the Luxury car market.

Appendix 4-8b Feedback control for automobile

		C (Auto co.)				
		C1		C2		
Construct	Measure	Level	 High	Level	 Medium	
Feedback control (stage gate)	Product assessment at stage-gate exist **(PPI)**		There is a significant amount of data coming back from dealers and customers, in one-hundred and seventy countries. Warranty claims is a critical process.		Warranty claims management is critical. There is significant focus on strategic suppliers	Warranty data product a mine-field of data for improving current and future product designs.
	SCC performance after concept stage **(SA)**		Supplier information management system records SCC performance data.		SCC feedback measures the overall business performance.	Modular SCC has reduced the number of variants and complexity in assembly, with customisation offered later in the SCC process. Increased profit margins area a result of improved economies of scale.
	NPD lead-time goal assessment **(LT)**		Concept to launch, is a key measure. Company is setting increasingly competitive NPIR targets. There is an acknowledgement that Japanese companies are superior on NPIR performance. There is a further twenty-five percent time improvement achievable.		Concept to delivery, is a key measure. The company limited the number of SKU's to achieve their NPD lead-time goal.	NPIR is the rate of product introduction relative to competitors, this company have halved this rate in the past five years.
	Product - SCC process performance trade-off analysis at product concept development **(TO)**		Strong focus on value engineering. Company sometimes trade-off on product weight versus performance.		Actual versus perceived quality, product features and availability are measured against Corporate goals.	There is a strong focus on elimination of potential environmental problems.

Appendix 4-8c Feedforward anticipatory control for automobile

Construct	Measure	Level	C (Auto co.)	Level		
			C1		C2	
						
			Medium		Medium	
Feedforward anticipatory control (FAC)	Level of FAC to deliver product architecture **(FPA)**		FAC was used to evaluate materials capabilities and process capability (Cpk).		FAC was used to add to architecture commodity library.	Modularity was designed in at the concept stage. FAC was used to communicate with suppliers to support fast time to launch.
	Level of FAC to deliver the SCC requirements **(FCA)**		FAC was used to pro-actively establish SCA goals across all tiers of the SCC.		FAC used for forward sourcing.	FAC operates equally upstream and downstream. This allows key suppliers and distribution channel partners to develop process capability before it is needed.
	SCC goal achievement **(PGA)**		NPIR goal setting is critical. It is recognised that Japanese firms are better at on-time SCC process design.		Measure KOI's that explicitly look at supply chain performance.	SCA knowledge must flow in both directions. FAC can be also face-to-face, it is inherently real-time and combines verbal and nonverbal information.
	Use of product and SCC architectural tools **(PCA)**		Modular process development is focused, and includes competitive teardown analysis.		Modular process development, with a focus on mass customisation.	Focus is on implementation of modular strategy. Fast feedback and FAC provide increased level of design control.

Appendix 4-9a Co-development for auto-driveline

		D (Auto driveline co.)				
		D1		D2		
Construct	Variable	Level	 High	Level	 High	
Concurrent Development (CD) at concept stage	Overall level of Co-development at the product concept stage **(CD)**		CD is a core practice. Manufacturing engineering plays a key role in the CD process. The product architecture concept and manufacturing are co-developed at the concept stage.		CD is a core practice. Application engineering play a significant role. The same person is responsible or PA and SCC.	As a tier one supplier of the drivetrain, CD is a critical activity.
	SCC function involvement at the concept stage **(SCI)**		Procurement, Product and Manufacturing engineering are involved		Late SCC involvement, with SCC involvement post phase gate zero.	This tier one supplier has a strong influence on the OEM's SCC.
	Knowledge sharing and concurrency between PA and SCC **(KS)**		Significant knowledge sharing with customer application engineers		Significant knowledge sharing with customer application engineers	Modularity allows for alternative powertrain concepts, offering flexibility in length, height, width, regional variations, and opportunities for low volume niche models.
	Co-development of product specification **(CI)**		In ninety per cent of cases the customer is involved, during the entire concept stage.		In ninety per cent of cases the customer is involved, during the entire concept stage.	Application engineers from the OEM are involved from the concept stage.

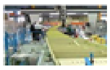
Appendix 4-9b Feedback control for auto-driveline

		D (Auto driveline co.)				
		D1		D2		
Construct	Measure	Level	 High	Level	 High	
Feedback control (stage gate)	Product assessment at stage-gate exist **(PPI)**		There is continuous communications with customer development engineers. There is significant warranty measurement.		There is continuous communications with customer development engineers. There is significant warranty measurement.	This company relies on feedback to influence product design improvement. Feedback is used to operate an effective product development process.
	SCC performance after concept stage **(SA)**		Voice of customer is managed at Chief Executive level.		SCC feedback is structured, process variability is a key consideration.	Feedback provides information to make better technical and economic choices.
	NPD lead-time goal assessment **(LT)**		Concept to launch, is key measure		New product introduction rate (NPIR) is heavily dependent on the OEM customer.	Companies manage new product timelines, rather than queues. The speed of feedback is important to product developers.
	Product - SCC process performance trade-off analysis at product concept development **(TO)**		This analysis is performed on a case by case basis.		There is active discussion on how to improve SCC design up front.	There is a strong focus on technical performance.

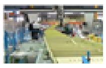
Appendix 4-9c Feedforward anticipatory control for auto-driveline

		D (Auto driveline co.)				
		D1		D2		
Construct	**Measure**	**Level**	 High	**Level**	 High	
Feedforward anticipatory control (FAC)	Level of FAC to deliver product architecture **(FPA)**		FAC is fundamental. Performance goals are established for fuel, noise, vibration and cost.		Application engineering focus. FAC in the area of SCC is in its infancy.	Early feedforward data from the OEM, allows this tier one supplier to counteract variability.
	Level of FAC to deliver the SCC requirements **(FCA)**		Company proactively establishes SCC performance goals.		Company acknowledges the need for increased SCC data analytics.	Acknowledgement that there is a requirement for improved SCC analysis, and knowledge sharing.
	SCC goal achievement **(PGA)**		NPIR goal setting is critical, but NPIR performance is inconsistent		NPIR goal setting is critical	The NPIR mirrors that of the final product assembly.
	Use of product and SCC architectural tools **(PCA)**		Modular process development		Modular process development	Focus is on implementation of modular strategy. Fast feedback and FAC provide increased level of design control.

Appendix 4-10a Co-development for aerospace

		E (Aerospace co.'s)				
		E1		E2		
Construct	Variable	Level	 High	Level	 High	
Concurrent Development (CD) at concept stage	Overall level of Co-development at the product concept stage **(CD)**		Process development preceded product concept development. Process development took ten years. Advanced carbon fibre and placement technology was approximately twenty years in development.		CD is core practice. In aerospace there are very few clean sheet designs. Key suppliers enter long term commitments with the aircraft manufacturers. They are an integral part of the CE team at concept stage.	Process and product development are inter-twined. CD is critical to the success of NPD.
	SCC function involvement at the concept stage **(SCI)**		Customers resides on-site, and is totally involved in all aspects of SCC process design.		Engine Suppliers are involved from the concept stage, together with other technology partners.	The SCC consists of a complex network of relationships. Automated technologies such as Product Lifecycle Management (PLM) are used extensively.
	Knowledge sharing and concurrency between PA and SCC **(KS)**		Complete knowledge sharing between tier one supplier and OEM.		Complete knowledge sharing between tier one supplier and OEM. There is extremely strong focus on improved economic factors.	OEM's, and tier one and two suppliers must manage risk across the supply chain, employing increased levels of knowledge sharing.
	Co-development of product specification **(CI)**		Expert interviews and knowledge brokers are involved throughout the concept stage.		Expert interviews and knowledge brokers are involved throughout the concept stage.	There is an increasing trend towards customers' enforcing performance based contracts.

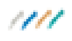
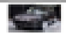
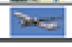
Appendix 4-10b Feedback control for aerospace

		E (Aerospace co.'s)				
		E1		E2		
Construct	Measure	Level	 High	Level	 High	
Feedback control (stage gate)	Product assessment at stage-gate exist **(PPI)**		There is strong output-input metrics correlation. This is a standard learning curve.		Output-Input metrics correlation. Customer Service Improvement Plan (CSIP) is a constant program. Customers are continuously engaged in the process.	Effective collaboration with customers, leads to improved feedback loops.
	SCC performance after concept stage **(SA)**		Output-Input metrics correlation, similar to VOC process		Output-Input metrics correlation. This is a constant process. Aircraft OEM is resident on site in customers site, to ensure that standards are met.	A key driver is the delivery of standardised processes and approaches to suppliers globally. The effective use of information technology is essential to meet customers' shipment targets.
	NPD lead-time goal assessment **(LT)**		Concept to launch, is key measure.		Concept to launch, is key measure.	Risk management plays a key role in achieving NPD lead-time goals. The company is careful to outsource only certain parts of manufacturing, to retail competitive advantage.
	Product - SCC process performance trade-off analysis at product concept development **(TO)**		Product development sheet.		Product development sheet. There is limited technology idea's sharing between aerospace and other sectors e.g. Automotive. An example is the lithium ion battery.	There is an increasing need for innovative technology solutions to satisfy existing and future environmental regulations and legislation.

Appendix 4-10c Feedforward anticipatory control for aerospace

		E (Aerospace co.'s)				
		E1		E2		
Construct	Measure	Level	 High	Level	 High	
Feedforward anticipatory control (FAC)	Level of FAC to deliver product architecture **(FPA)**		Need to evaluate materials and process capability (Cpk). The A350 was a 20 year development. There is a debate whether composites is the future or aluminium		Regulatory constraints mapping. Aircraft OEM and key suppliers are engaged in FAC years in advance of product launch	Protecting high value knowledge and intellectual property are key considerations.
	Level of FAC to deliver the SCC requirements **(FCA)**		Pre-defined performance spec. (drag, weight, loads, fatigue)		Performance spec. (range, payload and fuel consumption)	Stakeholders work together to eliminate single points of SCC failure.
	SCC goal achievement **(PGA)**		NPIR is less critical than product related risks.		Supplier risk is primary consideration. Aircraft OEM's must insist on unfledging quality and reliability, if there are any risks e.g. with hydraulic pumps on A330, the OEM will move in and if necessary take over the supplier.	The company is focused on the efficient use of new technologies in the areas of project and SCM to deliver added advantage.
	Use of product and SCC architectural tools **(PCA)**		Structural process development		Geo-political influence are significant. SC Managers have to balance the need to cut costs in the production process with the need to deliver quality end-products to the airline carriers.	The finished product must meet the standards of any given customer's jurisdiction's complex regulatory requirements, and quality control checks, irrespective of the fact that component parts are manufactured in various countries around the world.

