Engineering Change Modelling Using a Function-Behaviour-Structure Scheme

A thesis submitted to the University of Cambridge, Department of Engineering,
for the degree of Doctor of Philosophy

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October 2013

To my family and all my teachers and professors throughout my academic career, from the elementary school in Kabul to the University of Cambridge

Mr. K. once said:

“The thinking man does not use one light too many,
one piece of bread too many,
one idea too many.”
(Bertolt Brecht, German writer, 1898-1956)

Declaration

Unless otherwise stated, this report is the result of my own research and does not include the outcome of work done in collaboration. Any reference to the work of others is clearly indicated in the text. This report has not been submitted in whole or in part for consideration for any other degree or qualification at this University or any other Institution. This thesis contains 78 figures, 20 tables and fewer than 70,000 words.

Some of the work contained in this dissertation has been published and presented as below.

- B.Hamraz, N.H.M.Caldwell, D.C.Wynn, and P.J.Clarkson, (2013): Requirements-based Development of an Improved Engineering Change Management Method. Journal of Engineering Design, online first, DOI: 10.1080/09544828.2013.834039.
- B.Hamraz, N.H.M.Caldwell, and P.J.Clarkson, (2013): A Holistic Framework for Categorisation of Literature in Engineering Change Management. Systems Engineering 16 (4).
- B.Hamraz, O.Hisarciklilar, K.Rahmani, D.C.Wynn, V.Thomson, and P.J.Clarkson, (2013): Change Prediction Using Interface Data. Concurrent Engineering 21 (2), pp. 139-154.
- B.Hamraz, N.H.M.Caldwell, and P.J.Clarkson, (2012): A Multi-domain Engineering Change Propagation Model to Support Uncertainty Reduction and Risk Management in Design. Journal of Mechanical Design 134 (10), pp. 100905.01-14.
- B.Hamraz, N.H.M.Caldwell, and P.J.Clarkson, (2012): A Matrix-calculation-based Algorithm for Numerical Change Propagation Analysis. Transactions on Engineering Management 60 (1), pp. 186-198.
- B.Hamraz, N.H.M.Caldwell, and P.J.Clarkson, (2012): FBS Linkage Model – Towards an Integrated Engineering Change Prediction and Analysis Method. Proceedings of the International Design Conference (DESIGN'10), Dubrovnik, Croatia, pp. 901-910.

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Homerton College, University of Cambridge, October 2013

Acknowledgements

I would like to thank Prof P. John Clarkson for supervising and encouraging this research.

I would like to thank Dr Nicholas H.M. Caldwell and Dr David C. Wynn for their supervision, guidance, and valuable advice throughout this research project and Dr Geoffrey T. Parks for his helpful feedback.

Furthermore, I would like to thank Dr Warren P. Kerley and Dr David J. Seidel for their helpful comments on most parts of this report and all my colleagues at the Engineering Design Centre (EDC), in particular Dr H. Nam Le, M.C. Emre Simsekler, Emilene Zitkus, and Ghadir I. Siyam, for their assistance and constructive discussions.

Finally, I would like to thank the following people for their contribution: Seena Nair and Andrew Flintham from the EDC, for their programming support, Daniel M. Rosen for implementing the proposed method as a module into the CAM software, Tom W. Ridgman from the Institute for Manufacturing (IfM), University of Cambridge, for his support with the functional modelling of the diesel engine, Paul N. Turner and Sean G. Harman from Ford Motor Company for evaluating the method and the diesel engine model, Daniel Aldridge and Dr John Craven for their support with the scanning electron microscope (SEM) model, Bernard C. Breton from CAPE for his support with the functional modelling of the SEM, Jane Breton and Dr Richard S. Paden for evaluating the method and the SEM model, the Transatlantic Partnership for Excellence in Engineering Programme for providing me a six month mobility scholarship to visit McGill University, Prof Vincent Thomson, Dr Onur Hisarciklilar, and their team for hosting me at McGill University and for the fruitful collaboration, Prof David C. Brown from the Worcester Polytechnic Institute for his valuable feedback on the functional reasoning parts of this thesis, Prof Panos Y. Papalambros, Prof Olivier L. de Weck, and the referees from ASME Journal of Mechanical Design for their useful comments, Prof Rajiv Sabherwal, Prof Bin Jiang, and the referees from IEEE Transactions on Engineering Management for their useful comments, Prof Andrew Sage and the referees from INCOSE Journal of Systems Engineering for their useful comments, Prof Biren Prasad and the referees from Concurrent Engineering for their useful comments, Prof Alex Duffy and the referees from Journal of Engineering Design for their useful comments, Prof Yoram Reich and the referees from Research in Engineering Design for their useful comments, all colleagues from CRESCENDO for insightful discussions, and Agusta-Westland Helicopters Ltd., Perkins Engines Company Ltd., and the collaborating international SEM manufacturer that wished to remain unnamed in this thesis to preserve confidentiality for the extensive information and assistance.

Abstract

Engineering changes are unavoidable and occur throughout the lifecycle of products. Due to the high interconnectivity of engineering products, a single change to one component usually has knock-on effects on other components causing further changes. This change propagation significantly affects the success of a product in the market by increasing development cost and time-to-market. As such engineering change management is essential to companies, but it is a complex task for managers and researchers alike.

To address this challenge, the thesis at hand investigates the state-of-the-art of research in engineering change management and develops a method to support engineering change propagation analysis, termed FBS Linkage. This method integrates functional reasoning with change prediction. A product is modelled as a network of its functional, behavioural, and structural attributes. Change propagation is then described as spread between the elements along the links of this network.

The FBS Linkage concept is designed based on a comprehensive set of requirements derived from both the literature and industry practices as well as a comparative assessment of existing change methods and functional reasoning schemes. A step-by-step technique of building and using an FBS Linkage model is demonstrated. The method's potential benefits are discussed. Finally, the application of the method to two industrial case studies involving a diesel engine and a scanning electron microscope is presented. The method evaluation indicates that the benefits of the method outweigh its application effort and pinpoints areas for further refinement.

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List of Abbreviations

AIAG	Automotive Industry Action Group
ASME	American Society of Mechanical Engineers
CPM	Change Prediction Method
DESIGN	International Design Conference
DETC	Design Engineering Technical Conference
DMM	Domain mapping matrix
DRM	Design Research Methodology
DSM	Design structure matrix
EC	Engineering change
ECM	Engineering change management
ECR	Engineering change request
EDC	Engineering Design Centre
FR	Functional reasoning
FBS	Function, behaviour, and structure
FBSta	Function-Behaviour-State model
FBStr	Function-Behaviour-Structure model
ICED	Conference on Engineering Design
MDM	Multi domain matrix
PD	Product development
SD	System dynamics
SEM	Scanning electron microscope
SBF	Structure-Behaviour-Function model

1 Introduction

> *"There is nothing wrong with change,*
> *if it is in the right direction."*
> *(Winston Churchill, Former British Prime Minister, 1874-1965)*

Heraclitus, a Greek philosopher known for his doctrine of change as a central phenomenon to the universe, stated around 500 BC that *"The only constant is change."* For engineering products, this is definitely true and more so today than ever before. *Engineering changes* (ECs) can be broadly defined as amendments to released engineering documentation in connection with product modifications. ECs are essential in complex *product development* (PD); they may aim to improve, enhance, or adapt the product to new requirements, or to remove mistakes. In fact, there is no product improvement without ECs. Trends such as shorter development time, more customisation, and higher complexity have reinforced the increasingly significant role of ECs. Consequently, the appropriate management of ECs has become a crucial discipline.

This thesis presents a novel method for *engineering change management* (ECM) – *FBS Linkage,* an explanatory approach built around the concepts of the *Change Prediction Method* (CPM) and a *function-behaviour-structure* (FBS) reasoning scheme. The FBS Linkage method supports causal and numerical change propagation analysis.

This present chapter gives an introduction to the Ph.D. thesis at hand in five sections. Section 1.1 provides the background and underlines the motivation of the research. It explains the importance of ECs, the challenges of their management, the benefits of an efficient and effective ECM, and ways of achieving these benefits. Section 1.2 states the overall objective, the research hypothesis, and the research questions. Section 1.3 discusses the scope of the work. Section 1.4 presents the adopted research methodology of the thesis project, with the remaining structure being outlined in Section 1.5.

1.1 Background

"The main task of engineers is to apply their scientific and engineering knowledge to the solution of technical problems, and then to optimise those solutions within the requirements and constraints set by material, technological, economic, legal, environmental and human-related considerations" (Pahl *et al.* 2007, p. 1).

More specifically, product development (PD) is *"the transformation of a market opportunity and a set of assumptions about product technology into a product available for sale"* (Krishnan and Ulrich 2001, p. 1).

Within the early stages of PD, *"Engineering design is a process performed by humans aided by technical means through which information in the form of requirements is converted into information in the form of descriptions of technical systems, such that this technical system meets the requirements of mankind"* (Hubka and Eder 1987, p. 124).

Modifications to these descriptions of technical systems are referred to as engineering changes (ECs) (Wright 1997). In today's customer-driven and dynamic markets ECs cannot be avoided entirely; they are rather the rule than the exception (Clark and Fujimoto 1991). In fact, the existence of a successful engineering system is hardly imaginable without ECs (Fricke and Schulz 2005). ECs can be triggered by the customers, the management or company's internal departments, the suppliers or partners, and by market drivers such as technology and regulation. The purposes of ECs are manifold and can be generally grouped into variation or improvement, and correction initiatives. Well-known examples of ECs are those required to upgrade and improve existing products. This applies to the majority of product designs because hardly any product is designed from scratch (Bucciarelli 1994, Eppinger *et al.* 1994, Cross 2000). Product improvement is often preferred towards development of new products because of lower costs, and lower technical and economic risk compared to development of novelties. ECs are not limited to the development phase but occur throughout the lifecycle of products, from concept development, over detail design, to manufacturing, and service (Nichols 1990).

1.1.1 The increasing importance of engineering changes (ECs)

The continuously increasing *complexity* in engineering systems and their environment combined with the decreasing *development times* have increased the potential frequency and severity of ECs. Therefore, managing such changes has become an essential discipline with significant impact on a company's competitiveness (Leech and Turner 1985, Nichols 1990).

Complexity as a research area has increasingly attracted attention during the last two decades (Battram 2000, Alligood *et al.* 2001). Two key views on complexity involve *the structural complexity* of parts and connections (Simon 1996) and *the dynamic complexity* of behaviour (Dooley *et al.* 1995). In general, it is accepted that the more complex a system is, the more difficult it is to control and predict its behaviour. Thus, complexity in engineering systems and their environment is a driver for ECs (Fricke *et al.* 2000). Companies have to cope with complexity in mainly three areas: the product (e.g. parts, components, systems, product structure, product features, and product mix), the company organisation (e.g. processes, production system, supply chain and logistics, internal communication, company structure), and the business environment (e.g. suppliers, customers, competitors, complementary and competing products, and market regulators). The evolution of two factors has significantly increased the complexity in all three areas: the technology and the markets.

1. Technological inventions such as computers and microchips have enhanced the functionality of products. Complex products like aircrafts or automobiles are comprised of a large number of components, assemblies, and systems with many interdependencies between them. A single engineer is hardly able to understand the complete product (Clarkson *et al.* 2004). Thus, a change to one constituent part of a system is highly likely to result in a change to another part, which in turn can propagate further (Terwiesch and Loch 1999, Fricke *et al.* 2000, Clarkson *et al.* 2004).

2. Evolution in the market has led to a shift from the early 1970s supplier-driven mass market with its *economies of scale* paradigm towards customer-driven, fragmented marketplaces, where paradigms such as *economies of scope* and *mass customisation* (Maull *et al.* 1992, Pine 2nd 1993a, Da Silveira *et al.* 2001), *lean manufacturing* (Womack *et al.* 1991), and *agile manufacturing* (Kidd 1994, Brown and Bessant 2003) dominate. The customer with his individual and continuously changing needs determines the high variety and fast pace of PD. Globalisation has increased competition and the number of relations between market players across country borders. New markets are emerging rapidly while existing markets are continuously changing. To remain competitive, companies are forced to individualise their products and services, quickly place them into the market, regularly improve and update them, and rapidly introduce new models (Pine 2nd 1993a, Gupta and Souder 1998, Minderhoud and Fraser 2005).

Development times are required to be to continuously decreased due to markets with more intense global competition and increasingly faster changing customer needs. For example, Minderhoud and Fraser (2005) reviewed the overall lifecycle time of consumer electronics, including the technology development time, the PD time, and the transfer time to volume production, and found a drastic reduction from *10–15* years in 1970s to *2–5* years in 2000s.

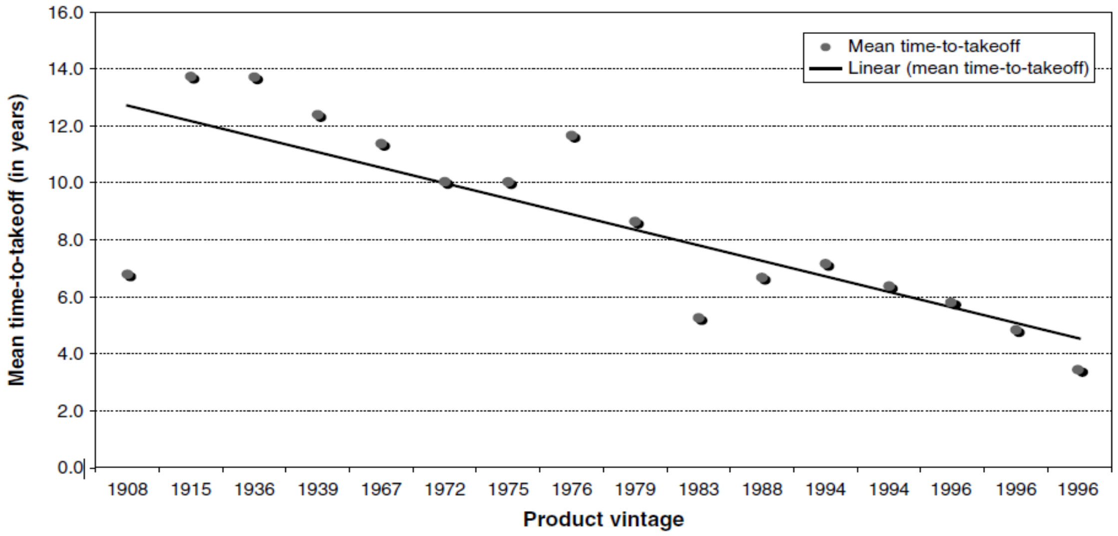

Figure 1: Mean time-to-takeoff of new consumer products over time

Source: Chandrasekaran and Tellis (2008, p. 9)[1]

Chandrasekaran and Tellis (2008) studied the launch of *16* new consumer products across *31* countries to analyse their *time-to-takeoff*, a metric which measures how quickly a market adopts a new product. *Time-to-takeoff* indicates the acceptance and willingness of customers towards innovations and can be considered as an external driver for the reduction of development times. Chandrasekaran and Tellis found that the mean *time-to-takeoff* differs between countries and is driven by factors such as culture, wealth, and product class. However, most importantly and as can be seen in Figure 1, it has continuously decreased over time and converged across countries.

1.1.2 Challenges of engineering change management (ECM)

Over the past two decades, academic interest has risen in ECM. Many in-depth company case studies have been conducted to understand the current practices and issues of ECM in order to derive the needs for future development (for a review, see Wright 1997, Jarratt *et al.* 2011). As a result, a variety of frameworks and tools aimed at aiding investigation, analysis, prediction of change propagation, and the management of ECs have been developed. However, ECs and their uncontrolled propagation still pose a challenge for industry. While many companies recognise ECs as being important for their businesses, very few have implemented dedicated change management tools with even fewer claiming that they can

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[1] Reprinted by permission from the Institute for Operations Research and the Management Sciences, 5521 Research Park Drive, Suite 200, Catonsville, Maryland 21228 USA.

handle change issues successfully (Huang and Mak 1999, Maier and Langer 2011). Thus, further design research is required to support the practice of ECM.

Dealing with ECs is not straightforward. Change initiated in one part of the system tends to have knock-on effects, triggering follow-up changes to other parts. This phenomenon known as *change propagation* (Terwiesch and Loch 1999, Fricke *et al.* 2000, Clarkson *et al.* 2004) is very common to engineering products due to the high interconnectivity between their components. The first change in such a propagation chain is termed *initiated change* and the rest *emergent changes* (Eckert *et al.* 2004). Change propagation can create a snowball effect, and in the worst case, an avalanche of change activity that may affect the whole system (Eckert *et al.* 2004) and involve many partners collaborating in its development (Prasad 1997). The resulting impact can be very severe as it often entails both an increase in costs as well as a delay in schedules.

The Automotive Industry Action Group (AIAG) reported for the North American automotive industry in total 350,000 ECs per year along with a processing cost (excluding materials and tools) of up to USD 50,000 per EC (AIAG 2012). Fricke et al. (2000) concluded from a survey with German companies that 30% of daily work of engineers and managers is related to ECs. Maier and Langer (2011) confirmed this for Danish companies based on a survey with more than 90 engineering firms from different industry sectors and sizes in Denmark. Loch and Terwiesch (1999) investigated the impact of ECs on costs and schedules and found that ECs consume 33-50% of the engineering capacity at the firm they examined along with 20–50% of tool costs.

Adopting the network of influencing factors from Blessing and Chakrabarti (2009), which consists of the factors (nodes), their interdependencies (arcs), symbols (+,-) for the influence direction and the factor states, and literature references, the current challenges with ECs can be depicted using the reference model in Figure 2. This network focuses on key factors and highlights some important relations between them without claiming to be complete. Most of these relations are backed up by the selected five key ECM articles. The rest is based on assumptions by the author.