Appendix 4-11a Levels of co-development

Level of co-development (CD)						
UoA		Overall level of co-development **(CD)** (Low, Medium, High)	SCC function involvement at the concept stage **(SCI)** (Low, Medium, High)	Knowledge sharing and concurrency between PA and SCC **(KS)** (Low, Medium, High)	Co-development of product specification **(CI)** (Low, Medium, High)	Median value of CD intervening mechanism
A1		High	Medium	Medium	High	High
A2		High	Medium	Medium	High	High
B1		Medium	Medium	Low	High	Medium
B2		Medium	Medium	Low	High	Medium
C1		High	High	High	High	High
C2		High	High	Medium	High	Medium
D1		High	High	High	High	High
D2		High	High	High	High	High
E1		High	High	High	High	High
E2		High	High	High	High	High

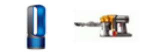
Appendix 4-11b Cross-case analysis of co-development

Construct	Variable	A (Med device co.)	B (Domestic appliance co.)	C (Auto co.)	D (Auto driveline co.)	E (Aerospace co.'s)	Cross-case analysis
							
Concurrent Development (CD) at concept stage	Level of Concurrent development (CD) at the product concept stage	CD focuses on discovering new product requirements, materials with a focus on experimentation. These products have a relatively long life-cycle, requiring a more open approach to design thinking.	This companies focus in the concept stage is on innovative product design. They are constantly exploiting core technology from previous products. The company use basic prototypes to avoid excessive tooling investments prior to detailed design.	Procurement, quality and manufacturing engineering are involved in concept design.	As a tier one supplier of the drivetrain, CD is a critical activity.	Process and product development are inter-twined. CD is critical to the success of NPD.	Product complexity is driving an increased requirement for concurrent product development, and knowledge exchange.
	Level of SCC at the product concept stage	SCC is a traditional area of lean thinking. Whilst there are opportunities for improvements in SCC. SCC knowledge needs to be refined and communicated.	This company consider the commercial potential of their invention before attempting to develop it. The company consider the price of a radically new product to assess if it can be set sufficiently high to be a viable proposition.	As company becomes more globally focused there will be more focus on local sourcing decisions.	This tier one supplier has a strong influence on the OEM's SCC.	The SCC consists of a complex network of relationships. Automated technologies such as Product lifecycle Management (PLM) are used extensively.	SCC complexity is driving an increased requirement for concurrent SCC development, and knowledge exchange.
	Level of knowledge sharing at concept stage	Tacit Product and SCC knowledge is a valuable resource for this medical company. Distributing this knowledge at the concept stage is key to building sustainable advantage.	The companies products focus on finite problems, within specific area's of knowledge. The company make excessive use of CAD, there is room for further use of SCC knowledge.	Concurrent modular teams play a significant role. On the horizontal axis there are the modules, on the vertical axis there are the platforms.	Modularity allows for alternative powertrain concepts, offering flexibility in length, height, width, regional variations, and opportunities for low volume niche models.	OEM's, and tier one and two suppliers must manage risk across the supply chain, employing increased levels of knowledge sharing.	Product and SCC complexity are driving a requirement for concurrent, real-time knowledge exchange.
	Level of customer involvement	Customer involvement is high, and leads to increasing levels of product customisation.	Customer involvement is high, the voice of the customer is preserved, which leads to strong brand loyalty.	VOC plays a significant role, in the Luxury car market.	Application engineers from the OEM are involved from the concept stage.	There is an increasing trend towards customers' enforcing performance based contracts.	Knowledge exchange commences with the definition of customer requirements.

Appendix 4-12a Levels of feedback control

Level of feedback control (FC)						
UoA		Product assessment at stage gate exist **(PPI)** (Low, Medium, High)	SCC performance after concept stage **(SA)** (Low, Medium, High)	NPD leadtime goal assessment **(LT)** (Low, Medium, High)	Product - SCC process performance trade-off analysis at product concept development **(TO)** (Low, Medium, High)	Median value of FC intervening mechanism
A1		High	Medium	Medium	Medium	Medium
A2		High	High	High	High	High
B1		Medium	Medium	Medium	High	Medium
B2		High	High	High	High	High
C1		High	High	Medium	High	High
C2		High	Medium	Medium	Medium	Medium
D1		High	High	High	High	High
D2		High	High	High	High	High
E1		High	High	Medium	High	High
E2		High	High	Medium	High	High

Appendix 4-12b Cross-case analysis on feedback control

Construct	Measure	A (Med device co.)	B (Domestic appliance co.)	C (Auto co.)	D (Auto driveline co.)	E (Aerospace co.'s)	Cross-case analysis
							
Feedback control (stage gate)	Product performance assessment	Material Science plays a key role in the concept development of this companies medical products.Customer feedback is important to product development teams.	There was poor use of prior product warranty data. Certain components are re-usable from prior designs.	Warranty data product a mine-field of data for improving current and future product designs.	This company relies on feedback to influence product design improvement. Feedback is used to operate an effective product development process.	Effective collaboration with customers, leads to improved feedback loops.	Closed-loop product performance data collection and analysis is key to product success.
	SCC process performance assessment	SCC process capability is prioritised. Other SCC variables include product traceability, Importantly design knowledge should be captured at the concept stage.	The company manage supplier power through in-house design and SCC knowledge.	Modular SCC has reduced the number of variants and complexity in assembly, with customisation offered later in the SCC process. Increased profit margins area a result of improved economies of scale.	Feedback provides information to make better technical and economic choices.	A key driver is the delivery of standardised processes and approaches to suppliers globally. The effective use of information technology is essential to meet customers' shipment targets.	Closed-loop SCC data collection and analysis is key to achieving SCC success.
	NPD lead-time goals	System design waste prevention involves the movement of information, products and customers through the futures system. This company are focused on process cycle efficiency.	Premium pricing places high pressure on time to launch targets being achieved. This requires strong IP protection, to maximise specilisation gains.	NPIR is the rate of product introduction relative to competitors, this company have halved this rate in the past five years.	Companies manage new product timelines, rather than queues. The speed of feedback is important to product developers.	Risk management plays a key role in achieving NPD lead-time goals. The company is careful to outsource only certain parts of manufacturing, to retail competitive advantage.	NPIR timelines are influenced by SCC process capability development, SCC proces readiness and IP protection.
	Product versus SCC process performance trade-off's.	The company evaluate the trade-off's between inventory 'waste' and SCC process time 'waste'. Inventory availability is a key consideration in both product instances.	Strong property rights enables this company to operate a diaggregated supply chain.	There is a strong focus on elimination of potential environmental problems.	There is a strong focus on technical performance.	There is an increasing need for innovative technology solutions to satisfy existing and future environmental regulations and legislation.	Trade-off decisions encompass inventory buffering, relative property rights, environmental, technical and legislative considerations.

Appendix 4-13a Levels of feedforward anticipatory control

Level of feedforward anticipatory control (FAC)						
UoA		Level of FAC to deliver product architecture **(FPA)** (Low, Medium, High)	Level of FAC to deliver the SCC requirements **(FCA)** (Low, Medium, High)	SCC goal achievement **(PGA)** (Low, Medium, High)	Use of product and SCC architectural tools **(PCA)** (Low, Medium, High)	Median value of FAC intervening mechanism
A1		Medium	High	High	High	High
A2		Low	Medium	Medium	Medium	Medium
B1		Medium	Medium	Medium	High	Medium
B2		High	High	Medium	High	High
C1		High	Medium	Medium	High	Medium
C2		Medium	High	Medium	High	Medium
D1		High	Medium	High	High	High
D2		High	Medium	High	High	High
E1		High	High	Medium	High	High
E2		High	High	Medium	High	High

Appendix 4-13b Cross-case analysis on feedforward anticipatory control

		A (Med device co.)	B (Domestic appliance co.)	C (Auto co.)	D (Auto driveline co.)	E (Aerospace co.'s)	Cross-case analysis
Construct	Measure						
Feedforward anticipatory control (FAC)	Level of FAC used to deliver product architecture	Future PA requirements were fed downstream to key suppliers.	Company successfully establish product claim at concept stage. Everything including the marketing of the products is related to this product claim.	Modularity was designed in at the concept stage. FAC was used to communicate with suppliers to support fast time to launch.	Early feedforward data from the OEM, allows this tier one supplier to counteract variability.	Protecting high value knowledge and intellectual property are key considerations.	FAC at the product concept stage is critical in complex product architecture concept design.
	Level of FAC used to deliver supply chain architecture	Early PA information permits this company to reduce any randomness in their SCC process.	There is an onus on SCC experts to increasingly communicate tacit and explicit SCC knowledge to NPD team, and establish credibility within the team.	FAC operates equally upstream and downstream. This allows key suppliers and distribution channel partners to develop process capability before it is needed.	Acknowledgement that there is a requirement for improved SCC analysis, and knowledge sharing.	Stakeholders work together to eliminate single points of SCC failure.	FAC at the product concept stage is critical in complex SCC concept design.
	SCA goal achievement	The long time-horizon goal is to introduce further automation to improve SCA goal achievement.	SCA goals relate to repeatable delivery of product quality, and reliability.	SCA knowledge must flow in both directions. FAC can be also face-to-face, it is inherently real-time and combines verbal and nonverbal information.	The NPIR mirrors that of the final product assembly.	The company is focused on the efficient use of new technologies in the areas of project and SCM to deliver added advantage.	SCA goal attainment is focused on the long time-horizon, and potential use of automation.
	Product and SCC architectural tools	New technologies are allowing this company to evaluate closed loop SCC systems, where the medical practitioner, and patient are included in the system, real-time. This is opening up opportunities for multiple control loops, and improved patient experience.	Product modularity is a primary FAC tool, focused on mapping of product requirements, functionality, interface standardisation and I.P. protection. These environmental products contain four basic modules, for power generation, power transmission, carrying load, housing and protecting the motor.	Focus is on implementation of modular strategy. Fast feedback and FAC provide increased level of design control.	Focus is on implementation of modular strategy. Fast feedback and FAC provide increased level of design control.	The finished product must meet the standards of any given customer's jurisdiction's complex regulatory requirements, and quality control checks, irrespective of the fact that component parts are manufactured in various countries around the world.	Modular strategies require co-consideration of Product and SCC architectures.

Appendix 4-14. Interview transcript for A2 (project two)

Extract of transcript from interview with Senior Process Design Engineer Medical device company

Date: 9th Sept. 2015

JC Thank you for meeting me, we discussed this research via telephone, I have five key attributes or variables relating to Product Modularity. These variables are deduced form the literature and define this construct. I would like to discuss these key variables. I would like the discussion to be interactive, we do not have to strictly stick with these questions, but I need to cover these questions. The product you want to talk about is a blood glucose meter? ***To what extent are meters modular?***

SME I want to take the Verio meter, which is a relatively new product. The meter itself follows the same pattern as other meters. This is not a modular design; it is an integral design.

JC Is this meter part of a product family?

SME It is a different type of strip. We have two types of strips. One is a carbon-based strip. The other one is a metallised strip platform. For accuracy and precision results, the Verio is based on Platinum and Gold which is very expensive, it is the higher range of meters. The Ultra strips you can buy off the shelf are the lower end, of the market. But they still work on the same blood biochemistry. They use the same algorithms. Inside they use the same chips, operating on the same software.

JC Are the strips inter-changeable?

SME No, they are not interchangeable. That is the whole point. We have Ultra, and we have different families. We have cut back on them now. They change the artwork; the meter would be changed to suit the product. You could not try and buy a test strip and use it in a more expensive meter. It will not work. The strips and the meter are designed together.

JC The strip design I am familiar with the design. It is like a printed circuit board?

SME That is what it is really. It is made up of several layers. There is a gold layer, a palladium layer and in between it there is a layer of biologics, and some plastics there to separate it. When the blood goes in it creates a circuit. It is the rate of the biologic decay and rate of response from the biologics that is fed back in to the meter. When you put it in to the meter, you set off a circuit. When you put your blood on the strip that completes the circuit. The electrical response of the blood is what allows you to figure out what your sugar levels are basically. There is an algorithm that measures key components of the electrical circuit.

JC As an analogy, I am familiar with the ink cartridge printers. The IP is in the actual cartridge rather that the printer?

SME The IP is in the strips, and the biochemistry, more than the meters. The meters themselves are relatively straight forward devices consisting of electronics and an LCD display. It you look at the bill of material it is relatively off-the-shelf componentry which is programed with algorithms to show an LCD display what the electrical response of your blood is. It is the algorithm, and the biochemistry which is what the IP is all about. The two, work hand in hand.

JC The first question relates to the level of modularity of this meter. Are we talking about the meter and strip combined?

SME I think you must, because if you change the strip as part of the strategy, you change the meter as well. We keep as much of the meter as common as possible, and change the strip design in one small part of the meter, to give you a lower end model that can only give you certain responses, by cutting through one of the electric legs. If you have different responses and different changes in the meter, it looks like the same strip but maybe it only gives a certain response, and you will have a lower end meter. We try and segment the market in to meters and strip.

The Ultra strip which is an ink based platform is web printed. It is printed on a web printer, a twenty-five-meter-long machine. There are 500 strips printed at one time. It really is a money printing press. They are just separated and coloured as well. It has a carbon ink, and insulation layer, the enzyme and some tape cover to draw the blood in. Hydrophilic tape covers, these are lower in accuracy than the Verio strip, which is a metal based platform. You are basically looking at a printed circuit board versus a cheap circuit board, they are two different circuit boards, they give different responses. Because of market demands which is now, where the EU and America asking for higher precision accuracy which is a struggle for the old print-based systems, while they are trying to move over the market to the metallised based one. That is where it is going.

JC Your company would be a leader in that range?

SME Yes, the Verio is the one they are trying to push the hardest. Our Scotland plant for strip production is buying the third and fourth Verio production lines at present. They are producing metallised and are trying to move away from producing carbon based strips. It is much harder to manufacture and control these paper-based strips. With the meters, the difference are the covers and the internal algorithms. The strips themselves are more difficult to manufacture, because there is so many variants. The metallised strips are produced in a smaller array, and much easier to control in production.

JC OK, now I am clear on the product it is a combination of the meter and the strips. To what extent is this product modular at the finished product level? Please explain. You were saying it is an integral product?

SME It is primarily an integral product, however there are some modular elements present. You can alter the strip port connector and the algorithms within the meter to do different things for different markets. We can cost reduce the strip by not having certain electrodes working in the meter. For the meter It might have a different plastic cover, but the chipsets and components are similar, just like iPod, for example. The higher end Verio meters will have wireless and Bluetooth connectivity on future variants. They will capture and transmit data, but the meter and strip hardware will be pretty much the same, as today.

JC Are any of the meters wireless of Bluetooth today?

SME Not now, they are moving in that direction. I believe the biggest problem doing these things is validating it to FDA safety of communications regulations. Today the USB port can be used for connecting to the meter.

JC In terms of level of modularity, you are saying it is more of an integral design with some elements of modularity?

SME It is making very small changes within the actual design, our meter manufacturer uses similar production lines. It is not completely different production lines of we need to customise the meter. There are different software configurations however.

JC Is this software developed in-house?

SME The software is developed in-house. There are different algorithms for different strips, depending on how they react to blood. This must be validated. It all goes through a stage-gate® process.

JC The next question is interface coupling, how loosely coupled are the modules within the product? Are the interfaces clearly specified?

SME Yes, because it is a regulated environment everything must go through a process development life cycle, a process development phase gate, you must validate it, including the algorithm design. Everything must be tested and tied together, to be able to sell in to the market.

JC I am focusing on the concept early design stage. In the Concept design stage what are the phase gates?

SME There would be your typical marketing requirements, what are the customers looking for, what are the critical quality requirements, critical to the customer requirements. What does the meter need to do? What does the product need to do? It needs to take a blood sample of X amount of size, give the result within X time, and be accurate and precise. These things get all laid down, we need to meet these deliverables, and improve on them. We follow the Technology Gap (V model), from when we receive the user requirement specifications. The user requirements are translated in to R&D requirements. What do we need to research and develop to meet these marketing requirements? Then there will be validation, once we have translated these in to algorithms. You have the product aesthetics and the actual functionality of the system to consider. Aesthetics incorporate user requirements, ease of use, error testing etc. Our stage-gate® process does not allow proceeding to the next stage without completing the current stage. It is a highly prescriptive process, because the product is going in to a validated market as a medical device. It is a V model, we use the development production equipment, in medical devices and Pharma it is a methodology you must go through. Then you trace back to your requirements to make sure you have completed each task, prior to FDA submission.

JC My unit of analysis is new-to-market product.

SME New-to-market products must go through a 510K submission, it is an FDA requirement basically it involves a small trial run of units, before you can release to market. It is quite an onerous task. If it just a minor modification of an existing platform then you probably don't have to do the 510K, you can just do a re-submission saying you have changed this, and have the background data to prove it. It could be cutting a new connector, or a new algorithm, but if it is a totally new product it must go through that whole 510K. If the FDA say it is suitable and you can now release to market before you were saying you just made a minor modification.

JC Typically how long does it take from concept to product Launch for something like a new Verio meter?

SME It would take two years for new meters. I know they have had a few meter launches in the last year, but they are variations of an earlier validated design. These are not new product designs.

JC So it is a hybrid modular design, the interfaces are very well specified, and tightly coupled?

SME There is the strip port connector interface between the strip and the meter. This port connector is heavily designed and validated. You can't really change that because your strip production platform is tied in to your strip port connector.

JC So the strips are not inter-changeable?

SME Not normally.

JC Is there some situations where they are?

SME It would be a marketing decision to try and use strip X in meter Y, but they try and keep them coupled, so they can segment the market. Verio was initially aimed at the Hospital market for doctors and nurses, and hospital testing, now these meters are slowly filtering to end-user use, in developed markets such as the UK, America, and Germany. Verio is getting pushed out to the normal user. In second and third world countries they will have the Ultra systems. They don't want high precision and accuracy they just want something that is quick and cheap. It is all about the Marketing plan to say where is this meter now?

Where is it going to be in X number of years? What strip and meter production do we need? Most of the meters are given away. The cost of production of the initial Verio meter was $30 or $40. We try and drive down the cost by internal design. The cost relates to the hardware components. The strip production is cents.

JC What percentage of meters go in to emerging markets, where consumers cannot afford to purchase them?

SME They spend hundreds of millions a year giving away meters. There is a budget allocated to distributing these meters, free of charge to the end user.

JC The next question is around data access modularity. Are the meters wireless, do they have Bluetooth functionality? To what degree does your meter allow access to system level performance data?

SME High end meters have a USB Connection to a PC to view the readings, these meters cannot do any more than that. Users cannot reprogram the meter since they are FDA regulated. The meter algorithms cannot be changed by the end user. The meters are programmed in the factory, in the field all is data access is prevented. One of our competitors tried to re-program meters to avoid a recall, and the FDA were very concerned. You are getting your customers to re-program your product when it is a validated system dealing with healthcare, they are not happy about it. So, access very limited.

JC So all you are doing is uploading the data file?

SME What we can give them is not widely used is a software suite, that analyses that data and provides trend analysis.

JC Have you done that?

SME That is becoming quite a thing, the whole point is the model used to be the meter and the strip, take a reading and give yourself insulin, but now with the internet you can see how you are trending over the week, analyse it and see your doctor and then let the software analyse the data and say you should be cutting down on this, getting information from the software. The level of software is expanding all the time.