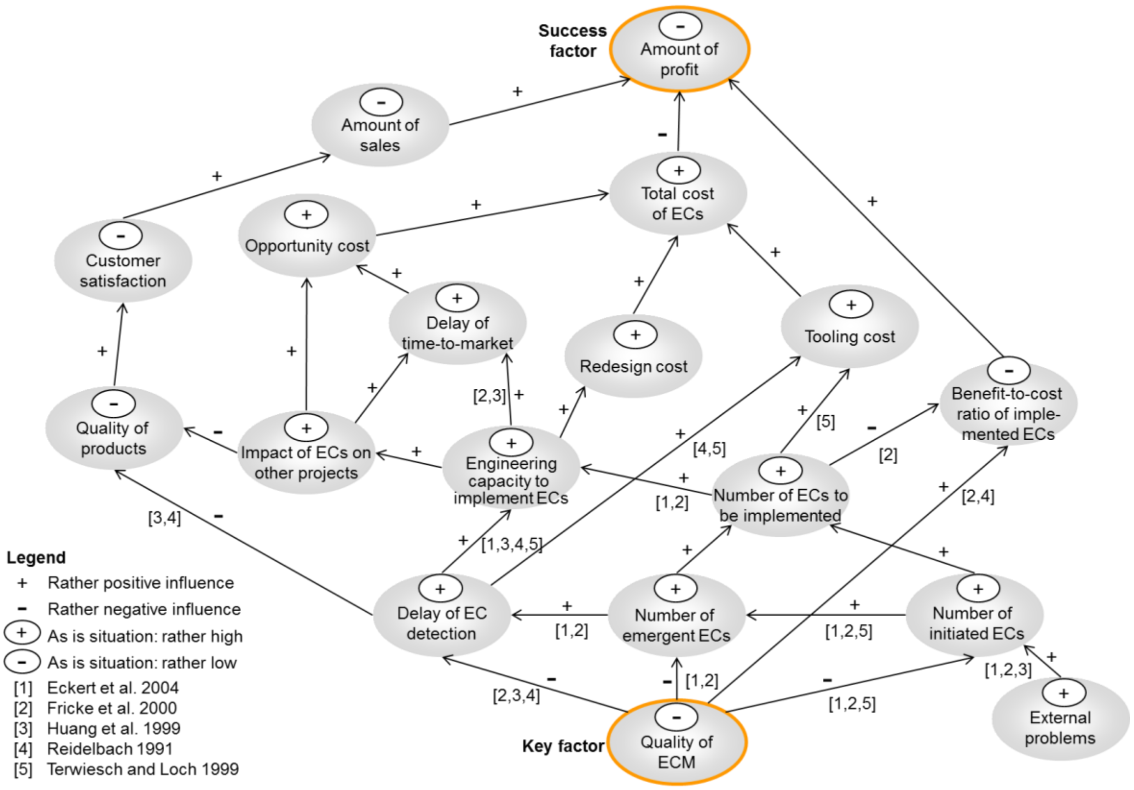


Figure 2: Network of influencing factors (reference model)

Source: Adapted from Blessing and Chakrabarti (2009)

1.1.3 Benefits of an efficient and effective ECM

Research on EC has primarily focused on the minimisation of the negative effects of ECs such as time delays and budget overruns and has led to a negative perception of ECs (Hegde *et al.* 1992, Loch and Terwiesch 1999). However, ECs are not only regarded as a problem but also as an opportunity (Maier and Langer 2011); they allow well-organised companies evolving their products to meet the changing customer requirements rapidly and outperform their rivals (DiPrima 1982, Acar *et al.* 1998). The effects of ECs can be beneficial when the product quality increases or a long-term cost cut is achieved (Fricke *et al.* 2000). In fact, effective and efficient ECM provides companies with a competitive advantage. Companies that adopt processes, suitable tools, and techniques to control and implement ECs improve their competiveness in all three aspects of cost, quality, and schedule. Thus, the benefits of a good ECM are twofold; they avoid the costs caused by ECs and generate additional profit by facilitating continuous product improvement. Fricke et al. (2000, p. 170) concluded that *“without an adequate change management only two alternatives exist: to die of changes, or to miss the chance of a successful product.”*

The benefits of such an improved ECM are presented in the prior developed network of influencing factors as a desired status (Figure 3).

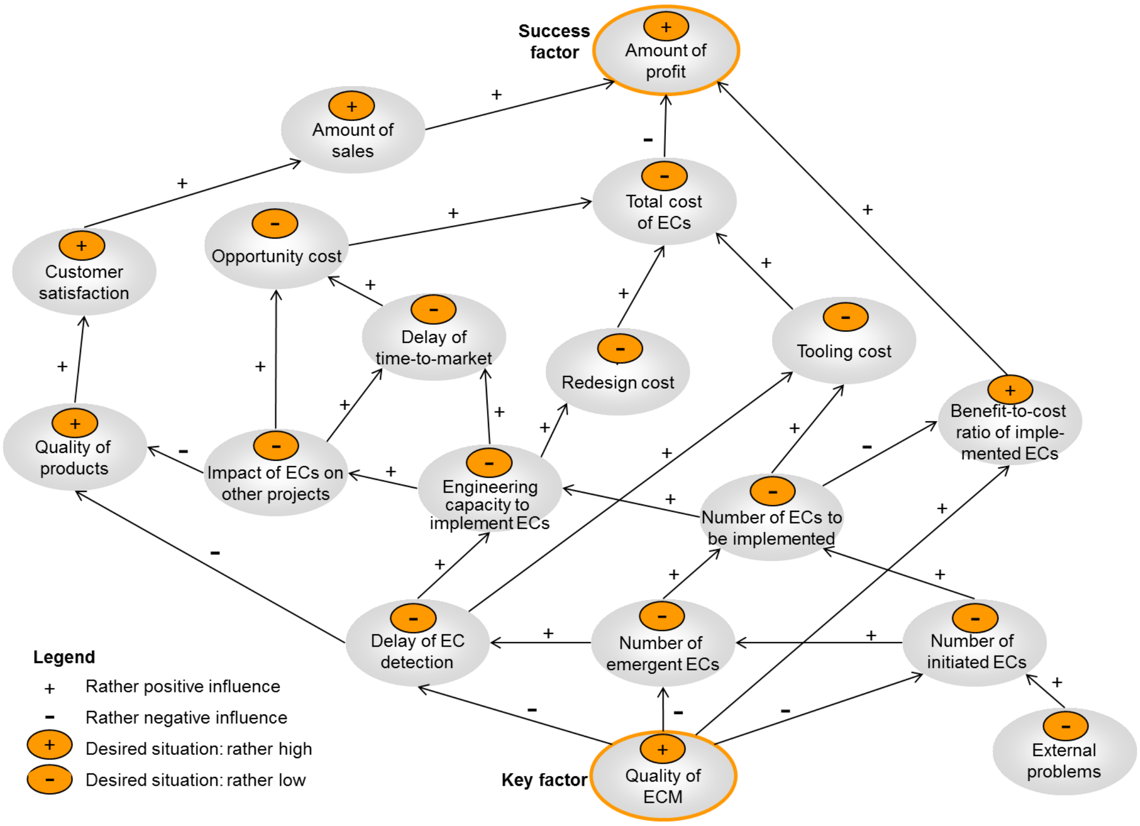


Figure 3: Network of influencing factors (desired status)

Source: Adapted from Blessing and Chakrabarti (2009)

1.1.4 Ways to improve ECM

In order to solve the problems caused by ECs and their uncontrolled propagation, an adequate change management is needed. Several authors have proposed guidelines for appropriate change management (Reidelbach 1991, Terwiesch and Loch 1999, Fricke *et al.* 2000). Widely accepted are those suggested by Fricke et al. (2000): (1) *Less*, (2) *Earlier*, (3) *More effective*, (4) *More efficient*, and (5) *Better*.

1. *Less* aims at a reduction of the number of ECs by preventing avoidable ECs. This strategy is supported by Clark and Fujimoto (1991) who stated that up to 66% of all ECs could be prevented by improving communication and discipline in decision-making. Furthermore, this strategy deals with increasing product robustness which reduces both the number of initiated and emergent changes.

2. *Earlier* aims at the earlier detection and implementation of emerging changes. The rationale behind this strategy is the so called *Rule of Ten* (e.g. Clark and Fujimoto 1991, Fricke *et al.* 2000), describing the exponential increase of EC costs by a factor of ten with each phase of the product life-cycle.

3. *More effective* aims at more specific assessment of the necessity and benefit of changes. Only ECs that are technically necessary or have a positive effort-to-benefit

ratio should be implemented. The results of a case study by Fricke and colleagues suggest that 50% of all ECs are technically unnecessary and thus could be declined based on economic evaluation.

4. *More efficient* aims at an optimisation of the change implementation process to reduce required resources, time, and cost.
5. *Better* aims at continuously increasing effectiveness and efficiency of ECM by putting in place an intelligent knowledge management system in order to learn from previously performed ECs.

The impact of these guidelines is demonstrated in the network of influencing factors (Figure 4). This network shows that an improvement on any one of these guidelines can be linked to an increase of the amount of profit.

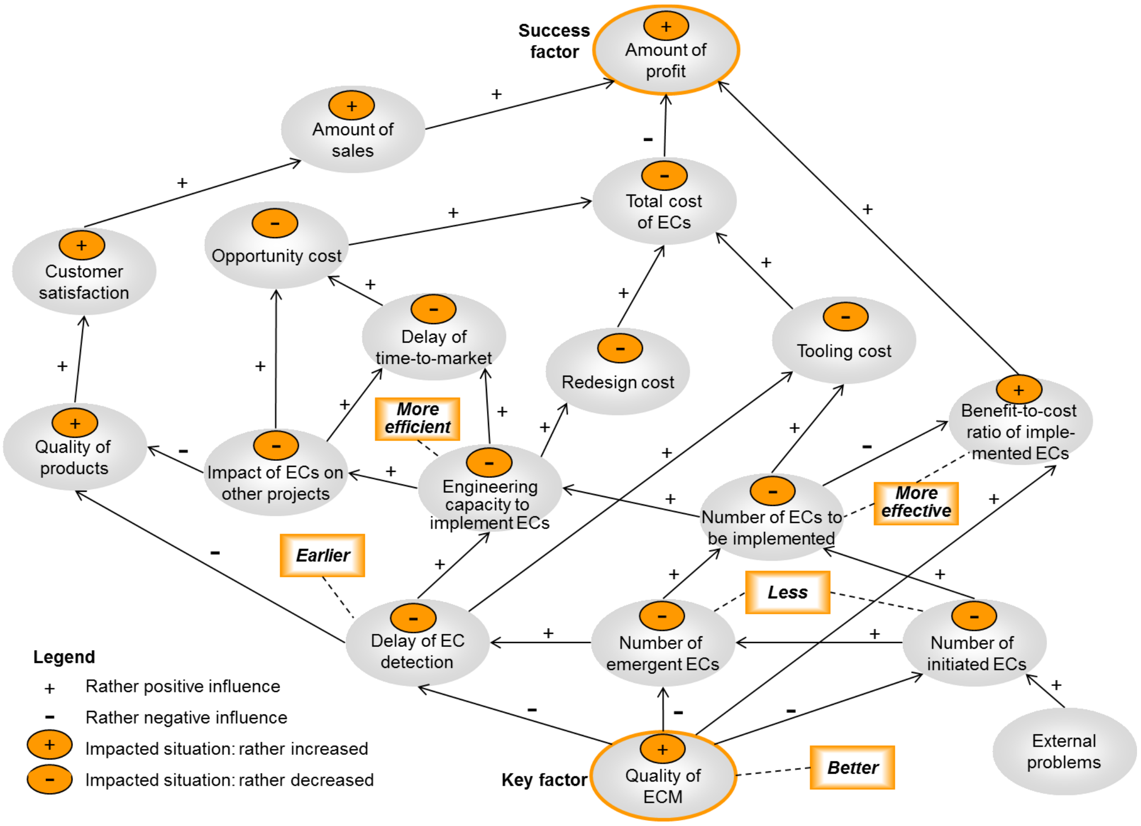


Figure 4: Network of influencing factors (impact model)

Source: Adapted from Blessing and Chakrabarti (2009)

In order to improve ECM, a number of ECM methods were proposed (Jarratt *et al.* 2011). These methods predominantly focus on the guidelines *Earlier*, *More effective*, and *More efficient* and accept the number of raised changes (i.e. *Less*) as well as the ECM learning curve and continuous improvement potential (i.e. *Better*) as being predetermined. This is reasonable because *Less* and *Better* may be achieved by other methods related to robust product architecture design, communication, and knowledge management while *Earlier*, *More effective*, and *More efficient* must be directly addressed by an ECM method. This understanding helped to draw a more specific research question from the overall research objective as will be discussed in the next section.

1.2 Research objective and hypothesis

As discussed in the previous subsection, ECs are an important aspect of PD; their propagation can cause severe profit losses; and adequate management of ECs can improve the cost, quality, and time-to-market of products. Therefore, the overall objective of this research was broadly formulated by referring to the desired status as depicted in Figure 3:

Overall research objective:
Improve the quality of ECM.

This objective is very comprehensive and allows many potential research questions. In order to narrow down the research scope and focus on the most promising areas, the following hypothesis based on the discussion in Subsection 1.1.4 was used:

Research hypothesis:
The predictive capability of ECM methods can be improved by more detailed modelling of the interactions between components.

This thesis sets out to test this hypothesis by elaborating the current understanding of ECs and ECM in literature, identifying the-state-of-the-art of research in ECM and current ECM methods, and developing and evaluating a more comprehensive ECM method.

To guide the course of this research, sequentially individual goals for the thesis chapters were developed and correspondingly addressed throughout the thesis. These goals were formulated as questions and termed *"research questions"* here; however, they refer to the research steps required to be investigated in order to explore the research hypothesis.

To establish an understanding about ECs and ECM, the first research question (RQ) formulated was:

RQ1: What is the current understanding of ECs and ECM in literature?

This question was answered by reviewing the key publications on ECs and ECM and elaborating on the main themes. The understanding generated from the answer to *RQ1* determined the formulation of the second research question:

RQ2: What is the state-of-the-art of research in ECM and which ECM methods exist?

This question was answered through a systematic literature search and categorisation and the use of these results to identify available ECM methods. While the answer to *RQ1* created the understanding of ECs and ECM, the answer to *RQ2* delivered the publications and ECM methods database for this research. Both answers guided the course of this research towards the development of an ECM method and determined the remaining research questions:

RQ3: What are the requirements for ECM methods and how well do current ECM methods perform against these requirements?

RQ4: What should be included in the concept of the ECM method to be developed?

RQ5: What are the detailed elements required to realise the chosen ECM method concept?

RQ6: How well does the developed ECM method perform in real world case studies?

These questions are stated here in their final formulation as specified after the answers to the first two research questions were available. They were addressed consecutively. The answer to *RQ3* delivered the requirements for an ECM method and an assessment of current methods against these requirements. This evaluation identified potential limitations and research opportunities which were used to address *RQ4* by developing the conceptual design of an improved ECM method. Then, as answer to *RQ5*, its detail design was developed. Finally, *RQ6* required an application to practice and evaluation of the developed method.

1.3 Scope of the research

1.3.1 Objects of investigation

Design may refer to *artefacts, software, services, processes,* and *organisations.* The objects of investigation of this research are technical artefacts and the corresponding design processes. *Artefact* comes from the Latin *arte factum* and means *a product of human art or workmanship*. *"Technical artefacts such as typewriters, hammers, copying machines or computers are different from social artefacts such as laws or money in that the realization of their function crucially depends on their physical structure. They are also different from physical or natural objects because they are intentionally produced and used by human beings to realize certain goals"* (Kroes and Meijers 2006, p. 1). Technical artefact may refer to objects at any level of product decomposition, e.g. single part, component, subsystem,

system, or the whole product itself. It is important to note that design produces the specifications and documentation for these artefacts, while their physical embodiment is produced later by manufacturing. Thus, artefact in the context of design refers to the specifications and documentation rather than the physical artefact itself. Technical artefacts can be categorised in terms of their complexity which could be measured for example by the number of constituent single parts and their interconnections. A threefold classification includes low complex (e.g. bottle, buzzer, table), medium complex (e.g. bike, hairdryer, camera), and high complex (e.g. aero engine, car, airplane) technical artefacts. The target artefacts of this research are those with medium to high complexity. However, technical artefacts of low to medium complexity will be used to develop and demonstrate ideas and methods, before testing them on technical artefacts of higher complexity.

1.3.2 Value chain and stakeholders

The *value chain* describes all of the activities related to an artefact, software, or service from the initial conception to final disposal after its use. Kaplinsky and Morris (2001) published a handbook for value chain research in which they present a four-stage simple value chain existing of: (1) *Design and PD,* (2) *Production,* (3) *Marketing*, and (4) *Consumption and recycling*. This research deals with engineering design and focuses on the activities within the *Design and PD* stage. Pahl et al. (2007) divide the latter into four sub stages: (1) *Planning and clarifying the task*, (2) *Conceptual design*, (3) *Embodiment design,* and *(4) Detail design.* The first sub stage deals with market analysis, product idea generation, and requirements formulation. This stage is fuzzy and not relevant for ECs, which is why it is out of the scope of this research. All other three sub stages are relevant for this work. The focus is more on the end of *Embodiment design* and *Detail design* because most rework caused by ECs happens in those sub stages. The direct stakeholders of this research are designers and other engineers or decision makers involved in activities within the *Design and PD* stage as well as design researchers.

1.4 Research methodology

1.4.1 Methodologies for design research

According to the Oxford English Dictionary, *methodology* can be defined as *"a system of methods used in a particular area of study or activity"*. Silverman (2006, p. 13) distinguished between methodology as "*a general approach to studying research topics*" and method as "*a specific research technique*" for attaining some objective. Blessing and Chakrabrati (2009) described a research methodology as a framework that helps develop and validate knowledge systematically, at the same time ensuring that the research is scientific and delivers valid results. In fact, Frankfort-Nachmias and Nachmias (1996) argued that the methodology makes a topic of investigation become scientific. Thus, the choice of a research methodology is crucial for a Ph.D. project. The methodology guides the selection and application of a suitable overall approach and appropriate specific techniques in order to make research more effective and more efficient towards the achievement of the research goal (Blessing and Chakrabarti 2009).

In the relatively young discipline of design research, a few methodologies for design research have been proposed (see e.g. Antonsson 1987, Duffy and O'Donnell 1999, Eckert *et al.* 2003, Blessing and Chakrabarti 2009). These methodologies have in common an emphasis on the formulation of hypotheses and contain descriptive and prescriptive studies.

Duffy and O'Donnell (1999) proposed a general research methodology consisting of six steps (Figure 5). This methodology is based on the design research framework by Duffy & Andreasen (1995) which describes conducting design research as the development of prescriptive and descriptive models and their evaluation to improve design performance. The methodology suggests that design research should draw design problems from both existing literature and design practice. The literature should then be examined in order to develop a hypothesis of how design can be better supported, formulate a research problem, and develop a solution for the problem. The solution should be evaluated in design practice and eventually documented. However, Duffy and O'Donnell (1999) did not explain their approach in more detail; suitable methods, deliverables, and possible iterations were not discussed.

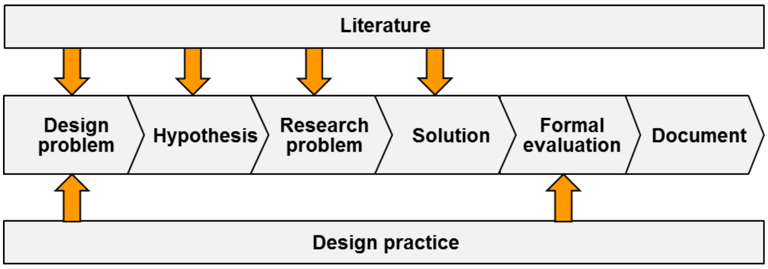


Figure 5: General six-step design research methodology

Source: Adapted from Duffy and O'Donnell (1999)

Blessing and Chakrabarti (2009) proposed the Design Research Methodology (DRM). DRM considers the two main strands of design research to be the development of understanding and the development of support. It is concerned with structuring design research and taking it through from empirical studies of designing to the introduction of new methods and tools to improve design. DRM is in particular useful for formulation and validation of methods and tools because it incorporates clearly defined criteria of success measurement. These criteria ensure that the research is undertaken with a clear goal and produces methods and tools as solution to a prior defined problem. The framework consists of four main stages with recommended basic means and defined main outcomes and deliverables (Figure 6).