JC It is getting in to lifestyle.

SME Yes, that is it because there are so many diabetics worldwide, this is an exploding market. Eventually most meters will contain wireless and Bluetooth technology. The user's phone will prompt them to take specific actions.

JC We are very heavily involved in the internet of things, the intelligence of things, but also has become a big area for us as well and especially in medical, it is the first area which has adapted wearable technology.

SME We constantly monitor. Google were trying to do one with a contact lens with us. A circuit in the contact lens would constantly monitor blood glucose levels. This technology is quite a way off. We tried in the past using interstitial fluids, it never came to market. That was a constant monitor idea, not having to stab yourself in the fingers five times a day, to get a blood sample.

JC Moving on to the next question which is limited life modularity. ***To what extent are the modules designed with respect to their useful life?***

SME There is a battery in there. The meter itself has standard off-the-shelf chips. The product Ultra which has been the main product for 10-15 years.

JC Was that at one of the first products?

SME No, there was products before then, but they are all deceased. There is a time to kill the product off, if there is no market for them, or it they don't work well. Some meters are in the market for five to six years.

JC So the meter itself could last one's lifetime, it is the technology which is driving new features and cost reduction, that creates product obsolescence?

SME It could because the LCD display and the chips are all non-moving parts. There was attempts to have an integrated mechanical system, which feeds strips in to a connector automatically and you just place a sample of blood on the strip. This design however is high. Customers are not willing to pay that price. A few competitors have tried this as well. It did not take off. The market for that kind of thing is not there.

JC Am I right in saying there is a temperature control of the strips?

SME In the vile the strips come in, for the life scan Ultra it is a desiccated vile. We validate the strip performance between a certain temperature, humidity and altitude range because these all effect how Glucose Oxidase levels react to measurement. It is constituent of the enzyme that gets weighed down by humidity. If you left the vile open in the shower, this will affect the accuracy of the test strips and not give you a correct reading. An expensive part of the product is the desiccated container that comes with it. We are trying to drive this out by reducing the sensitivity of the Verio strip. It has a different enzyme than the Ultra reducing the cost of these viles. The desiccant is within the vile, and is silicon based.

JC With the Ultra there is also a calibration fluid required, I believe.

SME This is no longer required. There is now a calibration table. Each print run is calibrated. The user enters in to the meter the calibration number contained on the vile. This is causing poor consumer experience however, since every vile, has a different number. We are working towards a single coded product.

JC The last question on modularity is variety use modularity. To what extent is the product customisable by the end-user?

SME The customisation will probably come in terms of the software, an app on an iPhone or an android phone, talking to your meter. This is where the customisation will come. Because of medical regulations user configurability is not an option today. That will come along in time, limited to simple changes in aesthetics.

JC Does your company have an internet of things (IoT) strategy?

SME It is just starting, our group is looking at it, in terms of factory automation. Other groups for example marketing are looking at what it means for them, 'can I see customer's X's meter? Can the customer order test strips automatically? That sort of thing.

JC In terms of product modularity, the Verio system has a medium level of modularity over-all. When the design team were sitting down designing this product, what were the main deign drivers?

SME The driver is a low-cost platform, since the platform was introduced in the US market, where the product is affordable, it has quite high costs. The drivers are the cost of manufacture, high volume, accuracy and precision. The key driver for the end-user is simplicity of use. Manufacturing high volume, precision and high accuracy, they are the kind of key drivers on the process platform side. As new products come along, you try to drag more out of the machinery, use the same platform, and obviously you don't want to invest in production platform or process platform if you do not have to. Ultra and Verio are two different production platforms. The Ultra has been churning along since the late 90's, early 2000's. Verio came along in the last six to seven years. It takes five to six years to validate the process. The product was 10 to 15 years behind this in product development.

JC The next construct is supply chain configuration. In terms of the definition of supply chain configuration this includes manufacturing, it includes the selection of material, suppliers, manufacturing through to determining the place, and appropriate levels of stock, and how the network is designed and setup.

The first question is around the degree of SCC modularity. Whilst there is a lot of clarity on what we mean by modular product it is not as clear what we mean by modular process, and it is different by industry sector. ***Does your supply chain provide supply chain process modules?***

SME I would say it is a pretty integral process. We have very limited suppliers who can produce the Verio metallised base material, and substrate. The substrate itself, the plastic comes on, we have two or three possible suppliers. So, you can switch between the two or three. They must all produce within a certain specification and electrolysing the palladium and gold, again there is only two or three companies we would go to for that. That is your base material. In terms of the enzyme which is used, for the biologics there is only one or two people we would go to. They are the key building blocks of the strip.

JC Do the suppliers have IP?

SME Yes, DuPont are one of the main suppliers of the Melanex material, which the plastic strips are based on. Covemay are another supplier of the Melanex material. If we change the material, we must undertake a lot of validation. It is not like I can buy my chips from so and so.

JC So is there a life-time relationship with these companies?

SME It is a long-term relationship; you have got to make sure you are very happy with them. A lot of the time it is very risky. You go to one supplier for oxidase, there are maybe only two companies doing this. Second sourcing is always a big thing, having a back-up. Having a back-up is a tough thing, proving you have equivalence, proving the strip is still equivalent. Is supplier X's product equivalent with Supplier Y? A large body of work must be done for that medical device. If we change from Covemay to DuPont does the product still work the same? Material changes require validation. There is rigorous testing required before components can be changed. Likewise, on the meter production, we only have one supplier, in Flex. There are obviously other people we could go to but again the problem comes with validating the production process.

JC How many levels of product bill of materials are there? You have the printed circuit board and the LCD. There are not that many components.

SME It is a relatively simple device, battery, battery holder, PCB with components on it, but not many chips, LCD and maybe backlight, and some other minor features. Again, we try and use the same base componentry. If that is a validated block they may build on to it. One cannot, or example change the amount of memory or the size LCD display. These are fixed, and require validation.

JC To what extent are differentiation / customisation sub-processes postponed to the time of receipt of the customer order?

SME There is no process postponement with the test strips. With the meters these are built to stock, and packed to order in the factory. The product is packed to country language requirement, and the software is language-specific.

JC You have spoken a lot about standardisation. To what extent can the process be broken down in to a standard process or sub-processes that produce standard base units and then customisation processes or sub-processes that further customise the base unit?

SME You do a run and that's it. In terms of the actual strip production it is a standard production platform and it must run at limits and rates. If you want to change it, you must re-validate it. The strip production is a web process. The gold gets unwound. The enzyme gets placed on it. The palladium gets placed on it, and it gets cut to shape, and singulated in to strips. The enzyme a biologic component of the test strip. It must be produced in a certain way and get added to the machine, at a certain time. It has a shelf-life. It must be produced in certain ways. Everyone gets the same enzyme; everyone gets the same strip. Likewise, with the meters, everyone gets the same meter.

JC The next question is around supply chain configuration resequencing. It does not sound like there is any process re-sequencing involved. Can processes be re-

sequenced?

SME The test strip has one process. The only differences are for example where product might be assembled or manufactured on the same machine, or there might be a different circuit board design, but it is still going through the same process. There could be a slight modification to the circuit design, but the process is equivalent. We can't switch off parts of the process. It is a very linear process. Raw materials go through all process steps.

JC Are samples of the product tested destructively?

SME Samples are taken away and tested in-house. That is the release samples. These are destructive tests. They will be release samples. The batch will get produced and put on hold. The release samples will get tested, taken at the start, middle and end of the batch run. There will be a statistical sample taken, for the batch. If they all pass testing successfully the batch will be released.

JC The next question is around place postponement. In this case to what extent are differentiation and customisation processes linked to customer order. I take it you are producing to stock, rather than to order?

SME We have an idea of what is the demand for the year. There is a production plan made up at the start of the year, on what the run rate should be. This forecast is revised based on product demand pull. If demand increases, we ramp-up production. If it goes down, we will slow production. If there is a new product launch, then we will build an amount to launch.

JC Because there is a one-to-one relationship between the strip and the meter then the forecasting processes I imagine are almost identical.

SME One meter will last you years. Meter wise you will be in the hundreds of thousands. You are in the billions with the strips.

JC For the strips you are looking at the installed base.

SME You have a predicted gain in the market, with a product launch rate. Obviously, you always like to go faster, and the feedback will provide understanding on how the launch is going.

JC Last variable on supply chain configuration is on supply chain configuration process module coupling. How easy can the process be decoupled by insertion of a customer order point? Let's say I am a retail customer who is not using your product, and I decide I want to buy from your company, what impact does this decision have?

SME Customer orders are all sequenced in the same manner. There is no place postponement. Every product goes through the same process.

JC Thank you for your time, this is much appreciated.

END

Appendix 4-15. Interview transcript for B1 (project two)

Extract of transcript from interview with Chief Operating Officer
Domestic appliance company

Date: 8th July 2015

JC Thank you for your time this evening, during this interview I am going to explain various research constructs and variables or indicators, relating to this research topic. These measures are deduced from the literature. If there is any area of interest, I will attempt to provide further background. The first area I want to look at the level of modularity within a new-to-market product. Do you have a product you would like to discuss?

SME Let's talk about our new air purifier

JC My overriding question relates to product modularity, if you take this product at the higher-level assembly how modular would you say it is?

SME It is not modular; it is probably ninety percent integral design.

JC Is the product in the market yet?

SME Yes it launched within the past six months

JC I will come back to that point; it is interesting that it is so highly integral for a new product. Was the product designed in-house?

SME Yes everything, the design itself is in-house, but we buy certain standard components. The electronic components are bought in. The PCBA is designed by us, but the components that go on that electronics board are industry standard. The bearings are industry standard, but everything else is our design. We use some suppliers that make parts to our design, but we design the speed and power of the motor. We outsource to someone to build it for us.

JC The next question relates is the level of interface coupling between the sub-assemblies. Given the product is integral, are the sub-assemblies tightly coupled?

SME Part of the reason for that is because of the form factor, the design aspect, the airflow, which is important, but probably more importantly the acoustics that is why we keep everything as tight as we possibly can, from that respect.

JC On the interface coupling most people would think about mechanical coupling and the tolerances between the different mechanical connections, is there embedded software within the system?

SME There is software, it is not the most sophisticated software, but as IoT kicks in and we start to look at the internet of things and how that would connect to the purifier type product that will bring a whole range of new challenges. On the first product we are talking about here it does not have Wi-Fi but going forward it will have, and it will have sensor technology as well, to sense the purity of the air, and a whole bunch of new software. When you add to that in addition to its own RF technology it will have to connect to other machines (M2M). Apple home kit is an example. If we want to connect to that then that is going to be another protocol, take Google which they call brill, this is going to be another protocol. NEST is another example. Then you have got Qualcomm. You have a lot of these different protocols out there and that is just on the language. Then when you look at the actual RF signal itself we have got Wi-Fi, Bluetooth, low energy Bluetooth, ZigBee. There is a whole bunch of these and you must figure how you connect to all these protocol languages. This is a challenge that's coming, not necessarily in this product but next generation.

The reason why that's important is because we are trying to design this generation, where we don't have to design the whole machine from the ground up, with the level of modularity (platform) that can be used in the next design, because we have already booked the next product in design.

JC The area I am most interested in is the concept stage. What is interesting about this product and a lot of consumer products, with the advent of more and more sensors is the almost unlimited abilities to access products, which brings me to the next question which is around data access. You talked about this being a generational product, at an early product stage. ***To what extent does your product allow access to component, module and system level performance data?***

SME For us we can interrogate that, but not externally. We would need to go into the actual PCBA itself. We can take that out. So, for example we can tell you how many hours the machine has run, how long the machine has been turned on, how many revolutions the propeller has done. Next generation when we put in more memory on that and it has been connecting to the internet, then that will give us a much richer data set. For the fan as an example in terms of connecting to the PSI and weather, how many times it dropped the signal. How many people are connected, how many different users in the household connected to that. One of the main things we are doing with the App, is turning it on/off, turning up the heat, connecting it to different parts of the infrastructure, within the house, connecting it to other fans, we will have access to all that data.

JC Before I move from this question the data does this include product reliability data?

SME Yes exactly, reliability and safety, it can stop the machine if for example the internal temperature is getting too hot, or the motor is running away, there will be that level of technology in it.

JC The next question is in relation to limited life modularity sometimes called useful life. ***To what extent are the modules or subassemblies designed with respect to useful life? This is looking at the serviceability of the product going forward.***

SME It is kind of interesting, I think it is product by product dependent. On a new product like this for example the whole industry is moving so quickly in this regard that I think the main components will be fine, the motors and the motors and bearings will be useful, the electronics will be continually updated, software will be continually updated. So mechanically we will probably be able to re-use a lot of the tools. Certainly, we may re-skin the product to make it re-usable. Internally a lot of that will be re-usable in that product life, and electronics, software and firmware will be updated almost one-hundred percent on new designs.

JC So you are not only looking at useful or limited life, you are also looking at upgradability.

SME Yes

JC Out of when you talk about the product platform for the purifier are they all similar form factor

SME No they will be different. We have a tower which is a floor standing unit, you have a desk fan, then we have different colour configurations, but we also have different products for different parts of the world. So, this is where the integral design comes in. We don't put in a standard motor. We have 50/60 hertz, 110/240V, part of that is to take cost out, and part of that is to make sure we get EMC. It is easier to get EMC regulation when you are running with a proposer power supply, so that makes it quite a bespoke design for the country.

JC The next question or variable I am interested in is product use modularity. ***To what extent is the product customisable by the end user?***

SME Not so much, only the settings. When you say it is not customisable people want to control the speed, you can oscillate it, and you can run it at zero. Other than that, it is not really customisable.

JC Before I move off product modularity one of the key constructs I want to talk for a few moments on how you believe these variables should be measured. If you were sitting down with the design engineering team now, you would want them to consider certain variables.

What would you say would be best way of measuring interface coupling?

SME That's a difficult question John, I would say from a design perspective because there are a lot of plastic precision parts in the product one of the biggest issues we have is obviously stack-up tolerance. We are looking to maximum the performance and minimise the acoustics because it is quite a big challenge for us. Even the types of materials we use to have safe in wall, but have strength in the product design. We are always trying to get the engineering guys to use as much CAD as they can use, to do that simulation, so that we minimise the amount of tooling changes. This also helps us get the product to market. And all those parts will fit together. At the end of the day if you take 100 different plastic and metal parts that need to fit together in that machine, between the bearings, the switches and the buttons, this is really the biggest thing. Software wise it is quite simple. That coupling is much easier. From a mechanical assembly point of view, it is about making sure we are using materials that mould well, that don't warp. We spend a lot of money on tools that make the part repeatable, with no sink marks. They take out cost a lot of the time, as you don't paint them. So, we are shooting standard plastic, and we want that high gloss finish. So, it is that balance between saving cost, think wall thickness, and stack up tolerance in the machine, because when you buy the product, you buy it partly because of the design, and how it looks as much as what it does. So, these gaps, all that stuff becomes of major importance, in terms of aesthetics.

JC Like a one-piece enclosure

SME Exactly, Apple do a good job at that. They make a product almost like a one-piece enclosure, and it is tough to do

JC In terms of data access modularity, you have talked about is more on the next generation of products, I suppose it is more about compatibility

SME Yes, it is more about compatibility for sure.

JC On limited life modularity do you have a metric that you use in terms of what is the useful life of each component within the system?

SME We don’t have a metric but for us when we release a product we try and release a range, so we have different sizes, so for example we have a fan, we have hot and cold, which is a fan and a heater. They look pretty much the same, but one has a heating element in it and one obviously doesn’t and then the amp on that, the part that blows the air will be different, but the base unit will be the same. You may have a round amp, or a longer tower amp, but the base will be the same. So, we have now got hot and we have got cold, we can also add to that purification, humidification so that it does extend the range. A lot of the parts will be the same, the amps will be different, look different. On use value we are looking at can we get one or two generations across the range, not just on that product, from a small fan to a big fan, from a heater and so on? Because when we have tested the part, and we know that bearing for example has been subjected to two-thousand-hour runtime, we know a propeller gives you the flow, we do not want to retest it. So, we say that’s good. Let’s try as much as possible to use that, because it saves the test time on the re-qualification. We are always trying to get our engineers to be designing new machines, rather than qualifying old parts. So, we don’t have a matric for that but there is an inherent culture within the company that they will use that part because it works well. It is not quite a parts spin, but we do have a lot of component libraries that we use.

JC Do you have a metric around component count?

SME We measure it, but we don’t have a metric, where score it, but we know where everything is. We don’t have guidelines which says less components are better, or more components are better its more the case, some of the designs need more parts. You could make it with less parts per machine, but the acoustics could be worse. It is really driven by what we focus more on, is what is the spec of the machine? I will give you an example. We want the airflow to be a certain speed, we want the acoustics to be a certain decibel, and we want the tonality of those acoustics to be at certain points throughout that harmonic scale. We will detail all that in the product specification right at the design stage and then to hit that we will have components. Obviously the less the better, but we are kind of governed along that creative process by the design specification and quite often that design specification will be led by trying to do something different, having a unique claim, what we would call a unique selling proposition in the market, the quietest fan or the fastest fan or the smallest fan, that will be part of the design guidelines we will try not to compromise.

That comes back to how to design it.

JC I will move on to supply chain modularity. I define supply chain configuration as the selection of suppliers, part sources, manufacturing and supply chain options at each stage in the supply chain. It is the source, procure make and deliver standard processes, involved in bringing the design to market. I don't go past the point of delivery. I am not looking at after-market at this stage. Again, the over-riding question is 'to what extent does your supply chain configuration for this product provide supply chain process modules?' ***You said the product if highly integral, so I am assuming it is a multistage process, is all the manufacturing in-house?***

SME It is all external.

JC Does one company make the complete product from start to finish?

SME Not, we have quite a few sub-assemblers. If we take the purifier product as an example someone will make the filter. Than will be shipped in as part of the design. The motor will be made usually by a specialist motor company, to our specification, the speed of the motor and all that stuff. The impeller will usually be moulded, usually by the same person who does the final design. There could be a mix match between the in-house and out-house moulding, depending on how that has been created. Then the printed circuit board will almost certainly be done somewhere else. That final assembly will come together at a contract manufacturer. They will put that together and test it.

In our supply chain what we find is there is a lot of single sourced components, there is a lot of stuff which is very unique because we have made it to fit that device, or to get a certain amount of airflow, or certain type of acoustic or whatever. That drives bespoke and reasonably complex, single source supply chain.

JC I will go back to the question, which you have answered, 'to what extent does your supply chain configuration for this product provide supply chain process modules?' all those process modules are being supplied by a multitude, so it is very modular.

SME Yes modular in terms of it is the suppliers who will come together. The integration of that is a direction we have moved in as we found more competent suppliers. For example, when we engaged with Flex who had PCB assembly capability, who had plastic injection moulding, who had tooling, whom had the assembly skills. They don't have a lot of the componentry we need because that is bespoke, in motors and so on, that helped us to develop a supply chain in a way which we took out time, we took out cost but more important we took out complexity.

Because we would have a tool made at a tool maker, and moulded by another guy. When the plastic part does not make the cycle, when the moulder with his hands in the air saving it's the tool maker, and when the part does not go together they blame the assembler, lining all that up in to a vertical supply chain is to say OK you do the moulding you do the tooling, you do the moulding you do the assembly just figure it out. This has really helped us bring products to market quicker.

JC You use the term PSA?

SME That is a prime sub-assembler

JC Would this be a tier-one supplier?

SME Tier-two, that's interesting they are tier-two, maybe tier-three. They probably about $500-600M in revenue, we are in most cases we are eight percent of their business, what has happened is we have grown them up. When we went in to Malaysia we took them on mainly as a contract assembler. They maybe had a little injection moulding capabilities, and that would have been augmented by another seven or eight injection moulding guys. They would have been the prime sub-assembler (PSA). They did some assembly themselves, maybe more complex tooling and moulding. The rest of the stuff was with the final assembler. They have grown up to be a decent size now.