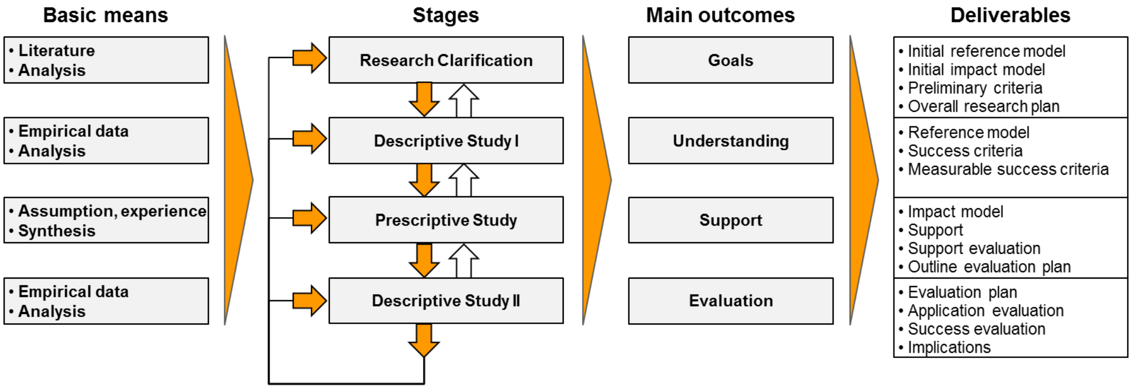


Figure 6: The DRM framework

Source: Adapted from Blessing and Chakrabarti (2009)

1. *Research Clarification* is concerned with defining the research goal and the scope of the following stages. The main deliverable of this stage is an overall research project plan.
2. *Descriptive Study I* deals with literature review and/or empirical studies to increase understanding of the research problem. The role of this stage is to identify factors that influence the measurable success criteria and to establish a state-of-the-art on the basis of which support can be developed to improve the design practice.
3. *Prescriptive Study* deals with the development of design support tools in form of an impact model or theory describing the expected improved situation.
4. *Descriptive Study II* deals with two types of evaluation of the developed design support - *Application evaluation* and *Success evaluation*. The former assesses whether the support can be used in the situation for which it is intended, and the latter assesses the usefulness, the implications, and the side-effects of the support.

1.4.2 Adopted methodology for this research

For this research, DRM has been enhanced with the methodology proposed by Duffy and O'Donnell (1999) (Figure 7). Both methodologies complement each other - DRM being helpful with the overall guidance of the project and with the developing and testing of solutions and Duffy and O'Donnell's methodology being more helpful in the beginning when a design problem is narrowed down by hypotheses to a research problem.

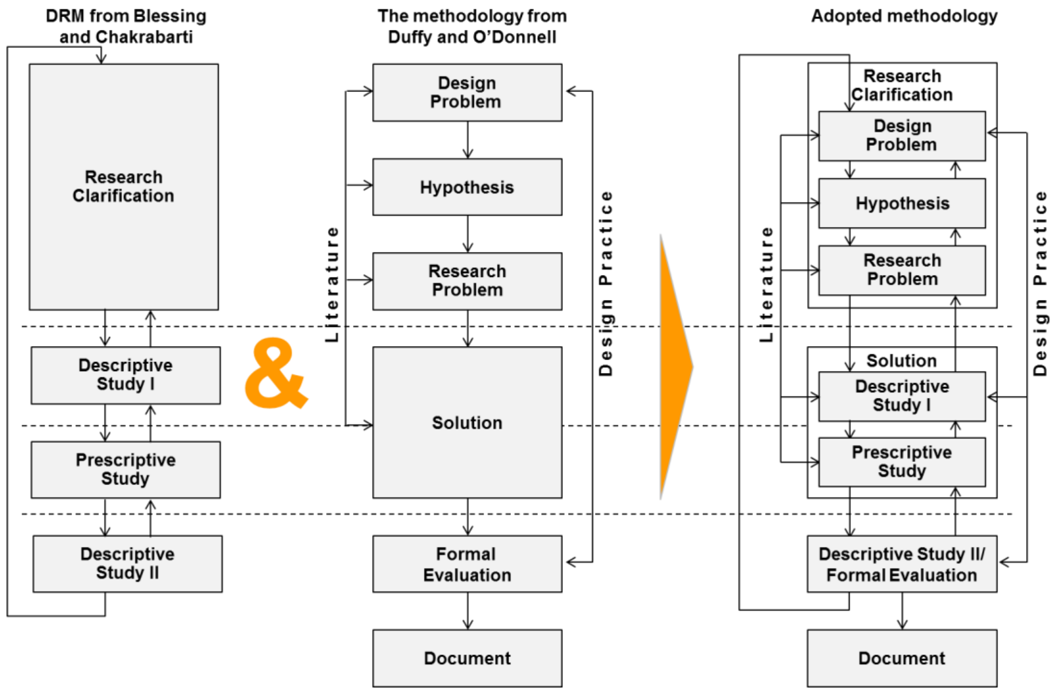
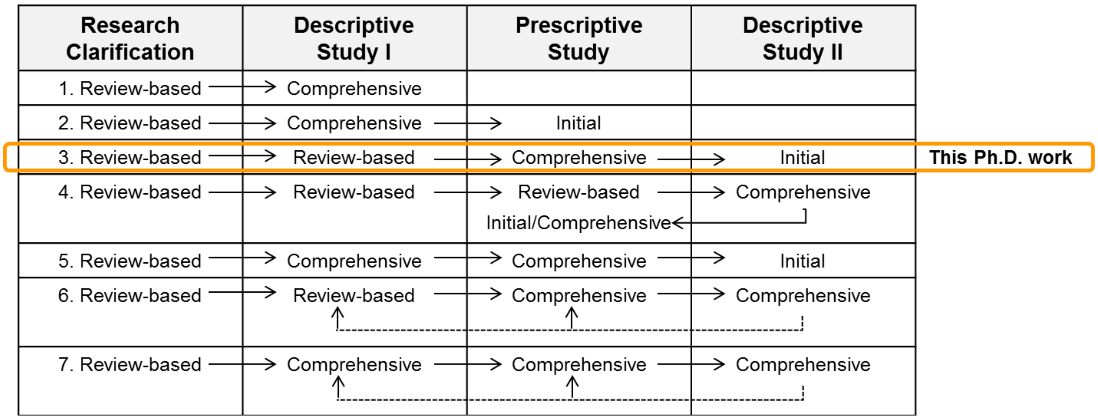


Figure 7: Adopted research methodology

Blessing & Chakrabarti (2009) acknowledged that it is unlikely for one research project to encompass all DRM stages in equal depth and classified seven different *types of research projects* (Figure 8).



Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II	
1. Review-based →	Comprehensive			
2. Review-based →	Comprehensive →	Initial		
3. Review-based →	Review-based →	Comprehensive →	Initial	**This Ph.D. work**
4. Review-based →	Review-based →	Review-based → Initial/Comprehensive ←	Comprehensive	
5. Review-based →	Comprehensive →	Comprehensive →	Initial	
6. Review-based →	Review-based →	Comprehensive →	Comprehensive	
7. Review-based →	Comprehensive →	Comprehensive →	Comprehensive	

Figure 8: Types of research projects and their focuses in DRM

Source: Adapted from Blessing and Chakrabarti (2009)

Dependent on the state-of-the-art associated with a particular stage and the resources available, the focus of the research project changes. For instance, if for a particular stage results are available, a literature review is sufficient, but if there are no results available, a comprehensive study (literature review plus additional work, e.g. empirical study) is required. The first four types of research projects are recommended for Ph.D. work. Projects of *types 5* and *6* are highly desirable but often unattainable in Ph.D. projects due to time and resource constraints. *Type 7*, which is the only type with three comprehensive studies, is more common for joint efforts undertaken by a research group. This Ph.D. work adopted the third research type and proceeded as follows.

1. In the *Research Clarification* stage, the literature was searched and complemented with insights obtained from discussions with the supervisors of this research as well as industry collaborators from the author’s group to define the research goal and develop an overall research project plan (Chapter 1).
2. In the *Descriptive Study I* stage, the literature on ECs and related areas was reviewed to increase understanding of the research problem (Chapter 2). ECM methods were searched in literature, and the associated publications and tools were reviewed to establish a state-of-the-art in ECM (Chapter 3).
3. In the *Prescriptive Study* stage, the understanding obtained from literature in the previous stages was complimented with industry experience from the author’s group to develop a set of requirements for ECM methods, and use them as criteria to assess eight promising ECM methods (Chapter 4). A concept for a design support method was formulated (Chapter 5), and this concept was detailed into the proposed FBS Linkage method (Chapter 6).
4. In the *Descriptive Study II* stage, an initial evaluation of the developed method was conducted based on case study applications and expert interviews (Chapter 7). The method was applied to two complex designs and the results were demonstrated to industry experts, who then assessed the method.

These four stages were not conducted in a strict sequential order but partly simultaneously and iteratively throughout the whole research project.

1.5 Thesis structure and dissertation summary

The overall structure of this thesis in the context of the adopted methodology is depicted in Figure 9. The thesis is structured in eight consecutive chapters which build on each other and proceed as follows.

Chapter 1 provided an introduction to the thesis by elaborating the motivation of this research, stating the research questions, setting the research scope, discussing the applied research methodology, and providing an overview of the thesis structure.

Chapter 2 addresses the first research question by establishing the background of ECM. It reviews the literature relevant for this research, provides a definition and description of ECs and their management, discusses strategies, methods, and tools of ECM, and elaborates functional reasoning (FR) and modelling approaches.

Chapter 3 addresses the second research question by elaborating on the state-of-the-art of ECM research in the broader sense and ECM methods in particular. It proceeds in three steps. First, it presents a holistic literature categorisation framework which helps to structure research in ECM. Second, based on a systematic literature search, it provides a relatively complete state-of-the-art picture of research in ECM by positioning 427 relevant publications in the proposed framework. Third, the categorisation is used to develop a list of current ECM methods and indicate the guidelines that they address.

Chapter 4 addresses the third research question by developing a set of requirements for ECM methods and evaluating current ECM methods against this list. The comparative assessment shows that overall the Change Prediction Method (CPM) is the superior method, but it can be improved with regard to some of the requirements by learning from other methods.

Chapter 5 addresses the fourth research question by developing the conceptual design of the proposed FBS Linkage method. Thereby, it follows a systematic benchmarking approach based on the comparative evaluation of ECM methods from Chapter 4. The FBS Linkage method integrates two established concepts, namely: CPM and FR.

Chapter 6 addresses the fifth research question by elaborating the detail design of the FBS Linkage method. The method’s FR scheme is developed based on a detailed comparison of three seminal FR schemes complemented with improvements to meet the requirements of change propagation modelling. This scheme is then integrated to the CPM approach by replacing CPM’s component dependency model. The modelling technique is detailed and demonstrated using a hairdryer as a simple example. Finally, the benefit and effort of the method are discussed.

Chapter 7 addresses the sixth research question by presenting the application of the FBS Linkage method to a diesel engine and to a scanning electron microscope and its evaluation based on that. The evaluation shows that the method is both feasible for complex designs and usable for supporting ECM.

Chapter 8 concludes the thesis. The dissertation is summarised, key findings and contributions are highlighted, the FBS Linkage method is reflected to the research hypothesis, limitations are stated, and future work is outlined.

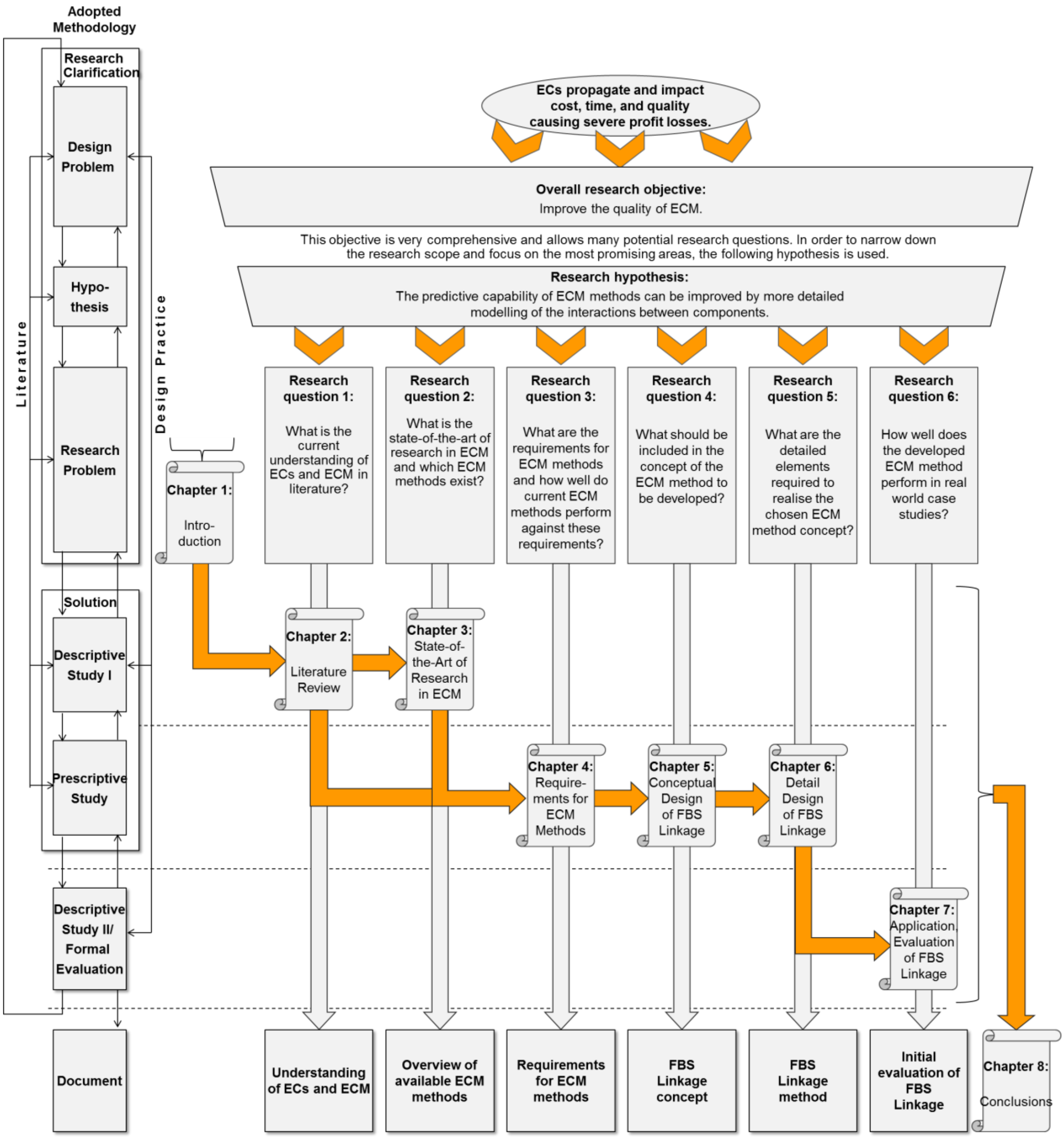


Figure 9: Overall structure of thesis in the context of the adopted methodology

2 Literature Review

“Life belongs to the living,
and he who lives must be prepared for changes.”
(Johann W. von Goethe, German writer, 1749-1832)

2.1 Chapter introduction

The previous chapter discussed change propagation as one of the main challenges of ECM and specified the objective of this research to the development of an appropriate ECM method. To lead the course of this research towards its objective, an initial research question was formulated (RQ1: What is the current understanding of ECs and ECM in literature?). This chapter addresses that question by reviewing the literature on ECM and elaborating the key themes. Furthermore, research on functional modelling and reasoning is discussed here because it will be used in the following chapters.

The chapter is organised in four remaining sections. Section 2.2 elaborates EC and ECM. Section 2.3 presents ECM methods. Section 2.4 discusses functional reasoning and modelling approaches. Finally, Section 2.5 summarises the chapter.

2.2 EC and ECM

2.2.1 Defining EC and ECM

Different terms and definitions for EC can be found in the literature. Other slightly differing terms used for EC are *engineering design change* (Leech and Turner 1985), *product change* (Inness 1994, Ulrich 1995), *design change* (Ollinger and Stahovich 2004), or simply *change* (Fricke *et al.* 2000).

The most seminal definitions for EC are:

- *“An engineering change (EC) is a modification to a component of a product, after that product has entered production”* (Wright 1997, p. 33).
- *“[Engineering changes are] the changes and modifications in forms, fits, materials, dimensions, functions, etc. of a product or a component”* (Huang and Mak 1999, p. 21).
- *“Engineering change orders (ECOs) [are] changes to parts, drawings or software that have already been released”* (Terwiesch and Loch 1999, p. 160).
- *“Engineering changes are changes and/or modification in fits, functions, materials, dimensions, etc. of a product and constituent components after the design is released”* (Huang *et al.* 2003, p. 481).
- *“An engineering change is an alteration made to parts, drawings or software that have already been released during the product design process. The change can be of any size or type; the change can involve any number of people and take any length of time”* (Jarratt *et al.* 2004c, p. 268).

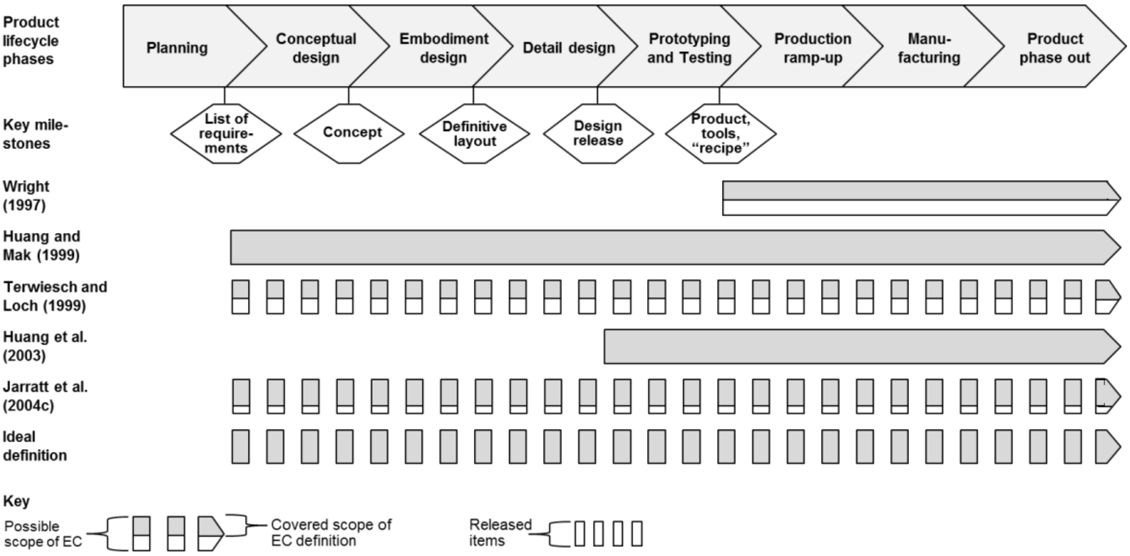


Figure 10: Mapping of EC definitions to the product lifecycle

The difference between these definitions can be visually demonstrated by mapping them against a product lifecycle as proposed by Pahl et al. (2007) and Ulrich and Eppinger (2010) (Figure 10). This mapping and comparison with an *ideal definition* shows that none of these definitions is comprehensive and distinctive enough – *comprehensive* referring to both the scope of the definition (represented by the height of the grey filling of the bars) and the lifecycle coverage (represented by the length of the bars) and *distinctive* referring to the distinguishing of ECs from design iterations (represented by the small bars with gaps in between).