JC ***When the product leaves the PSA is it complete?***

SME It is, it is in a box. They ship it for us. It gets taken to the dock and put in a container, and shipped to the market. We build to market demand forecast. We build to forecast but we don't build and hold. We build and ship immediately.

JC The next question on supply chain modularity is around process postponement. You have talked about repeatability and having a standardised process***, 'to what extent can the process be broken down in to a standard process that produces standard base units and customisation processes the further customise those base units?'***

To what extent would you say that processes standard to the point where you have that generic engine?

SME If we stick to the purifier then it is a standardised process, with limited process postponement. The reason for that is the only thing that will really change, is that it will be a standard process so much that almost everything will be the same, except for the plug for the country, maybe the motor, so that would not be standard but everything else would pretty much be. We have other products which are much more customisable, if that's the word, but not the purifier. I think in the future as new products come on you are looking from a purification stand-point to filter different things. So, for example in Beijing the smog is a big problem. In Europe it is pollen. I can see us being more customisable on filter designs.

JC Are the filters replaceable?

SME They are replaceable. Again, as we go forward as sensor technology becomes more sophisticated, as sensor technology develops you will be able to tell if the air is CO2, O2, O3, all that stuff. This will be very interesting.

JC ***To what extent are differentiation / customisation sub-processes postponed to the time of receipt of the customer order?***

SME The only other things that drive SKU proliferation is the power source, the motor, the colour and the box. Everything else is standard, these variants are all built within the standard process.

JC ***To what extent can the processes be broken down into standard sub-processes, that produce standard base units and customisation sub-processes that further customise the base units?***

SME Process flexibility is important from the point of view of the PSA being able to scale production, volume ramp. This requires close co-operation at the concept stage.

JC The next question is around the sequencing or the re-sequencing of the actual configuration, ***'to what extent can sub-processes be re-ordered, so that standard sub-processes occur first with differentiation and customisation occurring afterwards?' Another way of stating this for your product would be do is there a standard sequence for building these products?***

SME It's standard and the reason is we build and test it different things in the product. We build to a certain standard. We then test that the fan is working. At that point we don't care about acoustics. We check that everything, it has the right flow rate, everything is good. Eventually the final test will be acoustics, the electronics are working and there will be a physical check at the end. Then the product is packed. We do the full final test and then pack. It does not go off for storing or holding where it is called off when an order comes in.
So, we are standard at that point. It is built and put in a box the same day.

JC Do you do an out of box audit?

SME We do an out of box audit. We write all the quality control documents. The contract manufacturers conform to that. For a brand-new product, we write these. If we get failures, we do detailed checks.

JC The next question is on place postponement. ***To what extent are differentiation and customisation sub-processes postponed to the location where a detailed customer order is received?' do you ever wait until receipt of final customer order to do final configuration?***

SME We don't, we basically build the product to forecast, to the country forecast and we ship to that country forecast. The onus is on the regions to balance their customer demand and when it is in region the biggest issue is colour, or model, you have five or six different models. Going forward that is something we are really interested in, because we carry far too much inventory. The problem is when the product is built, it is built for the US or it is built for Japan one of the things we are looking at is can we put a standard low voltage motor in there that would usable for the whole of the world with just an adapter. So, you can build a generic SKU, hold that in say Malaysia and then wait to see if it is a good summer in Japan, or a good summer in the US, because we get a lot of stuff where it has been a great summer in the US, they stock-out and it's been a bad summer in Japan. They have too much stock, but we can't change the stock between them because it's already customised.

JC There is a high seasonality element to product. You mentioned that in Europe it is mainly pollen that people are concerned with, whereas in Asia is pollutants. Is it the same filter system?

SME Yes, it is the same filter system, it is hemp and carbon filter system. Now that's not to say going forward that people will not be looking for more sophistication. In China, for example they are very sophisticated with formaldehyde. In China people will be able to tell you the chemical formula for formaldehyde. In Europe I don't think most people recognise what this is. So even though it is the same filter we are looking for specific properties. When you are making a claim on a box for China, claiming this purifier filters out certain CFC's with particle sizes above 2.5 microns, this is the big thing in China, with formaldehyde you need to meet all these criteria.

JC Do they perform differently depending on the humidity and temperature?

SME They are designed to perform within a pre-defined range.

JC The last question relating to supply chain modularity is, ***'how easily can the processes be decoupled by the insertion of a Customer Order Entry Point (OEP)?'***

You said you build to country forecast but going forward because you have certain SKUs which you do not want to build too much to forecast, can the processes be decoupled so that you can have order entry points at different points in the process?

SME The biggest problem is that the cable is a fixed cable on the machine. The only thing we can configure in the purifier is colour, so the colour of that amp is a Snap-On in the process, so we could build a standard configuration of the base unit and Snap-On the different colour configurations. But we don't tend to do that. We tend to build the full unit to order. It could be done. Even in Europe we have a box which has got the main European languages, so we don't have a French SKU, and a German SKU, and a Spanish SKU. We have a standard box. Occasionally we will do specifics if we are doing a specific launch, where a retailer in Germany will do a specific SKU, it will just be German on the box. On the generic SKU's we have all those languages.

JC These are all domestic units are there industrial scale appliances

SME We don't, the only thing we do B2B is our hand dryers. It is the only product we sell B2B right now. That is through a completely different channel. That tends to go through distributors and architects, as opposed to retail stores.

JC Thank you sincerely for your time

END

Appendix 4-16. Interview transcript for A1 (project three)

Extract of transcript from interview with Principle Global Engineer
Medical device company

Date: 14th Sept 2015

JC ***Are supply chain configuration team members involved in your product development from the early stages, explain their level of involvement, and the inputs they make to product design?*** Thinking about the supply chain people who are out there working with suppliers, leaving IP protection aside for a moment would you say they are having an influence with the supply team on the architecture of the product?

SME A large amount of CE is applied at the product concept stage. CE is a core practice within our company, for patients, doctors, nurses, and the whole system.

JC ***Were manufacturing engineering, materials sourcing and supply chain engineering involved at the early concept stage?***

SME No it ends up being late in the process.

JC Is that changing?

SME Yes, it is.

JC You design the process technology, you seem to be coming in, doing the value engineering work on these products, after the fact and obviously you are highly valued for what you do, do you believe you will be invited earlier in the product design phase.

SME I think the opportunity that will arise here is that innovation that is going to arise from the evolution of delivering the product will feedback in to the core R&D, take this three-inch product, and if I am turning the process in to a continuous process, where something like this is on a reel, making it a continuous process. When you give that type of circular feedback to the R&D guys who are looking at the next generation of product, and you give them a core enabling technology that allows they completely rethink their original constraints, it is a liberation to their thinking. If you think about how complex it is to run that surgery, I liken this to an old gun that you must prime with a rod and gun powder, and bore, and someone came along with a semi-automatic rifle and an automatic machine gun, it is just a big step change in this type of technology. The big difference with that is the science of a bullet leaving a gun did not change, it is just how the bullet got in the gun changed. That is the kind of feedback that evolution or revolution in the manufacturing space can give to the product innovators.

JC You said you outsourced all the components associated with that, these suppliers were obviously involved in the very early stages.

SME There is a whole lot of complexity with achieving certain types of tolerances. There is an evolution and a refinement of what's capable, what are the capabilities of a process.

JC Are suppliers co-located?

SME No, but they would have on-site vendor representatives. Where the manufacturing sites are not that important, having Vendor reps at the table with the R&D and manufacturing groups is important

JC Do you use a phase review process for your designs, with phase gates? What is the level of knowledge shared at each stage in the process?

SME Yes, the work is tied to the Technology Release Level (TRL)

JC For phase gate zero you would have target cost in mind at that stage, target yield from the process, target process quality, the schedule for launch, all that would be determined, prior to phase gate zero?

SME Yes, our stage gate is tied in to TRL. Early technology phase gate zero you referred to there is more around the core proving science stuff, as the product becomes more scientifically proven, and becomes more applicable to a product, all those things come in, it is not quite stage gate. For us stage gate is tied in to TRL.

JC Which functions are involved at the concept stage of the development? Is a product development team used, and if so, who are the members? Are there supply chain people in the product development team?

SME Yes, they would be selecting suppliers, materials core capabilities

JC ***How much supply chain configuration design is done concurrently with product design?***

SME On this type of product because it is very mature you have a lot it, a lot of it is iterations of the same theme, they guys who are generating next generation of this know exactly who they are talking to.

JC Is the product part of a platform?

SME Yes

JC How long has this product been in the market?

SME Twenty years

JC It is very mature, have there been many design changes over the twenty years?

SME There have been hundreds of changes

JC What factors drove most of these changes?

SME The customer, the surgeon's, the further exploitation of the base science, so where this would have been used for removing cancer cells twenty years ago now it is used in much broader applications

JC The device is both for removing cells as well as sealing the wound?

SME Yes, it is for removing tissue, there is a knife that goes through the centre of the staple. As the knife cuts it leaves closure, as it goes. Usually it is live, you are sealing bodily fluids as cutting.

JC How do you remove the actual material you are cutting away?

SME It tends to be afterwards the surgeons are using multiple tools. You would end up having this device on the end of a gun, this would be like his scissors, he would be playing with surrounding tissue with tweezers, and scalpels and stuff like that.

JC With supply chain configuration team members involved in the early stages, what are the typical inputs made to the product specification?

SME Capabilities, you may want ten thou wire but I can only give you fifteen thou because ten thou is not robust. This is as good as we can achieve.

JC Does your company use formal techniques to translate customer requirements in to product and supply chain requirements? With surgeons for instance constantly coming with ideas for change, how are those ideas captured?

SME They have a whole school associated around, like teaching surgeons, re-educating surgeons, being heavily involved in the whole surgical procedures. Having doctors and nurse involved with R&D teams. It is a very collaborative exercise.

JC I have heard this many times that surgeons have significant input to product design

SME I don't know the in's and out's but there may be one-hundred expert practitioners using this product globally, a lot of them would be constantly interacting with the product developers.

JC You have a lot of competition in this space I presume?

SME Yes there is a bit, I would not say it is a lot. I don't think it is huge. There are people who compete in this space.

JC Does your company use feedback between the reference performance level and the actual performance level, to improve product design?

SME The feedback is person to person, it ends up with the best practitioners giving professional feedback. It is not like millions of data points. These data points are limited.

JC Since the device is twenty years in the field, it is obviously hitting its price point, you said earlier you are going to be looking at how you are going to further improve the product through changes in the manufacturing process, without compromising on quality etc. How will that all happen, how do you get the surgeons on board, how do you get them to buy in

SME Typically what I am talking about the surgeon would not know it even happens. You would absolutely insist that the people in the field would not even know, that a revolutionary step was happening in the manufacturing process. That's one of the constraints unfortunately, as you end up sometimes wanting to replicate inadequacies in the product that you could potentially make better, just because you are trying to keep it the same.

JC Using this as an example have your people done an FMECA on this product? Have you looked at the areas of opportunity for improving the product? You have come up with what you believe is an improved process. What would that improved process deliver? Would it reduce cost?

SME Cost, flexibility and quality. Quality not from a finished goods perspective, but from an in-process yield perspective.

JC Is there is room for improvement?

SME At the moment the key thing here, is this is a semi-automated process. If I could fully automate it, then I have taken out hundreds of people out of the supply chain. It is not just the people it is all the variability associated

JC Within you company that's an on-going process. Is this driven by the product management team? Who is the ultimate decision-maker who determines whether you would go ahead with the process change, or leave things as is? Is it product management?

SME Product managers, life cycle project manager, whilst this is an Ethicon bio surgery product typically as a product become more mature the product managers as they get further in to the product life cycle they are under a lot of pressure to try and reduce cost. And, when a business becomes more competitive you have a lot of price point. If I am happy to make this for $100 and someone else can make it automatically for $10, then my business is in jeopardy. I cannot wait.

JC Does your company use feedback about the gap between the actual performance achieved and the reference or planned performance level, to improve supply chain configuration?

SME The surgeons are the feedback

JC How does the change in product complexity, and the amount of product change compare to the previous release, impact on development lead time?

SME It could have been the market for the first ten years with just two SKU's, but in the last ten years it has gone from two SKU's to five-hundred. SKU's tend to proliferate at the end of a product. This is driven by the surgeon, it is driven by diversity of application

JC Does your company maintain a balanced scorecard for managing supply chain configuration and product design trade-off's? So, as you said earlier, you could try and take ninety per cent of the manufacturing cost out, and go for full automation, or you could hold back a little and go for a fifty percent cost reduction, and a level of automation

SME Within the make device world your ability to do something and your strategy for implementing it tend to be two different vehicles. Because I can fully automate it tends not to lead to fully automating it because of balance of risk. There is continuity of supply, there is a delay, there is potentially a significant investment, and there is a complex equation about a decision around automating something. It is not driven by the ability to do it. There is much more in play. It is not purely a technical decision.

JC When you are making these type of automation decisions do you look at all these factors?

SME There is a complicated conversation around whether we do. There is a lot tied in to the maturity of the product lifecycle. You may want to opt out of the business rather than automate it. Because at the point where you are seriously considering highly automating something you tend to be at the back end of the product life cycle. It becomes a mature competitive environment, and it is not necessarily the place you want to be. You want to be at the other end of the equation.

JC In terms of feedforward (anticipatory) control where you want to recommend changes, does your company use feedforward control measures in the NPD process?

SME In this circumstance the feedforward stuff is more complicated, all because you can does not mean you should, and quite often than not the ability to do something is not quite accepted robustly as I have a problem. Selling opportunities in to an organisation forget it.

JC If I was to extend the conversation out in to the supply chain, these products are in the field. Is there a shelf life associated with them?

SME There may be a sterility game, they are serialised. It is a sterile, metal steel product, it will oxide and go brittle. Taking a guess at it I would be surprised if this has a shelf life of more than three years.

JC Who within your company is the person involved in determining how the supply chain should operate. Let's say this has a three-year shelf life, it is serialised, someone must decide what levels of inventory to hold in the field, to meet customer demand

SME Supply chain product owner decides

JC Does your company select alternate supply chain configurations that focus on reducing NPD introduction rate?

SME Not as rapidly as they could I would say. They tend to stick with things that work, than looking at parallel alternatives

JC Taking this product launch, how did the total development lead-time compare with the launch goal?

SME This and other product very rarely hit the launch target goal. It is a very typically industry standard space, where made device products are not quick at getting to market. I will rephrase that, typically people do not chastise themselves for taking too long, having over extended goals, some people are OK with taking ten years to bring a product to market, is a challenge

JC Take the automation you are talking about here what sort of an overall timeline is involved? You are talking years?

SME The challenge we have typically, is that if we get heavily involved in automation of a product, by the time the product has reached market your control system is obsolete. You end up with a real challenge to automate efficiently in the early stages of the product life cycle. By design you end up thinking of it as a generational thing. So, each iteration of the product allows you to come back in and have a go at the whole automation.

JC I have noticed that with Medtech in general the focus is on getting the product out there. It really does not matter about manufacturing or process, if it is robust.

SME It ends up being a secondary consideration. This case study we are using here is not that typical having a product that is mature enough and clever enough that it is around for twenty years and this evolutionary growth thing is not typical of this kind of business. More and more you get onezy/twoxy kind of ideas, that may have much shorter lifecycle and you never get to go back in and manufacture it in the way you should be manufacturing it. Umpteen times you will see a poor manufacturing strategy applied to a product.

SME I would not think they are managing product launch faster than our competitors. It tends not to be executional excellence end that causes problems. A lot of the constraints here are around market definition, regulatory constraints, and those kinds of things rather than world class execution

JC When you say market definition can you elaborate on this?

SME What is the opportunity for something? How do you create a niche? One of the big things you have is no one has ever heard of it. Because you are having to teach somebody to become an expert at something they have never heard of, you don't immediately have a big market. These types of devices are not consumer goodies, if it's shiny and gadgetry people go for it, you end up having to create your market, you must create your need. You must turn the science in to a pull, it is very far away from making the next mobile phone.

JC I have gone through the questions, if we take another minute or so to recap. The product is highly modular, the process itself is semi-automated, and highly modular, do you see the process as you further automate it, becoming a lot more integral?

SME This will go from being pretty much a batch process to a fully automated continuous process. The challenge you have is ultimately where does this go? If I can build a manufacturing solution for this that's very revolutionary, I could make these where they are being used, rather than in a factory, because that is the type of opportunity that sits in front of us, with this type of evolution.

JC In terms of the materials you are using in this single use device, do you see any opportunity to use alternate materials, for some of those parts could you go for an additive manufacturing process

SME Yes that is where I was going to with making it in the place where it is used. My objective with this would be to make a machine that's using 3D printing and a small modular in-line stapling machine, they only must make ten a day, because that is as much a surgeon can use. This is very doable for this type of product.

JC Thank you for your time

SME Thank you….

END

Appendix 4-17. Interview transcript for B2 (project three)

Extract of transcript from interview with Director Global Manufacturing Domestic appliance company

Date: 27th July 2015

JC ***To what extent is concurrent engineering used for product concept development?***

SME This is a high level of CD because we cannot have one group working on something and feeding that back to other guys. They all must work concurrently.

JC Are people from the supply chain team who select vendors, involved in this process?

SME This is a tricky one. We are working on products that are considered so secret that we cannot go out to a supplier, and say how do you do this? Because we are then revealing what we want to do. We try to use third parties to go and do that, and say we are interested in your capabilities. Just doing a supply screening in the network can have constraints if you do not want to disclose what you are doing. We are working on models on how early can we engage suppliers? How early can we engage the procurement team internally? And how early can we engage some of the manufacturing folks? They need to be involved early, it is all based on a compromise between what is the risk of engaging a supplier who runs off and does something with another guy, or does something on his own, not getting right the inputs and validation. As the company matures and starts going in to new areas where they do not know everything, then they are forced to rethink the approach for engaging suppliers.

JC Rossetti and Choi discuss the risks and downsides of early supplier involvement.

SME We can do technology wise. In conversations with the persons who runs our procurement it is about us selecting which supplier we believe is innovative and has something to offer, and can put some brainpower in and speed up our product development. It is about taking their technology roadmap and trying to match that with our requirements, saying want we want, you need to work towards that. We need to have an 1800 min battery versus a 1500. It becomes more specific when we start to talk about the secret sauce of our company. Our digital motors are designed completely in-house. But it is fully automated. We basically use an integrator to do all the automation with use. They need to be involved early. You need to involve people if you don't know what you are doing. The way our company is organised, we just moved to a firm product category, before it was functional based but now it is pure category structure where a guy having for example our cordless range.

He is fully responsible for that, and he sources some resources on loan from our product group. We have the supporting engineering functions who provide either direct engineering resources or services to that category otherwise the whole team is under one roof. It is always a little bit tricky with the electronics piece because should it be inside the product development or outside? We still have not figured this one out.

JC ***How much supply chain configuration design is done concurrently with product design?***

SME Let me try and explain how it works from a product development level. We do all our engineering builds even the first engineering build with our contract manufacturer, with the injection moulding tools that we use for normal volume production. By default, we involve then 7-8 months before like any other contract manufacture being engaged by their customers. But half a year before that we need to engage the tool makers, and equipment suppliers. Even before that we need to go and engage our parts suppliers, whether this is a complete bought in module or whether that is integrated in to the product. So, we do concurrent work, we are reluctant to engage too early because our company has a little bit is a mentality that we want to manage this opening. There is also the IP protection risk if we are doing something that another person has not done before. That cuts a little bit on the back burner in terms of how we engage suppliers. It is opening up because suddenly, we are going in to territory where we want to be first movers, but at the same time also do not necessarily know everything in that field, then it becomes a compromise, a risk assessment on how early you bring in and how much do you think you can do. Do you go hire some people who knows that? Do you drag the water to the horse or the horse to the water? That's the risk assessment.

JC ***Are supply chain configuration team members involved in your product development from the early stages, explain their level of involvement, and the inputs they make to product design?*** Thinking about the supply chain people who are out there working with suppliers, leaving IP protection aside for a moment would you say they are having an influence with the supply team on the architecture of the product?