As depicted in Figure 10, Wright's definition covers only changes during the production stage and ignores changes during the PD and testing stages. Huang and Mak (1999) included in their definition a wider scope of ECs but left out the time aspect required to distinguish ECs from design iterations. In contrast to ECs, the latter usually occur before the release of documents. Iterations are inevitable for creative design processes which are characterised by a concurrent exploration of problem and solution space (Lawson 1980, Dorst and Cross 2001). Wynn *et al.* (2007) explored the nature of iterations and categorised them into *rework-related, convergence-related*, *refinement-related*, and *repetition-related.* The definition given by Terwiesch and Loch (1999) draws the line between ECs and design iterations by restricting the time of ECs to the post-release phase. In addition, it enhances the scope of ECs to embedded software, which is essential for most modern high-tech products. Also Huang *et al.* (2003) added the time aspect to their initial definition. Jarratt *et al.* (2004c) gave the most comprehensive definition but omited functions from the scope.

In order to cover a wide range of research on ECM, a broader definition of ECs drawing on the definitions by Huang *et al.* (2003) and Jarratt *et al.* (2004c) is used in this work:

Engineering Changes (ECs) are changes and/or modifications to released structure (fits, forms and dimensions, surfaces, materials etc.), behaviour (stability, strength, corrosion etc.), function (speed, performance, efficiency, etc.), or the relations between functions and behaviour (design principles), or behaviour and structure (physical laws) of a technical artefact.

The adjective *technical* in this definition is used in the broader sense to differentiate ECs from changes to non-technical artefacts such as social (e.g. laws) or artistic (e.g. painting). *Artefact* is an umbrella term which may refer to a single part, a component, an assembly, a system, or a whole product. Software and controller units may be parts of such technical artefacts and are included in this definition. The terms *structure, behaviour,* and *function* are used as defined by (Gero and Kannengiesser 2004): Structure defines, what an artefact is; behaviour describes, what it does; and function prescribes, what it is for. Changes to the manufacturing process or tools are not automatically ECs but can lead to those when they entail changes to released product attributes.

This definition is in consensus with the five modes of incremental change in design as developed by McMahon (1994), who distinguished between *explicit* and *implicit attributes*. Explicit attributes are those required on the drawings, technical documents, etc. in order to produce the product, whereas implicit attributes emerge from them. The former determine the product's structure and the latter its behaviour and function. Based on a framework consisting of these attributes, a design space, and product requirements, McMahon (1994) defined five modes of incremental change in design which lead to development of designs over time. These modes can be mapped to the product layers – structure, behaviour, and function – as shown in the following table.

Table 1: Mapping of McMahon's modes of design change to the product layers

McMahon's modes of design change (McMahon 1994)	Product layer
1. Parameter space exploration. Variation of explicit attributes within the limits imposed by feasible explicit attribute set.	Structure
2. Improved understanding of explicit-implicit attribute relationships. Exploiting an improved understanding of the relationships relating implicit to explicit values through improved analytical techniques, modelling or mathematical methods, experiments, etc.	Structure-behaviour relation (physical laws)
3. Change in product design specification. **3i.** Change in the specified values of implicit or explicit attributes or external factors that the design must meet. **3ii.** Change in utility function for the design, e.g. emphasis in automotive design from performance to economy. **3iii.** Extension of the set of functional requirements that the design has to meet.	Behaviour Function Function
4. Modifying the feasible design space. Development of the design due to change of explicit attribute space as a result of innovation e.g. by manufacturing process improvement such as reduction of minimum wall thickness for a casting.	Structure
5. Changing the design principle. Adoption of an alternative design principle with different design space.	Behaviour-function relation (design principles)

ECM refers to the organisation, control, and execution of ECs (Jarratt *et al.* 2011) and covers the product life cycle from the selection of a concept to the wind-down of production and support. ECM can be summarised according to its goals: to (1) avoid or reduce the number of engineering change requests (ECRs) before they occur, (2) detect them early when they occur, (3) address them effectively, (4) implement them efficiently, and (5) learn continuously for the future. These five goals correspond to the five guidelines discussed by Fricke *et al.* (2000), namely: *Less, Earlier, More effective, More efficient,* and *Better*. ECM can be regarded as the core of the larger configuration management (Jarratt *et al.* 2011). The latter deals with establishing and maintaining consistency of a product's performance, functional, and physical attributes with its requirements, design, and operational information throughout its life (ANSI/EIA 1998). Configuration management is an integral discipline within systems engineering (see e.g. Shishko and Chamberlain 1995, Sage and Rouse 1999). However, the focus of this work is ECM.

2.2.2 Relevance of EC in the context of design

The process of designing rarely starts from scratch but rather by modification of existing products (Bucciarelli 1994, McMahon 1994, Cross 2000). On the basis of research effort, knowledge and skill, and creativity required in the designing process, a broad classification of design into two types is without controversy (Pahl *et al.* 2007):

- The first case where a new product is entirely designed from scratch is generally referred to as *original design* (Otto and Wood 2001, Pahl *et al.* 2007). Other terms used to address this type are *novel design* (Prebil *et al.* 1995) or *creative design* (Gero 1990). Original designs usually require much research, knowledge, skill, and creativity (Pahl *et al.* 2007).

- The second case where a product is designed by modification of an existing one is known as *evolutionary design* (Frazer *et al.* 2002, Kicinger *et al.* 2005). This design type is initiated and driven by ECs. Some authors distinguish between two different types of evolutionary design, e.g. *routine design* and *innovative design* (Gero 1990), or alternatively *variant design* and *adaptive design* (Otto and Wood 2001). Variant design refers to designs with different values of specific parameters of the design elements, whereas adaptive design refers to designs with different specific design elements (Otto and Wood 2001). Evolutionary designs usually require less effort than original design.

Other authors distinguished between four different design types, e.g. *variant design, adaptive design, innovative,* and *original design* (e.g. Tavcar and Duhovnik 2005). In practice, it is difficult to decide of which type a product is as the boundaries are not clear (Jarratt 2004). However, it is generally accepted that the vast majority of designs are adaptive and variant design. Hence, *“it is absolutely necessary to understand changes and to have a good grip on them, as the entire PD process can be described as a continuous change management process”* (Fricke *et al.* 2000, p. 177).

2.2.3 EC propagation

Change propagation is the chain reaction that occurs when one change causes another change nearby, which then causes further changes, and so on, leading to a spread of changes. As engineering products are composed of many interdependent parts, this is a very common phenomenon. It can be well-compared to the domino effect, a term used for chain reactions as an analogy to a row of dominoes which fall one after the other. However, EC propagation is more complicated than the domino analogy suggests. In case of ECs, the dominoes (i.e. components, attributes, etc.) and their positions in the row (i.e. interdependencies) is difficult to determine, the dominoes have complex behaviours (i.e. change effect), and are more likely to be arranged in branching rows and cycles (i.e. a network of interdependent components). Moreover, EC propagation is affected by human intervention. A very clear example of change propagation comes from the Smart Tool Lab research group; their case illustrates how a change to a car rear window propagated over several intermediate components all the way to the front bumper (Smart-Tools-Lab 2005):

"For aesthetic reasons, it was decided that the rear window [of a car under development] should be given a shallower slope... [This] allowed more snow and ice to accumulate in the winter, thus necessitating a larger rear window defroster. Testing identified that the larger defroster had overloaded the electrical system, and thus a larger alternator was needed. The larger mass of the new alternator caused a vibration problem, thus necessitating larger structural supports. Eventually it was determined that these extra supports reduced the crush space for front end collisions, finally resulting in a redesign of the front bumper."

2.2.4 Characterising ECs

ECs can be characterised according to different facets (see e.g. Saeed *et al.* 1993, Lee *et al.* 2006, Eckert *et al.* 2009, Rowell *et al.* 2009, Sudin and Ahmed 2009, Jarratt *et al.* 2011, Maier and Langer 2011), a few of which are presented in the following.

Domain of origin (where changes arise from): The initial change which is raised by sources external to the product domain is termed *initiated change* (Eckert *et al.* 2004). The implementation of an initiated change usually produces knock-on effects on other components, which in turn lead to induced or *emergent changes* (Eckert *et al.* 2004). They are also conferred to as external changes and internal changes respectively (Rowell *et al.* 2009). *"Internal changes tend to be involuntary, representing mistakes, assumptions or inaccuracies, which are identified and amended accordingly"* (Rowell *et al.* 2009, p. 2).

Time of origin (when changes arise): ECs are raised from the point of time when initial design documentations are released throughout the product lifecycle to the wind-down of production and support. Pikosz and Malmqvist (1998) proposed a time-based categorisation focused on the stages of PD. They differentiated between changes caused during the customer requirement phase, the technical requirement phase, the fabrication or assembly phase, the prototyping phase, the quality control phase, and the development phase for future product revisions. Surveys show that more than half of all changes occur whilst the product is already in production or released to the market (Ahmed and Kanike 2007, Maier and Langer 2011). This is remarkable when considering the exponential cost increase along the lifecycle stages - development, prototype testing, manufacturing, and field. The costs of change implementation are estimated to increase by a factor of ten along these lifecycle stages, i.e. changes in the prototyping phase are ten times more expensive than changes in the development phase (Huang and Mak 1999, Fricke *et al.* 2000).

Purpose (why changes arise): ECs are raised for two fundamental reasons (Eckert *et al.* 2004):

1. to improve, enhance, or adapt the product to new requirements, and
2. to remove mistakes, or make the product work properly.

These categories overlap mostly with the distinction between initiated and emergent changes. Changes from the first category are initiated and the majority of changes from the second category are emergent.

Initiator (who or what initiates changes): ECs are raised by a number of different initiators; they can be grouped into company-internal and company-external. Internal initiators are management, design office, purchasing department, shop floor workshop, quality control department, marketing department, etc. External initiators are, for instance, customers, suppliers, and lawmakers. Huang et al. (2003) listed the following initiators in their questionnaire: design office, purchasing department or suppliers, shop floor workshop, quality control department, industrial department, marketing department or customers, and the store. They found that design office, shop floor workshop, and customers were the three main initiators of ECs. These findings were supported by the survey from Maier and Langer (2011).

Cause (why changes arise)*:* The causes or drivers of ECs can root in different areas, e.g. product, company, industry, user, environment, etc. Based on a literature review, Lee *et al.* (2006) grouped the causes into six clusters: careless mistakes, poor communication, snowballing change, cost saving, ease of manufacturing, and product performance improvement. Rowell et al. (2009) listed also external causes such as contract scope change and customer requirements.

A two-dimensional scheme of EC causes, plotting the domain facet against the time facet, was suggested by Eckert et al. (2004). The domain facet includes the distinction between initiated and emergent changes. The time facet covers the three phases: pre-contract, designing and manufacturing, and post-delivery. In this work, an extension to that work has been developed – a three-dimensional scheme. As depicted in Figure 11, the scheme allows categorisation of EC causes considering the time facet on the horizontal axis, the domain facet on the vertical axis, and the initiator facet by boxes. The time axis applies only to changes raised within the designing and manufacturing phase.

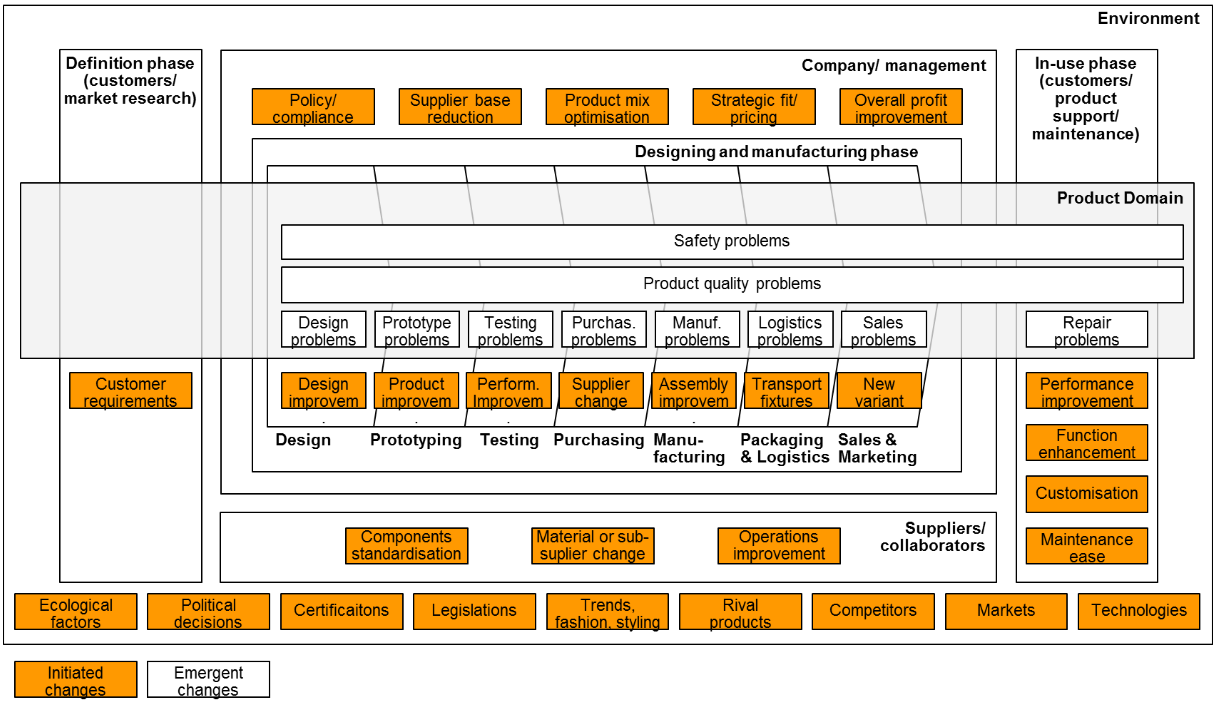
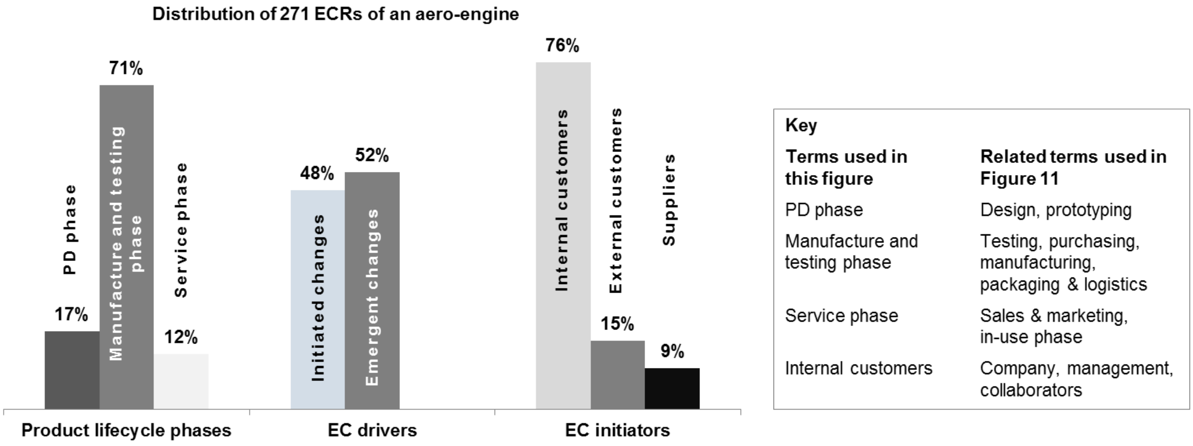


Figure 11: Classification of EC causes

Eckert et al. (2009) conducted a survey among nine companies from different industries and found that ECs due to regulations, technology, requirements, and project management are prevalent across all companies. Maier and Langer (2011) found that *insufficient clarification of requirements* followed by *human error in process execution* is the most common cause.

Sudin and Ahmed (2009) calculated the distribution of 271 ECRs to the product specifications of an aero-engine according to different criteria (Figure 12). On the time scale, the majority (71%) of ECs are raised during the testing, purchasing, manufacturing, packaging & logistics phase; the purpose of changes is rather (52%) error correction than product improvement; and the majority (76%) of initiators are from the company and collaboration-network.



Terms used in this figure	Related terms used in Figure 11
PD phase	Design, prototyping
Manufacture and testing phase	Testing, purchasing, manufacturing, packaging & logistics
Service phase	Sales & marketing, in-use phase
Internal customers	Company, management, collaborators

Figure 12: Distribution of ECRs

Source: Adapted from Sudin and Ahmed (2009)

In their ECM report, Maier and Langer (2011) surveyed more than 90 engineering firms in Denmark. Their results support the findings from Sudin & Ahmed to a large extend. They found that: (1) most of the ECs occur in the later phases of the PD process when the product is already in production or released to market, (2) around half of the ECs are to improve the product or integrate new innovative technologies and the other half stem from change propagation and are to remove problems, and (3) customers, end-users, market trends, development and R&D are the top initiators.

2.2.5 Prioritisation of ECs for execution order

The above discussed classification scheme cannot be used directly to decide on the execution order of ECs. To do so, their urgency must be assessed. Dale (1982) observed three different change types according to their urgency in practice: *emergency*, *as-soon-as-possible*, and *phase-in*. Similarly, DiPrima (1982) proposed the urgency categories: *immediate* for safety and defect-related ECs that must be implemented immediately, *mandatory* for ECs that must be implemented but have some flexibility in timing, and *convenient* for less urgent, improvement ECs which should be phased-in.

Maull et al. (1992) prioritised ECs according to their impact on the company to *A*, *B, C,* and *D class* changes: A class changes occur for safety or technology reasons and are mandatory; B class changes are brought about by competitive moves and are required; C class changes provide minor competitive improvements and are convenient; D class changes are discretionary and can be implemented with low effort. A class changes are implemented immediately and B class changes as soon as possible, whereas C and D class changes are phased-in.

2.2.6 EC process

Generic ECM process models have been proposed on different levels of abstraction. Dale (1982) split the process into two stages: *procedure to approval of ECs* and *procedure on approval*. Maull et al. (1992) proposed an IDEF0 model of the EC control process including the five key activities: *(1) filter proposal, (2) design investigation, (3) appraise design, (4) authorise change*, and *(5) execute change.* Riviere et al. (2002) proposed a three-stage process model including *(1) EC proposal, (2) EC investigation*, and *(3) EC embodiment*. For each stage, they suggested more detailed process steps. A four-stage model for the formal process of ECs was proposed by Lee et al. (2006), including the stages *(1) initiating an engineering change request (ECR), (2) evaluating the ECR, (3) issuing engineering change orders (ECOs) to relevant participants*, and *(4) storing and analysing the ECOs for management purposes.*

Jarratt et al. (2004c) proposed a more comprehensive process model including six steps structured in three stages (Figure 13). This generic process covers the complete life cycle of ECs, from their initiation over their implementation to their review. Furthermore, the two most likely iterations and four possible break points, at which the change process can be brought to a halt by the control mechanism, are marked in the process chart.

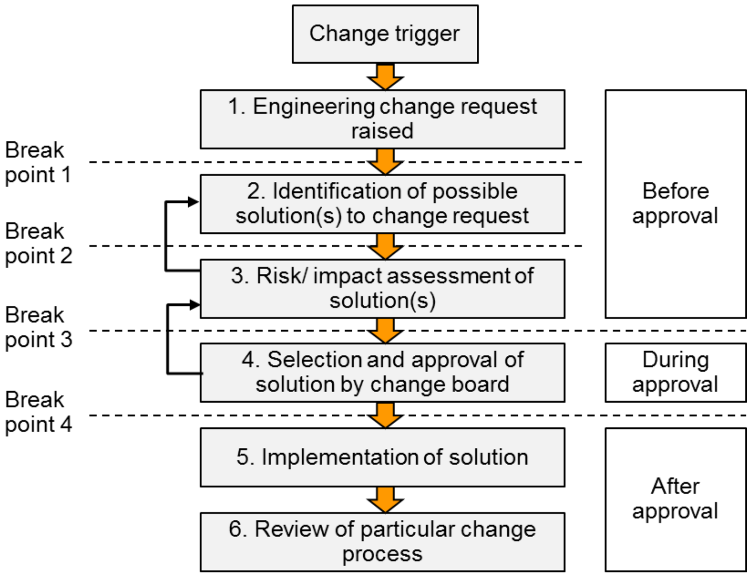


Figure 13: Six-step EC process

Source: Adapted from Jarratt et al. (2004c)

2.2.7 Consequences of ECs

The consequences of ECs are manifold and have received much attention in academic literature. Many authors have listed possible effects (e.g. Rivière *et al.* 2002, Eckert *et al.* 2004, Jarratt *et al.* 2011). A few authors have conducted surveys to quantify the effects (e.g. Hegde *et al.* 1992, Hsu 1999, Rios *et al.* 2007, Rowell *et al.* 2009, Maier and Langer 2011). In general, ECs impact all determinants of competitive advantage (Nichols 1990): *cost*, *quality*, and *time-to-market* of products.

Consequences of ECs on cost: The costs associated with ECs can be divided into (1) *direct costs (i.e. implementation cost)* and (2) *indirect cost (i.e. supporting cost)* (Figure 14):

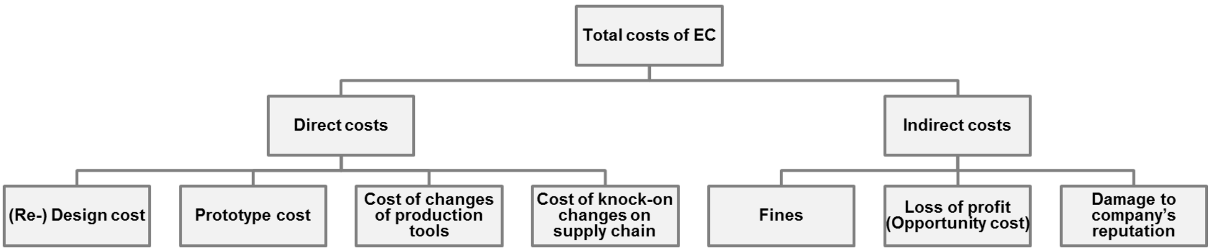


Figure 14: EC cost break down

1) Direct costs measure the company's actual spend undertaken in order to implement the change. Terwiesch and Loch (1999) broke the direct costs down into cost of design (redesigning man hours), prototype costs, and cost of changes in production tools. These costs comprise also costs of knock-on changes on other value chain stages such as purchasing, manufacturing, packaging, delivery, and after-sales services. Direct costs are subject to the *Rule of Ten* and thus increase exponentially along the design process phases. Considering the generic PD lifecycle model proposed by Ulrich and Eppinger (2010) – namely: *Planning, Concept development, System design, Detail design, Testing, Production ramp-up, Manufacturing,* and *Product phase out* – a change made during manufacturing would be 1000 times more expensive than during detail design. Clark and Fujimoto (1991) reported that ECs cause between 20% and 40% of development costs (i.e. direct cost) in vehicle development. AIAG (2012) reported redesign costs of up to USD 50,000 per EC for the North American automotive industry. Loch and Terwiesch (1999) reported that ECs consumed 33-50% of the engineering capacity along with 20–50% of tool costs at the firm they examined.

2) Indirect costs are all costs caused by the change but not directly related with its implementation. They include fines and loss of profit due to delays (also referred to as opportunity cost) as well as costs associated with a reputational damage. Thereby, loss of profit includes not only the missed out profit of the changed product but also of other products which possibly need to be delayed to free resources and machines for the change implementation. Case studies in the early 1990s showed the unexpectedly high impact of time delays on profit and led some companies (e.g. General Electric, Hewlett Packard) to adopt time-to-market as their main PD metric (Cohen *et al.* 1996). For instance, Clark (1989) estimated a loss of USD 1mn in profit per day of delay of introducing a new model for a USD 10,000 car. The costs resulting from reputational damage are difficult to measure. For companies that are listed on the stock exchange, the market value can be used as an indicator. Stock nosedives after bad press show how tremendous the impact of company’s reputation could be (Fombrun 1996).

Consequences of ECs on quality: Due to change propagation, the implementation of one raised EC may result in a number of emergent ECs. While raised ECs usually aim at a product improvement, the resulting emergent ECs are per definition required in order to rectify knock-on effects. Some of those emergent ECs might be insufficiently executed, ignored by mistake, or even deliberately neglected because of time and cost pressure. Such an incomplete implementation of required ECs negatively influences the product quality and, in the worst case, leads to failures during the product usage. Once the product is launched, any error correction has negative impacts on the customer satisfaction and thus on the perceived quality, in addition to the huge costs involved. The aftermath of such correction measures on the brand image is tremendous. Many examples can be found in the automotive industry, where for safety reasons the companies are obliged to recall their cars. For example, in the end of 2009, Toyota Motors recalled over 8mn cars worldwide that were potentially prone to uncontrolled acceleration. The costs of this massive vehicle recall was estimated up to USD 2bn (GBP 1.25bn), whereof more than a half of the 2bn would result from the fixing of the vehicles (i.e. direct costs) and the rest from reduced value and lower sales (i.e. indirect costs) (CNNMoney 2010).

Consequences of ECs on time-to-market: ECs are known to cause disruptions in the processes leading to project overruns (Dale 1982, Bashir and Thomson 1999). Change propagation impacts not only the processes within the product design stage but throughout the value chain also most other downstream and upstream processes, thereby, causing severe time delays.

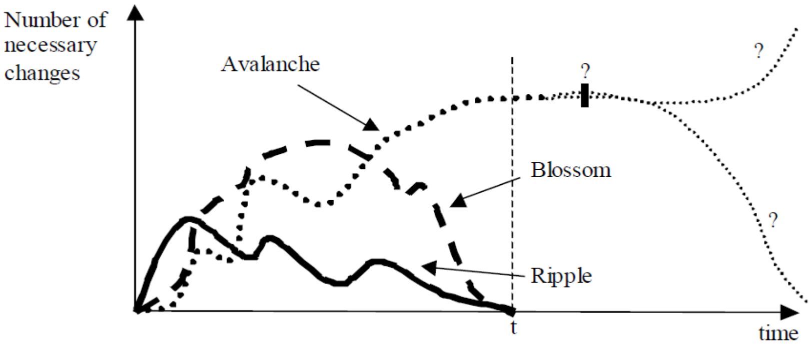


Figure 15: Types of EC propagation paths

Source: Eckert *et al.* (2004, p. 18)[2]

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[2] Reprinted by permission from Springer Science and Business Media, Van Godewijckstraat 30, 3311 GX Dordrecht, Netherlands.

As illustrated in Figure 15, Eckert et al. (2004) differentiated between three possible outcomes of EC propagation:

1. *Ripples* are propagation paths with continuously decreasing number of ECs.
2. *Blossoms* are propagation paths with increasing number of ECs in the beginning that can be brought to a close within expected time limits.
3. A*valanches* are unending propagation paths with increasing number of changes. They are often the result of major unexpected emergent changes that are not necessarily within the defined problem scope. Avalanches cannot be brought to a close within required time limits. This propagation type is also referred to as *snowball effect* (Nichols 1990, Terwiesch and Loch 1999).

2.3 ECM methods

Many methods, tools, and systems have been developed to support ECM. In their core, most methods include a model and a technique to predict and analyse the impact of change propagation. Traditional methods predominantly focus on a single product layer such as the structural or behavioural layer. They are discussed in 2.3.1 and include *C-FAR* from Cohen et al. (2000), *RedesignIT* from Ollinger and Stahovich (2004), and the *Change Prediction Method (CPM)* from Clarkson et al. (2004). Some methods aim specifically at change propagation between different organisations in alliances. They are presented in 2.3.2 and include *the distributed ECM* from Chen et al. (2002), *the parameter based method* from Rouibah and Caskey (2003), and *ADVICE* from Kocar and Akgunduz (2010). More recent developments have a stronger focus on multiple information layers and try to consider not only intra-layer but also cross-layer paths that change can take for propagation. They are elaborated in 2.3.3 and include the *pattern-based method* from *Chen et al. (2007)*, the method using a *unified feature modeling scheme* from Ma *et al.* (2008), the *multi-domain change propagation network* from Pasqual and de Weck (2011), the *Contact and Channel Model* from Albers *et al.* (2011), the method using the *Axiomatic Design Matrix* from Janthong (2011), the i*nterface representation model* from Rahmani and Thomson (2011), and the *multi-domain system network* from Van Beek and Tomiyama (2012).

2.3.1 Traditional methods

The *C-FAR* technique proposed by Cohen et al. (2000) defines artefacts as entities (i.e. components) represented by vectors and describes them by their attributes (e.g. diameter, length, material) represented by vector elements. Additional so called *C-FAR matrices* capture dependencies between attributes of two entities comprising the values low, medium, and high based on assessment of domain experts. Subsequently, matrices and vectors along selected change propagation paths are multiplied to calculate the linkage values between two attributes. The technique has been used by Cohen and colleagues to examine several industrial case studies (e.g. a car bumper, a printed wiring board, and an injection moulding). However, the amount of required effort degrades the technique and makes it only appropriate for small or relatively simple products. To avoid an unmanageable number of matrix and vector multiplications, relevant change propagation paths have to be pre-defined. Thus, the technique can only assess the propagation of changes along these given paths. It is not suitable for an exhaustive analysis because of the immense amount of required matrix and vector multiplications.

The *RedesignIT* tool put forward by Ollinger and Stahovich (2004) models a product as a direct dependency graph built based on the following concepts:

- *relevant physical quantities* referring to both physical properties of the product’s components and descriptions of the product’s operations,
- *constraints on quantities* describing design requirements on quantities, and
- *causal relations between quantities* describing how a change to one quantity influences other quantities.

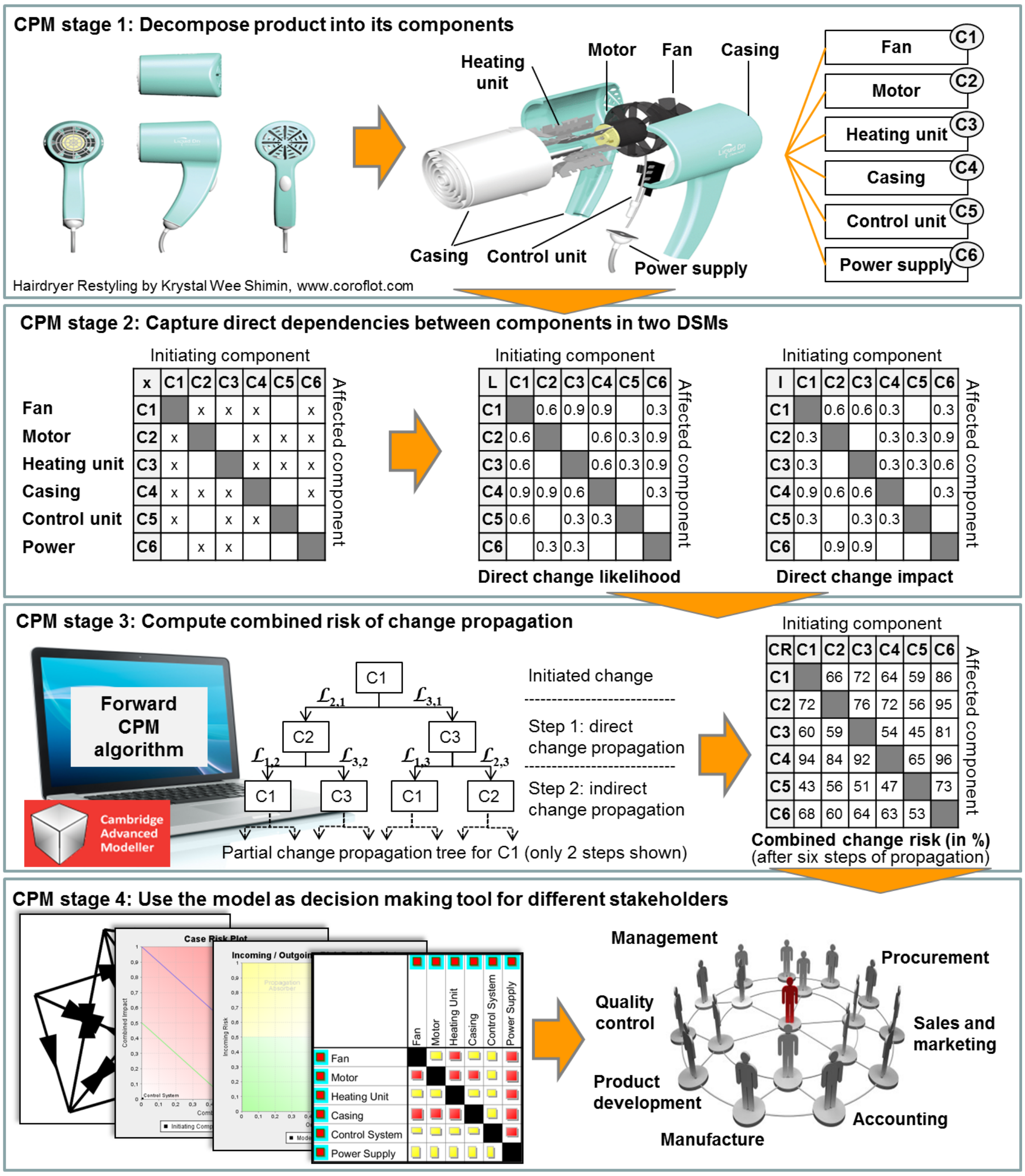
The model is used to generate possible change plans to support causal propagation analysis. As Ollinger and Stahovich note, the plans generated are rather abstract; they indicate the quantities and the direction in which these quantities have to be modified to achieve a specified performance goal but do not specify the exact numerical values for the quantities. However, the tool helps the designer to understand possible consequences of redesign by indicating the key product parts that will be affected by a change.

The *CPM* approach proposed by Clarkson *et al.* (2004) is a numerical and probabilistic change prediction method which uses a model of dependencies between component pairs to compute and visualise the overall risk of change propagation imposed on other components if one component is changed. The result of CPM is a design structure matrix (DSM), where the column elements indicate components that initiate changes, the row elements indicate components that receive changes, and the cells between two given components include the risk values. For more background of DSM, the reader is referred to Browning (2001), Karniel and Reich (2009), Eppinger and Browning (2012).

As the CPM approach is adopted in this research, it will be elaborated in more detail here. The approach is structured in four stages as depicted in Figure 16 using the example of a hairdryer for demonstration.

1. The product is decomposed into its systems, components, or parts dependent on the selected level of decomposition. The hairdryer is decomposed into six components: *Motor*, *Fan*, *Heating unit*, *Casing*, *Power supply*, and *Control unit*.
2. First, the direct dependencies between the components are captured in a binary DSM, where "*x*" indicates the existence of a link. Subsequently, from this binary DSM two numerical DSMs, which include direct likelihood and impact values of change propagation, are elicited from experts based on their prior experience and knowledge of the product. Direct likelihood considers the relative frequency of change propagation between two components, and direct impact considers the relative severity of propagated changes. The change likelihood from component *C1* to *C2* is defined as the proportion of changes to *C1* which propagate to cause change in *C2*. For instance, if every second change of *C1* causes a change to *C2*, the likelihood is 0.5. The change impact from component *C1* to *C2*, on the other hand, considers the average proportion of the original design effort that would be required to modify *C2* to accommodate a change propagated from *C1*. For instance, if a propagated change from *C1* to *C2* affects the whole design of *C2*, the impact is 1.0.
3. The combined risk of change propagation is calculated using the *Forward CPM* algorithm, which considers how change can propagate between any pair of components through multiple direct and indirect paths. In overview, the algorithm operates by applying intersection and union operators along the change propagation paths to calculate path likelihoods and impacts while excluding self-dependencies and cyclic paths. The Forward CPM equations can be found in the appendix. Full detail is provided in (Simons 2000, Clarkson *et al.* 2004, Keller 2007). Combined risk of change propagation is the sum of direct and indirect risk, where d*irect risk* between two components is defined by the product of direct likelihood and direct impact between them, and *indirect risk* considers change spreading via intermediate components. The indirect risk from an initiator to a target is defined by the sum of all risks imposed from penultimate components (other than the initiator) to the target. The imposed risk of a penultimate component to the target is the product of the combined likelihood from the initiator to the penultimate component and the direct risk from the penultimate component to the target.