SME Yes, it is opening based upon the manufacturing engineering team and the procurement team being able to add value. If the procurement team has a nett promoter score of two in the design organisation, they are never going to value them, and they will never be invited to the conversation. The product will cost a fortune; we will do cost downs afterwards based on alternative parts. How much are you willing to spend and how do we get the best compromise? That is opening inside our company, it is more about how do we have the design folks working in parallel, with the sourcing folks to find out where is the best design compromise, and supply chain architecture, cost versus specs, and time to market.

JC If you take this concept of concurrent engineering area within your company from years ago to where it is at today obviously there is increasing time to market pressures. When in Digital my involvement in NPI was around supplier selection, and mechanical layout and design of the PCBA that we used to manufacture in-house. I was only there because I provided some value, because there was a cost of having me there. I was constantly in communication with the manufacturing site where we built the prototypes, and we were able to reduce time to market by improved prototype builds. A lot of manufacturability issues were dealt with early, we were not waiting for the second, third, fourth, fifth engineering prototype.

SME We done quite a bit there, as a reference we probably doubled the number of manufacturing NPI people, and the procurement people that is involved early on, both test specification, parts specification both from operational quality and procurement perspective. So, has evolved from a low point because our company as a culture has been successful because they thought they were smarter than everybody else. When you have that DNA of a company it takes a little bit of time to go change. We have moved quite a bit forward, but still at an immature perspective. This will determine success going forward, because as you said the clock is ticking.

JC You mentioned nett promoter score, In the case of an internal NPS, I have not come across this. Do the NPI team provide a score?

SME I was having that conversation with my manager and our procurement director that works for me. If you want to be invited to the good conversation early on, then you need to be seen to be adding value. We are discussing whether we want to formalise that in having an NPS for each of the each of the product categories, and try to tie that together to the cost avoidance and cost savings clean-up afterwards. The typical pitfall in that space is that the design engineers are typically those guys who think they know design better than everyone else. They call suppliers, they go look at the supplier, and just need someone who can meet the spec not someone with the best price, an immature organisation. The only way you are going to get supply engagement is by having people who brokers that conversation in terms of IP protection and understand the technology, but having core competencies in picking suppliers, and having the suppliers contributing. That comes down to how much confidence the design team has because in a typical product company, these are the ones calling the shots. You have areas where this is where people are very successful. In the tooling and the mechanical design where you bring in supplier early engagement, you can de-risk by one giving a supplier a part, and not the whole piece. Where they have not been so successful in many companies is when you go and outsource a whole system piece because that takes a lot of confidence. This is where you need to have a bit more maturity. You need to be sure you know all the uncertainties, and then we are back to the S-curve.

JC How much customer involvement is done concurrently with product design? What knowledge sharing takes place with SCC and product design?

SME How can a customer tell us what they want if they do not know what is available? by identifying technologies that address a need in the market. If people knew about this, it would already be out there by someone else. It’s a little like a black and white approach. We do pull people in like anyone else does, for user course and user survey. We are more a product company. We push things out and we think we are smarter than the customer in some cases. SCC are involved but later in the concept stage. With increasing use of design simulation there is less requirement to involve SCC early, although there is a lot of learnings from plastics materials and tooling suppliers.

JC Does your company use formal techniques to translate customer requirements in to product and supply chain parameters, at product concept design stage?

SME Our company employ a Manufacture for Design (MFD) approach. Form factor design is an important consideration and is increasingly managed by electronic simulation. In some instances, modularity is sacrificed for the sake of design. Design stays in the concept stage until our company has acquired the right technology.

JC ***On feedback planning and control, does your company measure planned versus actual product performance, to improve product design, against its specification?***

SME Yes there is all the usual stuff. How do you measure good, with field returns, reliability issues all that stuff? I think most companies are doing that stuff to a certain level. Our stuff is not over complicated. We have good opportunities to get the feedback. I would say that we are immature as a supply manufacturing organisation, compared to how we are designing product.

JC ***Are you using feedback to assess and improve supply chain configuration?***

SME For sure all those things are used with scorecards, network evolutions. When you talk about supply chain configuration there are different nodes, the simple selection / deselection based upon performance. Performance being cost, quality and delivery. Then you also have elements about dual sourcing, alternative AVL's based upon de-risking and the level of partnerships. If you cannot work together with a supplier in a true partnership then you probably want to have two suppliers, to play them out against each other. The latest one in terms of knowledge based management is how do you speed up the innovation by engaging the right suppliers and building processes related around technology investments in the whole supply network. This is tricky and hard to measure. How do we work closely enough with our suppliers, so they can cut TTM away by having upfront investment? This is a tricky one because you need to have a strong partnership. The car industry can do it because they have modular systems, outsourced where they say you and I are going to work together for the next twenty years. If we fail you fail, and vice versa. We don't have that relationship yet because we have been fairly introvert, in terms of our design thinking and our design activities. That will come over time, it is just hard to measure.

JC ***How does current product complexity impact on product lead time? Sticking with the cordless vacuum cleaner, I am not sure where this is at in its design evolution, is the design becoming less or more complex?***

SME What I found is that stuff comes and goes in waves. You start with a product that sells above expectation, then it leads to more SKU's and complexity. As you work forward and as you have more complexity with too many models the pendulum swings the other way. It becomes too complex; we choke the supply line. Let's keep it simple here. So, I would say it is controllable it is discussed, I am having discussions with the guy responsible for the product line, you can't have fifteen different motors. It is a good dialogue. We are probably at the right level now. But it is one of these things that can go completely out of whack, if the organisation is not aligned. Our company is still a small organisation. Our strength in these areas is you don't have firm processes or system to control SKU proliferation, but we are small enough that we can have the right conversation between the right stakeholders. When I speak to larger organisations like Nokia, Samsung or Microsoft they have no contact whatsoever with the design teams. The organisation is too big. If you come in complaining about too many products because you did not have that relationship. Having these tough conversations is quite often not about structure but about what relationship you have, is the organisation focused on sales, is everyone trying to sell everything to everyone? In our company it is a much smaller organisation.

JC ***Does your company maintain a scorecard for managing supply chain configuration and product design trade-offs? It's back to the SKU proliferation, is there a financial model for indicating the ROI by SKU?***

SME Not on SKU level but on a product level. We manage it based upon inventory, we manage SKU's based on when the market is running out of stock. We do not have a SKU level cost model. On paper it does not cost much to introduce a new SKU. It is just packaging. It is the complexity that ends up killing you.

JC ***The next questions are on feedforward control. It is on new product and new technology, for example your investment in the solid-state lithium ion batteries, I am sure they will have huge uptake when they hit the market. For product like that we are thinking more about feedforward than feedback control. Does your company use anticipatory feedforward control in the NPD process, to align the product with its design specification?***

SME It really depends on what you mean by feedforward control.

JC My definition of feedforward control or anticipatory control is preventative action taken before the difference between planned and actual performance occurs. It looks at leading indicators. The stage-gate model establishes control during the stages. It includes anticipatory feedback, anticipating deviations; expected profitability of outputs; expected outcomes; anticipating needs and trends. What you end up doing, because you have not been down this path before. Taking for instance the battery you take what is critical.

SME We have that but it's never going to be better by the best estimates, by the predictions by the best people you have available. All the guys are figuring out, we have a new product, how are we going to test it? what is important? How do we control this? How do we control that? Everybody is using it; the question is how buttoned up is that process? I would say we are doing certain things but if you read our CEO's book he speaks about doing 2000 prototypes. I and our CEO are saying this can't be right. That's about 1950 to many! We have a few things where for example when we did the tap, it required some FDA approvals related to drinking water we did not plan. Now when we are going in to new systems, new product like a robot, and other stuff that is still confidential, and we have not done before we need to start doing a lot of brain finding to figure out what is important here. How do we predict user acceptance? How do we predict this that and whatever? We are entering new territory, but we also know that if we do not do feedforward planning and control then we have an issue. As you can imagine there is a lot of blind leading the blind.

JC ***I have come across so little research on feedforward planning and control. For new technology areas there is a need to incorporate feedforward planning and control. Does your company select input variables that make a material difference in improving NPD introduction time?***

SME We use a design FMEA thinking approach. We have the PFMEA, this goes back a little in to the design, set against the user expectations. A scientific approach in defining acceptance levels and user requirements in the early design stages is random at best. I have not seen anything either. On the feedforward I think this is where you need to tap in to the aerospace the automotive industry, and medical industry. If they don't have it, then I can't imagine anyone else having it.

JC ***Are pre-defined NPD goals set? If so, what are they? Is data collected, to establish NPD goals, and is data collected to establish SCC goals?***

SME Yes.

JC ***Are input variables measured in terms of their relationship to the NPD introduction rate (NPIR), and cost targets?***

SME Yes, again who is setting the target? Is this the design boys, then they are playing games, so in absolute terms launching products in our company is faster but not radically faster?

JC ***Does your company select alternative supply chain configurations (input variables) that focus on reducing NPD introduction rate (an output variable)?***

SME Yes

JC ***Taking the more recent one how did the total product development lead-time compare with the goal? Did you achieve your targets on launch?***

SME I think it got achieved in relative terms, but it is always red in our company. When the guys go to our CEO and ask for a four-week's delay, they come out with four weeks to speed it up. Even we are smashing our numbers and making profit, last year we were still red. It's a little bit of a funny culture inside our company. I would say in relative terms we are getting better at launching product fast.

JC Taking your new product introduction rate versus your competitors, I know you don't have competitors in certain areas but taking the cordless vacuum cleaner, I know there are a few others on the market, I wouldn't say they are comparable but how would you say you compare with your competitors in terms of time to launch?

SME I think it is a little hard because we are first movers. We spend some fifteen years of research on some of the digital motors. Our products are twice as powerful as some of the other guys. But I would say that we have longer time to market than other companies, but is this because we start away earlier, we are doing real product innovation, a little bit of imitation. I am probably not the best guy to answer that question.

SME You can make a lot of comparisons between the automotive industries particularly Toyota has been strong in effective planning (feedforward).

JC Thank you for your time, this is greatly appreciated

END