4. The combined risk matrix provides insight to different stakeholders, e.g. in management, product design and development, and manufacturing, helping them assess how changes might propagate and thus supporting ECM decisions.



x	C1	C2	C3	C4	C5	C6
Fan C1		x	x	x		x
Motor C2	x			x	x	x
Heating unit C3	x			x	x	x
Casing C4	x	x	x			x
Control unit C5	x		x	x		
Power C6		x	x			

L	C1	C2	C3	C4	C5	C6
C1		0.6	0.9	0.9		0.3
C2	0.6			0.6	0.3	0.9
C3	0.6			0.6	0.3	0.9
C4	0.9	0.9	0.6			0.3
C5	0.6		0.3	0.3		
C6		0.3	0.3			

I	C1	C2	C3	C4	C5	C6
C1		0.6	0.6	0.3		0.3
C2	0.3			0.3	0.3	0.9
C3	0.3			0.3	0.3	0.6
C4	0.9	0.6	0.6			0.3
C5	0.3		0.3	0.3		
C6		0.9	0.9			

CR	C1	C2	C3	C4	C5	C6
C1		66	72	64	59	86
C2	72		76	72	56	95
C3	60	59		54	45	81
C4	94	84	92		65	96
C5	43	56	51	47		73
C6	68	60	64	63	53	

Figure 16: The CPM approach

An implementation of the method is freely available in the software program *Cambridge Advanced Modeller* (CAM) (Wynn *et al.* 2010). The technique has been applied to several industry case studies with promising results, including: a helicopter (Clarkson *et al.* 2001a), a railway valve (Jarratt *et al.* 2002), a diesel engine (Jarratt *et al.* 2004a) and an injector (Keller 2007). More recently, Ariyo *et al.* (2008) have enhanced the approach by developing a hierarchical aggregation method which enables risk prediction across multiple levels of decomposition (i.e. components, systems, and product). Koh *et al.* (2012) combined the method with the house of quality to assess different change options in the light of product requirements. Hamraz *et al.* (2012b) developed a matrix-based algorithm which enables the execution of the model's calculations with spreadsheet programs and suggested a technique to account for multiple changes at a time. Finally, Ahmad *et al.* (2013) enriched the method by incorporating the information domains of requirements, functions, components, and the detail design process.

Several other methods use the DSM-based approach of CPM and incorporate other information trying to make the change propagation modelling more deterministic.

A good example is the approach by Rutka et al. (2006). Their *Change Propagation Analysis* replaces the direct likelihood and impact values with relations dependent on the type and level of change. The idea is to describe change propagation case-by-case, thereby, using change specifications. Dependencies between the initiating and target items are outlined in a DSM and specified in more detail by defining the type and level of change for each item. This consideration of change types and levels refines the dependency information between components and allows more accurate case-by-case analysis compared to CPM. However, as probabilistic, numerical dependencies are replaced with deterministic, non-numerical dependencies, this method requires, on the one hand, more information and, on the other hand, does not support numerical change propagation analysis.

Also the method proposed by Reddi and Moon (2009) considers different types of changes. Their model captures dependencies rated on discrete levels (i.e. low, medium, and high) between component attributes for different types of changes (e.g. material, shape, and geometry). Change propagation is conducted dependent on the initiator component and type of change. Indirect changes are considered at multiple orders. As a result, the tool generates a list of affected components along with the types of changes they are expected to undergo. However, the model's level of detail hinders its application to complex systems.

Another method that can be related to CPM was proposed by Aurich and Roessing (2007). Their concept focuses on the elements of a production system which are affected by multiple ECs simultaneously and aims to identify similar ECRs that can be combined into change projects. As the means for visualisation, they make use of *virtual reality*, a technology characterized by immersion of the user into a three-dimensional virtual environment and real-time simulated interactions. The authors suggested that such a simulation can provide users with a better understanding of the EC context. It can ease the management of changes by tagging relevant information such as technical data, history, and location directly to each object. The impact analysis is based on the algorithm of CPM. The similarity analysis involves calculation of change similarity numerator and factor. The virtual reality visualisation and the similarity calculation features could potentially be used as an add-on to

CPM to package ECs into change projects. However, the basis of the impact calculation remains equal to CPM.

One more approach which is very close to the CPM was pushed forward by Cheng and Chu (2011). They proposed a change impact analysis based on the *theory of weighted networks* and three changeability indices derived from it. A product is modelled as a weighted network of parts, subassemblies, or subsystems. While in CPM dependency relationships between those items are captured by change likelihood and impact values, this approach uses coupling degrees. Similarly to the former, these values are drawn from domain expert interviews and captured within a component-component DSM. In contrast to the Forward CPM algorithm which considers all possible change paths by weighting their impacts with their respective likelihoods before summarising them, the proposed changeability indices consider only the paths with the maximum impact between two components. However, as a real-world case study of a Roots blower showed (Cheng and Chu 2011), these indices might be useful for change impact assessment.

It is important to note the differences between the three traditional change propagation modelling approaches. CPM focuses on components and relies on structural relations between them as cues for change propagation (Clarkson *et al.* 2004). It is a probabilistic method which shows the risk imposed on other components if one component changes. RedesignIT ignores components and focuses on physical quantities (e.g. shaft temperature) which describe the behaviours of systems (Ollinger and Stahovich 2004). It supports causal reasoning about change propagation between those physical quantities. C-FAR examines the attributes of the product’s key elements (e.g. type and volume of a liquid) and how they are linked to attributes of other elements (Cohen *et al.* 2000). It supports change propagation on the attribute level. However, all three methods focus on change propagation mainly within one product layer and do not consider other design information layers.

2.3.2 Multi-company methods

Chen et al. (2002) proposed a *distributed ECM* approach for allied concurrent engineering to manage the processes, systems, and information of ECs within both an individual company and across multiple companies of an alliance. The methodology includes a life cycle model, a hierarchical and distributed management framework, and a reference model for ECM. The corresponding system is developed using the Unified Modelling Language. However, the system does not account for change propagation.

Rouibah and Caskey (2003) presented a *parameter-based approach* to support multi-company concurrent engineering efforts and ECM. Their approach aims to provide quick and early insights to involved parties about the impact of proposed changes. Parameters are referred to as *"the most elementary engineering variables"* specifying the system and its interfaces such as dimensions, forces, movements and other elementary engineering decisions (Rouibah and Caskey 2003, p. 23). Change propagation analysis is conducted on the parameter level taking into account the grade of dependency between parameters. As pointed out by the authors, the challenge of this approach is the identification of relevant parameters to be modelled.

Kocar and Akgunduz (2010) proposed *ADVICE*, a virtual environment for ECM incorporating virtual collaborative design environments and sequential pattern mining techniques to facilitate ECM. It is important to highlight that the change propagation agent within ADVICE uses historic data as an input and applies a sequential mining technique to suggest potential patterns and probabilities. Thus, the tool cannot help in the case of unusual changes where no similar past experience is available. Furthermore, the system requires a huge amount of historic data collected and stored in the right format in the ECM database – it cannot retrieve information from textual data collected during design reviews.

2.3.3 Multi-layer methods

Chen and Li have proposed a *pattern-based method* for redesign planning to effectively control and reduce design change propagation (see e.g. Chen and Li 2005, Chen and Li 2006, Chen *et al.* 2007, Li and Rajina 2010). Their approach proceeds in three phases. In the first phase, a general redesign problem is formulated as a constraint-based model composed of parameters and functions, where the parameters describe the physical constituents and/or behavioural properties and the functions define their interrelations. These relations are captured in the binary so called design dependency matrix. In the second phase, upon a redesign request, alternative redesign pattern solutions are generated to form a solution selection space. Finally in the third phase, the optimal redesign pattern solution that entails the least potential redesign effort is searched and selected. More recently, Li and Chen (2010) presented an extension to their method by pre-generating and storing redesign patterns proactively before any redesign is requested to accelerate the second phase.

Ma *et al.* (2008) proposed the modelling of associative engineering relations in a *unified feature modelling scheme* along with a change propagation algorithm. This scheme models the whole product information as a dependency network of features, where *feature* may refer to functions, behaviours, product specifications, or process planning details. Change propagation is analysed between features based on the dependencies of their variables. When a variable change is proposed, the algorithm searches within the network whether the connected features can accept this change and sends a notice if any feature cannot meet the change. Two case studies were used to illustrate the proposed method. However, the dependency network requires extensive information and seems to be very complicated to develop. Furthermore, Ma et al. did not sufficiently address how features and variables can be identified and, more critically, how their interrelations can be defined.

Pasqual and de Weck (2011) proposed a *multi-domain change propagation network* model including the domains *product, change (process),* and *social*. Thereby, the product domain is a network of the components, the change domain a network of change requests, and the social domain a network of people. For the analysis of changes within this network, they proposed a repository of existing tools and metrics.

Albers *et al.* (2011) implemented their *Contact and Channel Model* in the *Cambridge Advanced Modeller (CAM)* software environment. Their tool supports the modelling of functional interrelations between function and form and helps reveal the links between functional requirements and physical parts on multiple levels of abstraction. Their model can support change prediction analysis in combination with CPM (Boerstring *et al.* 2008).

Janthong (2011) used the *Axiomatic Design Matrix (DM)* which maps the layers of design parameters to functional requirements to estimate the effects of changes. The use of DM to trace and analyse design changes was suggested in earlier work by Guenov and Barker (2005). Fei et al. (2011a, 2011b) proposed a modelling method which helps to trace change propagation within and between the functional requirement layer and the physical structure (i.e. components) layer.

Rahmani and Thomson (2011, 2012) proposed an *interface representation model* and implemented it in a Java based software. Their tool helps linking product data from multiple engineering domains and classifying and representing interfaces in a structured format. It improves the information sharing and coordination between collaborating design teams and can be used to support the management of cross-domain and cross-discipline changes.

Van Beek and Tomiyama (2012) presented a *multi-domain system network* including the domains of product use, function, behaviour, state, and stakeholder. They suggested that this cross-domain network can be used to facilitate the management of engineering changes. Their work extends their initial approach as presented by Van Beek *et al.* (2010), which applied graph theory principles to the *Function-Behaviour-State* model from Umeda and Tomiyama (1997) and aimed to support modularisation.

2.4 Functional modelling and reasoning

The method that will be developed in Chapters 5 and 6 will draw on functional modelling and reasoning. To provide a complete literature review for this thesis in one place for the convenience of the reader, the review of this research stream is presented here.

2.4.1 Structural, behavioural, and functional knowledge

The product domain in the context of mechanical design is concerned with the object of design: the artefact, which as an umbrella term may refer to a single part, a component, an assembly, a system, or a whole product. As depicted in the following figure using the hairdryer example, an artefact can be described in the context of three interrelated types of knowledge – structural, behavioural, and functional knowledge (Gero 1990, Umeda *et al.* 1990, Chittaro and Kumar 1998). Behavioural knowledge builds thereby the bridge from structural to functional knowledge and a direct connection between structural and functional knowledge is not established (Gero and Kannengiesser 2004).

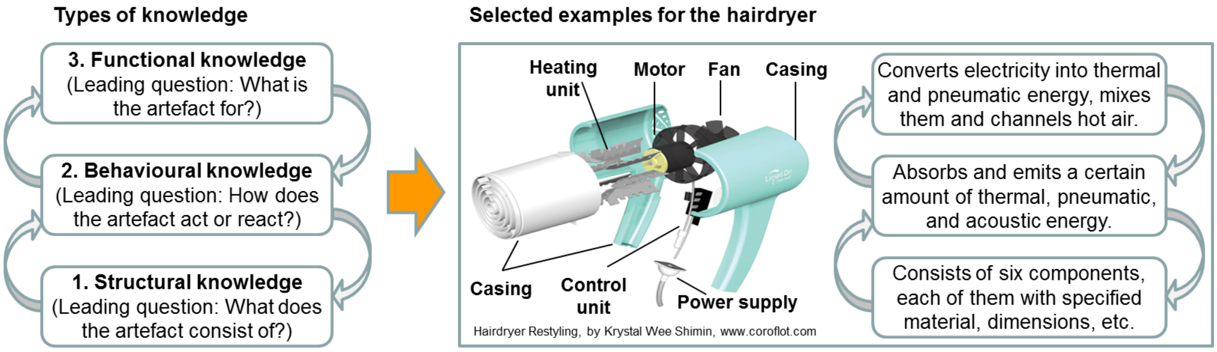


Figure 17: Types of design knowledge

1) Structural knowledge includes definitions of the material, form, and dimensions of the artefact, its constituent components, and their arrangement and connection to each other. A structural description is sufficient to construct the artefact. It includes the necessary information about the artefact's explicit parameters, which a designer directly determines in order to generate a physical solution to an abstract problem.

2) Behavioural knowledge includes the description of the artefact's potential behaviours in response to its environment. Behaviour is defined as a description of the artefact's actions or processes in response to its environmental conditions (Rosenman and Gero 1998). Behaviours are derivable by means of a physical theory from the structure of the artefact and possibly some properties of the environmental conditions (Gero 1990). Many other researchers relate to the physical state of an artefact to describe its behaviour (Keuneke 1991, Ullman 1993, Umeda *et al.* 1996): Under the influence of its environment, an artefact either changes its physical state (state transition), or maintains its physical state unchanged (static state). The physical state of artefacts can be described by parameters and their state transition (or static state) by physical laws.

3) Functional knowledge describes the role (i.e. intended purpose) of the artefact. Function is a popular term which is used in various disciplines including philosophy, medicine, sociology, and engineering to name a few. The important role of function as a fundamental concept is generally accepted in the design research community (Keuneke 1991). However, its definition remains ambiguous and controversial with a multilateral spectrum of meanings depending on the field of usage (for a discussion, see e.g. Far and Elamy 2005, Crilly 2010, Eckert *et al.* 2011). In general, it can be concluded that researchers place function between behaviour and purpose. A distinction can be made between two views of functions: one placing function closer to purpose and the other closer to behaviour. The Purpose of an artefact is the answer to the following leading question: Why does the artefact exist? Purpose relates to human values of utility in a socio-cultural environment, whereas functions exist in the techno-physical environment and enable the artefact's purpose (Chittaro and Kumar 1998, Rosenman and Gero 1998). In fact, both views reside in the same design and are reflected within the functional decomposition of an artefact; they depend on the degree of abstraction. Chakrabarti (1998) proposes that functions on a high level of abstraction can be seen as purpose and on a lower level as behaviour. Furthermore, the concept of function can be distinguished from affordance (Brown and Blessing 2005). The latter is understood as the potential uses of artefacts within a *"designer–artifact–user complex system"* (Maier and Fadel 2009, p. 22).

2.4.2 Functional modelling

Functional understanding, modelling, and representation of artefacts are fundamental for engineering design (Hubka *et al.* 1988, Suh 1990, Otto and Wood 2001, Hirtz *et al.* 2002, Ullman 2003, Pahl *et al.* 2007, Ulrich and Eppinger 2010). Functional modelling is used, for instance, in the conceptual design phase as an approach to capture a form-independent description of the product's working principles. Subjectivity and ambiguity of defining and particularly representing functions poses a challenge to functional modelling and design communication (Stone and Wood 2000, Eckert *et al.* 2012). In pursuit of developing a common functional modelling language, several authors proposed taxonomies (see e.g. Hundal 1990, Koch *et al.* 1994, Kirschman and Fadel 1998, Pahl *et al.* 2007). Little et al. (1997) addressed this problem by developing a function and flow representation based on an empirical study of over 100 products. The flow set uses the flows of material, energy and signal from Pahl et al. (2007) on the highest level and breaks them down into more specific categories. The function set adopts previous work of Value Engineering as well as the five function categories from Pahl and Beitz into eight function classes, which are broken down into more detailed categories.

Stone and Wood (2000) carried the work from Little et al. (1997) on and developed the *functional basis*, a taxonomy scheme of flows and operations organised in three levels of hierarchy. This functional basis subsumes seminal classifications schemes from Pahl et al. (2007), Hundal (1990) and the Soviet Union era design methodology known as the Theory of Inventive Problem Solving (TRIZ) (see e.g. Altshuller 1984, Malmqvist *et al.* 1996) and supports generating of consistent functional models in product design. This vocabulary contains 40 functions (action words) and 31 flows (objects). Independently, Szykman et al. (1999) developed a common functional design vocabulary. Later, both taxonomies were merged together into the *reconciled functional basis* (Hirtz *et al.* 2002). This latest version of the functional basis consists of 53 functions and 42 flows both arranged in three hierarchy levels. The hierarchy is of type specification-generalisation and should allow designers to describe functions at different levels of detail. Hirtz et al. (2002) suggested that high level functions from the primary level are more useful for original design problems to build a functional model from scratch, while the more specific lower level terms of the secondary and tertiary level could be used for adaptive and variant design problems where an initial functional description is already available. Based on that, function block diagrams can be developed which include subfunctions in the blocks and flows on the links. These subfunction blocks are described in verb-object form by putting together a function from any level of the function hierarchy and one or more objects from any level of the flow hierarchy which the function is applied on, (e.g. transfer mechanical energy). Functional basis models of over 180 consumer products (as of June 2012) have been collected in the *Design Repository* at the Design Engineering Lab at Oregon State University (available at http://designengineeringlab.org/delabsite/repository.html). These models haven been developed through reverse engineering and disassembly.

Caldwell and colleagues (see e.g. Caldwell *et al.* 2008, Caldwell 2009, Caldwell *et al.* 2011) conducted a comprehensive empirical evaluation of the functional basis using the models from the repository. The first part of the evaluation was based on a statistical analysis of eleven function block models and 110 function lists from the repository to determine the frequency of usage of functional basis terms. This analysis showed that many instances of functions and flows use non-functional basis vocabulary, which is more specific, e.g. hot air instead of gas, and approximately 90% of functions and flows are described at the secondary hierarchy level (Caldwell 2009). The second part of the evaluation was based on a hierarchical composition experiment of those eleven function block models. The results indicated that the hierarchy levels of functional basis represent varying levels of specificity of terms but are independent from functional decomposition (Caldwell 2009). Functions of the primary hierarchy level are too general and the terms from the tertiary hierarchy level do not provide sufficient additional information (Caldwell *et al.* 2008, Sen *et al.* 2010). When changing from secondary level to primary, the context gets lost and the description becomes ambiguous. Such an ambiguous first level expression is, e.g. *channel material*, where channel can refer to e.g. transfer or guide and material to e.g. solid, liquid, gas. To develop functional basis models at different level of functional decomposition, Caldwell and colleagues (see e.g. Caldwell 2009, Caldwell and Mocko 2012) proposed pruning rules. Their technique removes component specific details that describe how the main functions are realised without making the description ambiguous.

2.4.3 Functional reasoning (FR) schemes

Since the early work from Sembugamoorthy and Chandrasekaran (1986) on FR, the current stream of functional research has established a multi-disciplinary research area with special issues of journals, dedicated conferences, and workshops (for an overview, see Umeda and Tomiyama 1997).

In the engineering context, the major concerns of FR are theories and techniques to explain and derive functions of artefacts. In the design research community, many FR approaches have been developed to support design tasks (Chandrasekaran 2005). Initially, the focus has been on analytical tasks such as diagnosis and explanation. Later, this focus has moved more towards synthesis tasks such as developing a model of an object (Umeda and Tomiyama 1997). Typical for FR approaches in engineering design are representational mechanisms of functional concepts together with description mechanisms of state or structure and behaviour and explanation mechanisms for functions (Far and Elamy 2005), also referred to as ontologies. Gero and Kannengiesser (2007, p. 379) defined ontology as *"structured conceptualizations of a domain in terms of a set of entities in that domain and their relationships, [which] provide uniform frameworks to identify differences and similarities that would otherwise be obscured."* In the following, a short review of established FR models will be presented. More detailed reviews of functional approaches and techniques can be found in (Chakrabarti and Blessing 1996, Chakrabarti and Bligh 1996, Umeda and Tomiyama 1997, Chandrasekaran 2005, Far and Elamy 2005, Erden *et al.* 2008). The underlying FR theories are reviewed by (Far and Elamy 2005).

Sembugamoorthy and Chandrasekaran (1986) proposed a hierarchical representation of artefact’s functions and behaviours. Chandrasekaran, Iwasaki, and colleagues have extended this representation scheme into the Causal Functional Representational Language (CFRL) (Iwasaki *et al.* 1993). Goel and colleagues developed the Structure-Behaviour-Function (SBF) model, which also relies on the former, and proposed the tools called KRITIK, KRITIK2, and IDEAL (see e.g. Goel and Stroulia 1996, Goel *et al.* 1997, Goel *et al.* 2009). In the late 1980s, Gero and colleagues (see e.g. Gero 1990) and Tomiyama and colleagues (see e.g. Umeda *et al.* 1990) independently developed FR schemes for representing artefacts and understanding the process of designing. Gero’s work has led to the Function-Behaviour-Structure (here: FBStr) framework (Qian and Gero 1996); Tomiyama’s work has led to the Function-Behaviour-State (here: FBSta) modelling, where state is a generalised concept of structure (Umeda *et al.* 1990), and a conceptual design-support tool called FBS[ta] Modeler based on it (Umeda *et al.* 1996). Further FR schemes were developed in the 1990s among others by Chakrabarti and Bligh (1996) and Stone and Wood (2000).

As a result, there are several FR schemes today, of which the seminal three-layered schemes are SBF, FBSta, and FBStr. It is important to note that although these three FR schemes have many aspects in common, their ontologies and also their purposes are different. The three schemes do not only incorporate different views of functions as discussed above but also differ in terms of their definitions of behaviour. For example, behaviour in the FBSta model from Umeda et al. (1990) stands for output behaviours of an artefact of which its functions are a subset, whereas the SBF model from Goel et al. (2009) refers to behaviour as causal processes of artefacts (internal behaviours) that result in its functions. Gero’s FBStr, on the other hand, refers to behaviour as the properties of structural elements (Gero 1990). The purpose of the latter is to model the overall design process, whereas the SBF and FBSta focus on the product side. Section 6.3 includes a detailed comparison of these three schemes structured according to the three layers, structure, behaviour, function, and the two joining spheres between structure and behaviour, and behaviour and function.

2.5 Chapter summary

This chapter has reviewed the literature relevant for this thesis in three main sections.

Section 2.2 elaborated EC and ECM. It provided a manifold understanding of EC and ECM by reviewing various EC definitions, discussing the relevance of ECs in design, describing EC propagation, characterising ECs along multiple facets, presenting EC prioritisation alternatives, elaborating the EC process, and finally discussing the consequences of ECs on cost, quality, and time-to-market.

It was learned that ECs are crucial for PD because new designs are mostly developed by changing previous designs and product improvements or error corrections require ECs. The multifaceted characterisation of ECs showed that they can be raised by multiple sources along the complete product lifecycle. Due to the high interconnectivity of complex designs, ECs tend to propagate from one part to another and multiply. The literature agrees that ECs determine about one-third of the development cost in automotive industry and can cause severe quality issues or delays. Thus, change propagation seems to be an important phenomenon that needs to be addressed by ECM.

Section 2.3 reviewed a number of ECM methods divided in three groups: traditional methods which predominantly focus on a single design product domain, multi-company methods which specifically aim at change propagation between different companies, and multi-layer methods, which include more recent developments considering multiple design domains through which changes may propagate.

The evidence demonstrates that many methods were proposed to support ECM. Most of these methods describe how to model a design and use the model to analyse the potential impact of change propagation. Traditional methods model designs as a single-layered network of structural or behavioural attributes. Some methods were developed for multi-company environments focusing on cross-company change propagation. It was discovered that recent methods consider multiple design information layers and try to account for more possible change propagation paths. Thus, understanding and considering different design information layers seems to be of importance for ECM methods.

Section 2.4 elaborated research on functional modelling and reasoning. The knowledge about the product was presented in terms of structure, behaviour, and function, and functional modelling approaches and FR schemes were discussed.

It was shown that a design can be described using the three interrelated layers of structural, behavioural, and functional knowledge. Hence functional understanding, modelling, and representation of artefacts are fundamental for engineering design. To support systematic and structured generating of consistent functional models in product design, Hirtz et al. (2002) proposed the reconciled functional basis as a common functional modelling language. The literature review revealed several FR schemes that were developed to support design representation and explanation of artefact functions. Of these, the seminal schemes which consider all three information layers are SBF, FBSta, and FBStr.

Altogether, this chapter established the basic understanding for this research, upon which all the following chapters can build. Thereby, it has answered the first research question. In overview, it was learned that ECs and their propagation are crucial for complex designs and that support for managing changes is provided by ECM methods. These findings raised the second research question which will be addressed in the next chapter (Figure 18):

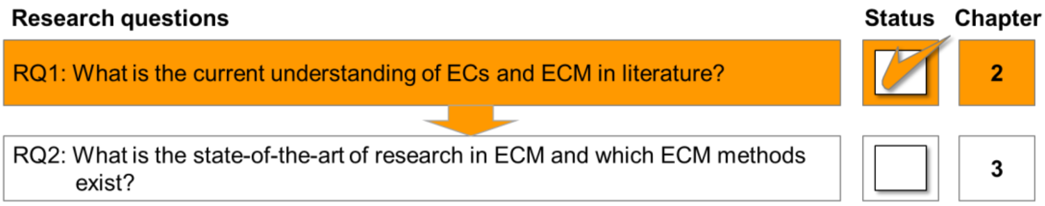


Figure 18: Research questions and status after Chapter 2

3 State-of-the-Art of Research in ECM

"If anybody were to start where Adam started
he would not get further than Adam did…"
(Sir Karl R. Popper, Austro-British philosopher, 1902-1994)

3.1 Chapter introduction

Chapter 2 created the required understanding of ECs and ECM for this research by reviewing key publications and elaborating relevant themes. The findings led to the formulation of the second research question (RQ2: What is the state-of-the-art of research in ECM and which ECM methods exist?). This chapter addresses RQ2 by conducting a systematic literature search and generating an overview of current ECM methods. To provide an overview of the state-of-the-art of research in ECM, a holistic literature categorisation framework is developend and used to structure ECM research and organise the identified publications according to their main contribution.

The remainder of this chapter is structured in six sections. Section 3.2 provides the background for the proposed categorisation framework by elaborating existing literature reviews and categorisation frameworks. Section 3.3 introduces the proposed categorisation framework. Section 3.4 presents the systematic literature survey and positioning of relevant publications. Section 3.5 presents the list of existing ECM methods. Section 3.6 discusses the results of the survey, positioning, and the ECM method examination. Finally, Section 3.7 summarises the chapter.

3.2 Existing literature reviews and categorisation frameworks for ECM

To investigate the state-of-the-art of research in ECM, a systematic literature search is required. The results of this search may be organised using a framework which helps to structure the research and categorise relevant publications according to their contribution. Several literature categorisation frameworks arising from literature reviews were proposed and will be reviewed here.

The first widely acknowledged survey on ECM, which covered literature published between 1980 and 1995, was conducted by Wright (1997) who identified only 15 core papers and eight further articles, after studying the citations of those core papers. Wright suggested a tree-structured ECM research categorisation framework which differentiates between two main categories of related research: (1) *Computer tools* for the analysis of EC problems and synthesis of solutions and (2) *Methods* for the reduction of EC impact. These categories were further subdivided as shown in Figure 19. Another similar tree-structured framework was proposed by Ouertani (2004).

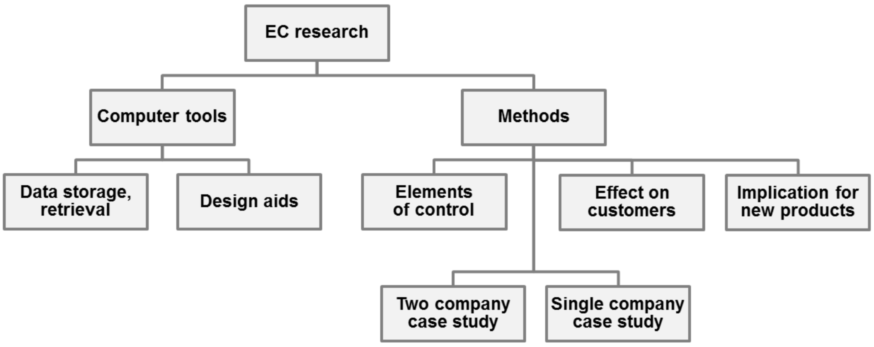


Figure 19: Tree-structured ECM research categorisation framework

Source: Adapted from Wright (1997)

More recently, Jarratt *et al.* (2011) conducted a literature review. Their survey highlights more than 100 relevant articles published until 2010 and aims to provide an up-to-date coverage of the relevant ECM topics. Their categorisation framework classifies relevant publications into the three main categories (1) Process, (2) Tool, and (3) Product, and two additional categories for (4) General studies, and (5) Strategies and methods to cope with ECs. In contrast to the tree-structured categorisation frameworks suggested by Wright and Ouertani, these categories overlap and allow an article to be assigned to multiple categories.

A systematic survey on literature published between 2005 and 2010 including statistical analysis and an overview of different research groups around the globe can be found in Ahmad (2011) and Ahmad *et al.* (2011a). The survey considers 314 publications for statistical analysis – mainly conference papers from International Conference on Engineering Design

(ICED), International Design Conference (DESIGN), and ASME Design Engineering Technical Conference (DETC). The four main categories proposed are (1) *Change management*, (2) *Design taking into account of changes*, (3) *Organisational changes*, and (4) *Others*. Furthermore, according to the addressed domains of design, the literature is categorised into (1) *Requirements*, (2) *Function models*, (3) *Component/ Subsystem models*, (4) *Detailed design process*, and (5) *Cross domain models*. Both category dimensions are used to build different clusters. However, neither a complete list of the analysed publications is provided nor are the clusters clearly distinguished against each other.

Literature surveys looking at certain aspects of ECM are presented by Huang and Mak (1998), and Rouibah and Caskey (2003). Huang and Mak reviewed computer aids for EC control; Rouibah and Caskey reviewed ECM literature relevant for concurrent engineering and categorised them into (1) *Survey research or field research*, (2) *Industrial case studies*, (3) *Methods and frameworks for implementation*, and (4) *Tools and IT solutions*. There are other literature reviews on related topics, most noticeable on PD process models by Browning *et al.* (2006), and Browning and Ramasesh (2007), on product platforms by (Simpson 2004), and on concept selection methods by Okudan and Tauhid (2008).

Other categorisation schemes can be found in conference proceedings. For example, in ICED, since 2009 design research has been categorised into the nine categories: (1) *Design Process*, (2) *Design Theory and Research Methodology*, (3) *Design Organisation and Management*, (4) *Product and Systems Design*, (5) *Design Methods and Tools*, (6) *Design for X and design to X*, (7) *Design Information and Knowledge*, (8) *Human Behaviour in Design*, and (9) *Design Education*. Although ECM papers are more likely to be part of the groups 1, 3, 5, and 7, relevant papers may be found within all nine groups. A concurrent classification scheme for research in engineering design was proposed in a keynote presentation of ICED 2011 titled "*Design Research: Embracing the Diversity*" by McMahon (2011). This applied faceted classification using eight facets – including addressed time period, number of activities and issues, number of people, and product lifecycle phase – to classify the 340 conference papers from ICED 2009 – excluding the Design Education papers. He found that the patterns differ between the eight categories. For the group *(1) Design Process*, where in ICED 2009, the majority of the ECM related papers were assigned to, the pattern suggested studies of weeks or a few months, medium range of number of activities and issues, primarily focused on single people and small teams, components and assemblies, high level of abstraction, medium level of originality, conceptual design phase, and using preferably modelling, experimental methods and tools. Such a faceted classification of related ECM publications might deliver additional insights.

In summary, there are several literature reviews on ECM available, but none of them provide a comprehensive up-to-date coverage as intended in this chapter. The reviews either consider only a given period (e.g. the reviews by Wright, and Ahmad), or focus on selected articles (e.g. the review by Jarratt et al.), or on particular aspects of ECM (e.g. the reviews by Huang and Mak, and Rouibah and Caskey). This chapter supplements those existing reviews with a nearly-complete coverage of all relevant publications in the field of ECM as shown in Figure 20. This schematic Euler diagram shows the overlap of the references of the three literature review based publications – Jarratt *et al.* (2011), Wright (1997), and Rouibah and Caskey (2003) – with the list of categorised publications in this chapter. The diagram suggests that the categorised list of publications in this chapter includes the majority of the references of each of those three publications plus 300 additional publications which are not cited by either one of them. The references included in the reviews but not categorised are either publications with low relevance for ECM or reference types which are not included in the categorisation such as e.g. Ph.D. theses, technical standards, or homepages.

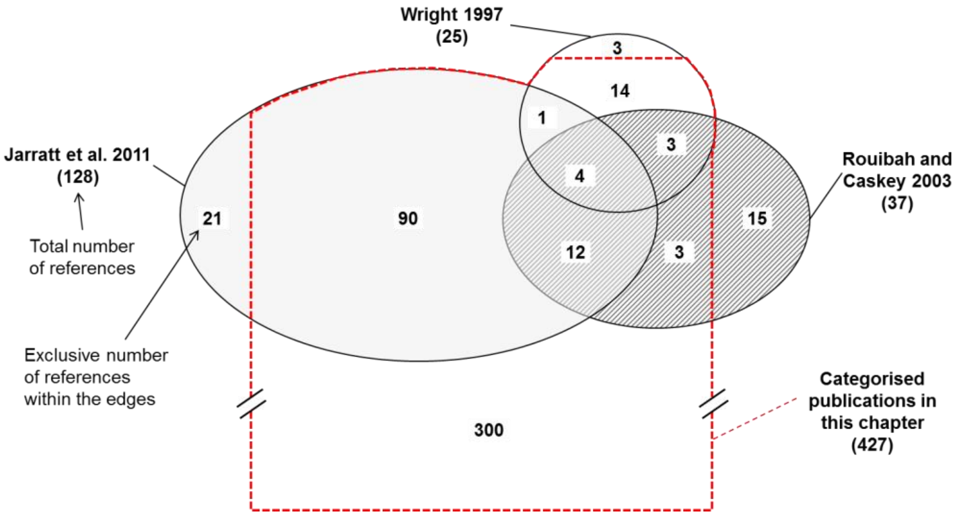


Figure 20: Euler diagram for the coverage of references by the literature review publications

The proposed categorisation frameworks are either too narrow focusing only on *core papers* (e.g. the framework by Wright, Ouertani, and Rouibah and Caskey), not disjunctive enough (e.g. the framework by Jarratt et al.), or too specific (e.g. the clusters by Ahmad). There is no framework which allows a disjunctive categorisation and comprehensive coverage of related literature in ECM and related topics in its broad context. This is the aim of the framework presented in the next section. This framework complements the existing literature reviews with an illustration of the position of the publications in the context of the big picture of ECM.

3.3 A Holistic categorisation framework for ECM literature

3.3.1 Framework overview

In pursuit of providing a broad overview of the state of research in ECM and allowing a more precise positioning of relevant publications, a new categorisation framework was developed (Figure 21).

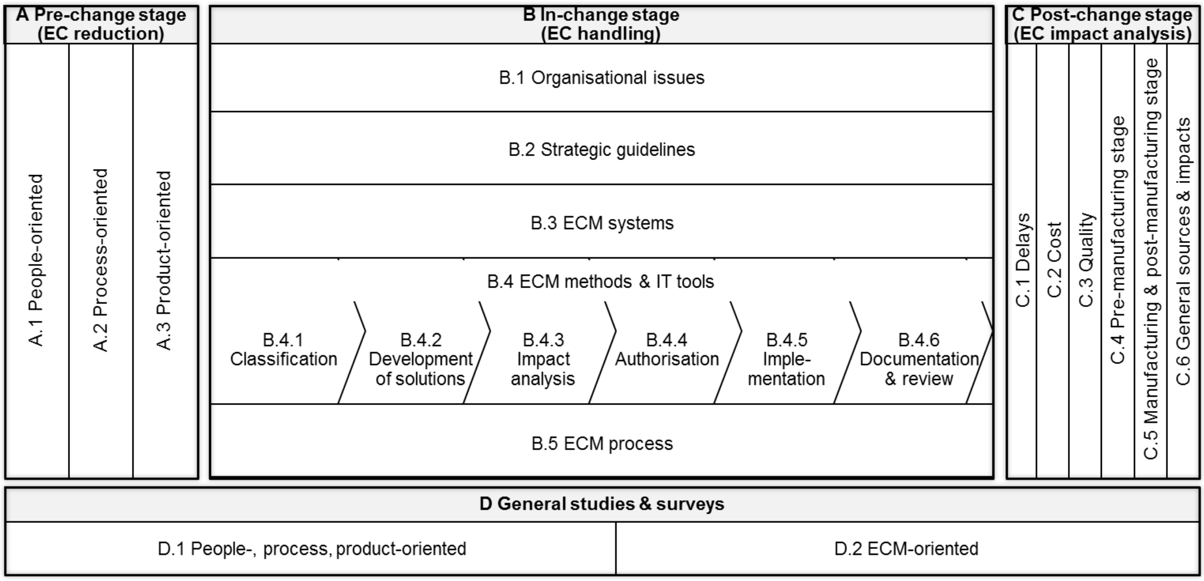


Figure 21: Holistic ECM research categorisation framework

This framework is holistic as it covers not only ECM but also related cross-disciplinary areas. It is roughly structured along the five guidelines from Fricke et al. (2000) (i.e. *Less, Earlier, More effective, More efficient, Better*) and includes the EC process from Jarratt *et al.* (2004c) in its core. The purpose of this framework for this thesis is to provide a state-of-the-art of research in the broader sense of ECM and identify current methods which address the guidelines *Earlier, More effective, More efficient*. Beyond this, it can be used to reveal research gaps and opportunities. This has been discussed in the journal article by Hamraz *et al.* (2013a) and will not be repeated here.

The main blocks of the framework are *(A) Pre-change stage, (B) In-change stage, (C) Post-change stage*, and *(D) General studies & surveys.* They will be defined in the following subsections.

3.3.2 (A) Pre-change stage

Research in Pre-change stage is concerned with concepts to prevent or to ease the implementation of ECs before they occur. The research predominantly focuses on the guideline *Less*. This block is subdivided into the categories *(A.1) People-oriented, (A.2)* P*rocess-oriented,* and *(A.3) Product-oriented* research. People-oriented research deals with training and development of designers and other employees across the whole process chain in order to create awareness of ECs, and provide the people with knowledge and skills of how to handle them. Process-oriented research focuses mainly on PD process modelling and optimisation. Product-oriented research focuses mainly on the product architecture and covers concepts such as design for variety, design for changeability, axiomatic design, robust design, set-based design, systems architecting, requirements management and flexible product platforms.

3.3.3 (B) In-change stage

In-change research is concerned with methods, tools, systems, strategic guidelines, and organisations to handle ECs when they occur. This research predominantly focuses on the guidelines *Earlier*, *More effective*, and *More efficient*. This block is subdivided into the categories *(B.1) Organisational issues*, *(B.2) Strategic guidelines*, *(B.3) ECM systems*, *(B.4) ECM methods & IT tools*, and *(B.5) ECM process.* While the other categories address the whole ECM process, ECM methods & IT tools are more specific and targeted at certain process steps. The latter category is therefore further divided into subcategories along the generic ECM process as suggested by Jarratt *et al.* (2004c). When the systematic literature survey and the categorisation of relevant publication is conducted in Section 3.4, the categories *(B.3)* and *(B.4)* will contain the papers with current ECM methods which address the three targeted guidelines. This will complete the answer to the second research question.

3.3.4 (C) Post-change stage

Research in Post-change stage is concerned with the ex-post exploration of effects of implemented ECs on *(C.1) Delays*, *(C.2) Cost*, *(C.3) Quality*, *(C.4) Pre-manufacturing stage*, *(C.5) Manufacturing & post-manufacturing stage*, and *(C.6) General sources & impacts*. To keep the categorisation mutually exclusive, the last category includes all publications which address more impacts and could be categorised into two or more of the categories *(C.1)* to *(C.5).* Referring to the five guidelines above, research in this area predominantly aims at *Better*.

3.3.5 (D) General studies & surveys related to ECM

General studies & surveys cover research which explores the discipline of ECM and related topics as well as general surveys about ECM practice in industry. They can be subdivided into the categories *(D.1) People-, process-, product-oriented* and *(D.2) ECM-oriented.*

3.3.6 How to position publications

The assignment of publications to the categories should be based on their main contribution to ECM. The framework categories are mutually exclusive and collectively exhaustive. Thus, each contribution must be assigned to exactly one category. Most journal articles and conference papers have one main contribution to ECM which facilitates an unambiguous assignment. However, some have multiple distinct contributions allowing them to be assigned to multiple categories. This framework could also be applied to position other more comprehensive publications such as books and theses. As those kinds of publications usually address more diverse topics, they can be assigned to multiple categories.

3.4 Literature survey and categorisation

3.4.1 Scope of the literature survey

The aim of this categorisation is to provide a comprehensive and up-to-date picture of research that has been undertaken in the field of ECM in its wide context of mechanical design. The respective list of publications should serve as a useful data base for both researchers and managers in the field of ECM. To account for the originality and quality of publications, only journal and conference papers were considered. However, to provide a full list of references, in a second separate categorisation, books, book sections, and other reports were positioned. As there are already several limited literature reviews on the core field of ECM, which includes the blocks *(B)*, *(C)* and *(D.2)* in Figure 21, this review aims to provide a relatively complete picture of research in those blocks. The wider context of ECM, which includes the blocks *(A)* and *(D.1)* in Figure 21, is related to other research fields such as organisation theory and project, process, and product design and management. Therefore, only the most relevant publications concerning ECM were covered in those blocks and the list is not complete.

The objects of inquiry for this survey are publications related to ECs as defined in Section 2.2 – in the context of mechanical design. In the literature, ECs are also used to term changes in the context of construction (see e.g. Hanna *et al.* 1999), software engineering (see e.g. Lindvall and Sandahl 1998), and Integrated Circuits and Systems (see e.g. Kirovski *et al.* 2005). Publications from those areas were included if they contribute to ECM in a mechanical design context.

3.4.2 Literature survey approach and results

The collection of publications followed four phases. First, a systematic search was conducted for the period from January 1996 (after the survey by Wright (1997)) to 31 August 2011. This phase started by longlisting publications which included the word *change* in their title or abstract and progressed by shortlisting those referring by change to EC. In this phase, the search included the following journals and conference proceedings.

- Journals: Research in Engineering Design; Journal of Engineering Design; Design Studies; IEEE Transactions on Engineering Management; Product Innovation Management; Computers in Industry; Systems Engineering; Artificial Intelligence for Engineering Design, Analysis and Manufacturing; and International Journal of Design Engineering.
- Conference proceedings: ICED; DESIGN; DETC; and International DSM Conference.

Second, the results of the systematic search were completed with the references of existing literature surveys. Third, the key publications were cross-referenced. Fourth, the list was completed with an open search for the words *engineering change* using IEEE Explore, SpringerLink, Scopus, and Google Scholar.

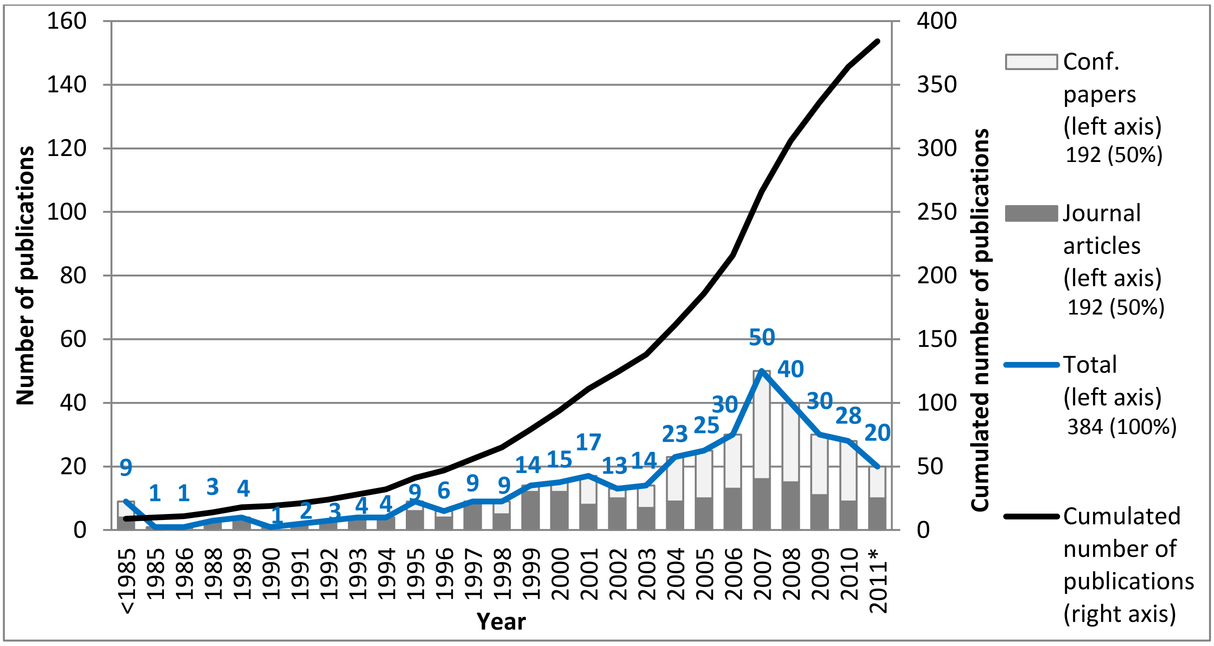


Figure 22: Distribution of number of journal articles and conference papers

Note: * indicates incomplete year, i.e. from 01 January to 31 August.

The final list of journal articles and conference papers selected for the categorisation included 384 publications from more than 110 different sources. To provide a more complete list, conference papers which were superseded by journal articles were kept in the list. A distribution of the number of publications over year by type is shown in Figure 22. 192 (50%)

of the publications are journal articles and 192 (50%) conference papers – these numbers are equal by chance.

3.4.3 Categorisation approach and results

The positioning of the journal articles and conference papers was completed in three steps. In the first step, a rough categorisation to the main blocks *(A), (B), (C),* or *(D)* of the framework was conducted based on titles and abstracts. In the second step, the contents of all publications were screened to create a more precise categorisation. Finally in the last step, publications with multiple distinct contributions were positioned according to their primary and secondary contributions. Furthermore, to provide a more complete list of publications, in a second attempt, 43 books, book sections, and other reports were categorised separately according to their primary contribution. Table 2 provides the distribution of the number of journal articles and conference papers categorised according to their primary contribution over category and year. Figure 23 depicts all 427 publications categorised according to their primary contribution within the framework. A full account of the results including associated publication details can be found in (Hamraz *et al.* 2013a).

Table 2: Distribution of number of journal articles and conference papers over year by category according to their primary contribution

Category	<1985	1985	1986	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011*	No of journ. art.	No of conf. papers	Total
A.1 People-oriented									1							1	1						2	2	1		1	**6**	**3**	**9**
A.2 Process-oriented					1				2	2	1		4	1	4	1	4	3	2	2	2		5	1	2			**27**	**10**	**37**
A.3 Product-oriented										1	3		2	2	3	6	2	3	1	5	8	7	11	8	4	6	2	**36**	**38**	**74**
B.1 Organisational issues	2																											**1**	**1**	**2**
B.2 Strategic guidelines						1	1								1	1					1	1	2	1		1		**5**	**5**	**10**
B.3 ECM systems			1											1	1	1	4	3	4	1	2	3	4	8	6	5	3	**23**	**24**	**47**
B.4.1 Classification								1							1					1								**3**	**0**	**3**
B.4.2 Development of solutions	1			1							1	1					1		2	2	1	2	2	1	2	3	1	**7**	**14**	**21**
B.4.3 Impact analysis											1			1		2	2		2	4	2	4	11	6	4	6	3	**11**	**37**	**48**
B.4.4 Authorisation																												**0**	**0**	**0**
B.4.5 Implementation																1	1			1		2	2	3	4	3	2	**9**	**10**	**19**
B.4.6 Documentation & review	2			1			1				1	4	1	1		2		2		3	4	2	2	5	1	2	1	**18**	**17**	**35**
B.5 ECM process	2							1						1	1						2		3	1	1	1		**6**	**7**	**13**
C.1 Delays				1				1					1									1		1				**4**	**1**	**5**
C.2 Cost											1	1								1	1		1				1	**4**	**2**	**6**
C.3 Quality																						1			1			**1**	**1**	**2**
C.4 Pre-manufacturing stage		1			2				1	1					1		1		1			1						**9**	**0**	**9**
C.5 Manufacturing & post-manufacturing stage	2																											**0**	**2**	**2**
C.6 General sources & impacts					1													1		1			1	1	3		4	**5**	**7**	**12**
D.1 People-, product-, process-oriented studies & surveys															1		1	1		2	1	5	4	1		1		**11**	**6**	**17**
D.2 ECM-oriented studies & surveys													1	2	1				2		2	1		1	1		2	**6**	**7**	**13**
Total	**9**	**1**	**1**	**3**	**4**	**1**	**2**	**3**	**4**	**4**	**8**	**6**	**9**	**9**	**14**	**15**	**17**	**13**	**14**	**23**	**26**	**30**	**50**	**40**	**30**	**28**	**20**	**192**	**192**	**384**

Note: * indicates incomplete year, i.e. from 01 January to 31 August.

This exercise was completed within a period of three months. Overall, the author spent around 300 hours on the categorisation of all publications, i.e. on average around three-quarters of an hour per publication. Although the categorisation was exercised with due care by following the stepwise approach described above, it should be noted that the outcome includes a certain amount of subjectivity because it was undertaken only by the author. However, the result was counter-checked, presumably in samples, by the first co-supervisor of the thesis and by five anonymous reviewers of the journal Systems Engineering. Hence, the categorisation can be considered as sufficiently accurate for this thesis. To reduce the bias, ideally such a categorisation would be exercised by several researchers independently and discussed to obtain consent. However, due to the enormous amount of time, this was not possible within the scope of this thesis.

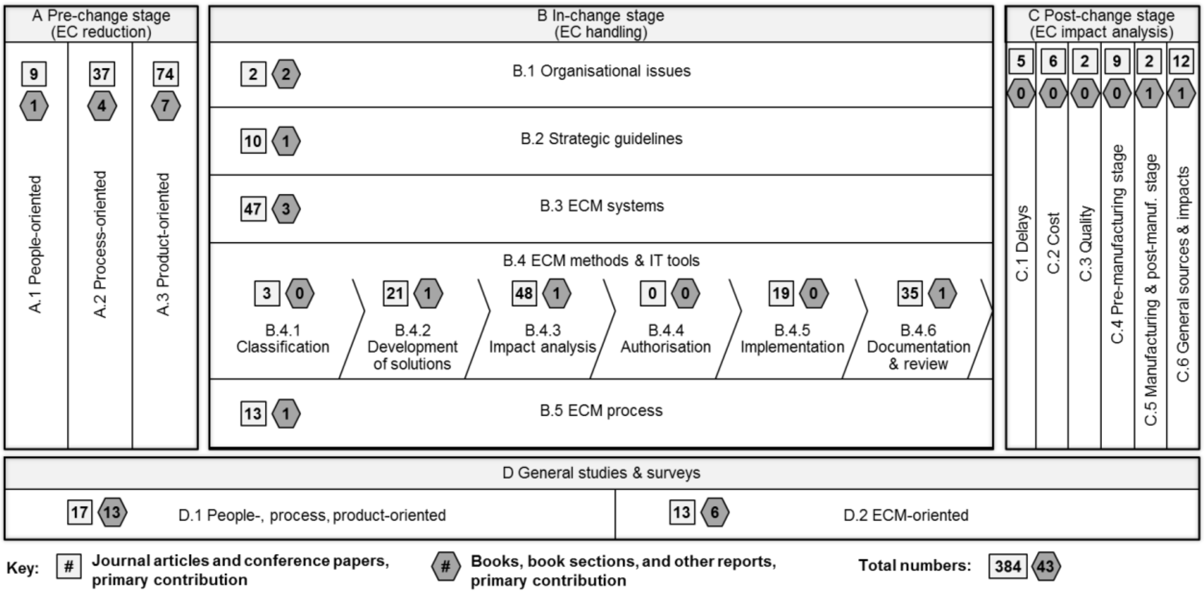


Figure 23: Categorisation result for all 427 publications according to their primary contribution

3.5 Overview of existing ECM methods

The literature review revealed and categorised a vast number of publications relevant for ECM. As discussed in Subsection 3.3.3, publications that predominantly address the guidelines *Earlier, More effective,* and *More efficient* are listed in the block *(B) In-change process;* and more specifically, the corresponding ECM methods are categorised in *(B.3) ECM systems* and *(B.4) ECM methods & IT tools*. However, on one hand, not all 173 journal articles and conference papers listed in these categories report on ECM methods and on the other hand, some ECM methods are reported in more than one publication. Therefore, these publications were revisited to generate a list of unique ECM methods (Table 3). These methods were categorised according to their focus on *Earlier, More effective,* and *More efficient* handling of changes. Furthermore, the list indicates whether, along with the methods, a computer tool was proposed and whether this computer tool was available as of April 2013. To determine this, the publications were searched for links or hints; Google was used to search for the method name on the internet; and the departmental homepages of the first and last authors were searched.

The guidelines have been discussed in Subsection 1.1.4. From an ECM method perspective, they can be briefly defined as: *Earlier* is addressed by a method if it provides means by which ECs can be detected earlier and communicated better; *More effective* is addressed by a method if it provides means by which the impact of ECs can be evaluated and used to prioritise or reject ECs; *More efficient* is addressed by a method if it allows the implementation of necessary ECs to be completed in less time, incurring lower cost, and with better quality.

Table 3: ECM methods and computer tools addressing Earlier, More effective, and More efficient

No	Method/ reference name	Title or short description	Author(s) and year of respective publications	Handling of ECs			Computer tool	
				Earlier	More effective	More efficient	Pro-posed	Avail-able
1	ADVICE	A virtual environment for ECM	(Kocar and Akgunduz 2010)	x	x		x	
2	Ahmad et al.	MDM-based approach to manage EC processes across domains of the design process	(Ahmad *et al.* 2010a), (Ahmad *et al.* 2009), (Ahmad *et al.* 2010b)	x	x	x	x	
3	CECM	Integration of collaborative activities and knowledge management throughout the lifecycle of ECs	(Lee *et al.* 2006)	x			x	
4	C-FAR	Change evaluation at the attribute level using matrix calculations	(Cohen and Fulton 1998), (Cohen *et al.* 2000)	x	x		x	
5	Chen & Li	Pattern-based redesign planning	(Li 2010), (Chen and Li 2005), (Chen and Li 2006), (Chen *et al.* 2007), (Li and Chen 2010), (Li and Rajina 2010)	x	x	x	x	x
6	Chen et al.	Methodology for ECM in the context of allied concurrent engineering	(Chen *et al.* 2002)	x			x	
7	Cheng & Chu	Network-based assessment approach for change impacts on complex product	(Cheng and Chu 2011)	x	x			
8	CIRA	Combining Characteristics-Properties Modelling and Property-Driven Development for Change Impact and Risk Analysis	(Erbe *et al.* 2011), (Conrad *et al.* 2007), (Köhler *et al.* 2008)	x	x			
9	CMCEA	Change Mode, Cause and Effects Analysis	(Huang and Johnstone 1995)	x	x			
10	CPA	Change Propagation Analysis between items (e.g. components) considering types and levels of change	(Lemmens *et al.* 2007), (Rutka *et al.* 2006)	x	x		x	
11	CPD	Concurrent Parameter Design based on constraint network	(Fan *et al.* 2004)	x	x	x	x	
12	CPM	Change Prediction Method based on numeric component DSMs and stochastic propagation analysis	(Ariyo *et al.* 2006b), (Ariyo *et al.* 2007b), (Ariyo *et al.* 2007a), (Clarkson *et al.* 2001a), (Clarkson *et al.* 2001b), (Clarkson *et al.* 2004), (Eger *et al.* 2007a), (Eger *et al.* 2007b), (Jarratt *et al.* 2004b), (Keller *et al.* 2007a), (Keller *et al.* 2005a), (Keller *et al.* 2006a), (Keller *et al.* 2007b), (Keller *et al.* 2005b), (Keller and Clarkson 2008), (Tang *et al.* 2008)	x	x		x	x
13	CPM-House-of-Quality	Merging House of Quality and the Change Prediction Method to model the performance of different change options	(Koh *et al.* 2009a), (Koh *et al.* 2007), (Koh *et al.* 2008b), (Koh *et al.* 2009b), (Koh and Clarkson 2009)	x	x		x	x
14	Cyber-Review	Web-based system for ECM	(Huang 2002), (Huang *et al.* 2001a), (Huang *et al.* 2001b), (Huang *et al.* 2000)	x			x	
15	DEPNET	Re-organising design activities during EC process based on product specification dependencies	(Ouertani 2008), (Ouertani 2009), (Ouertani *et al.* 2007), (Ouertani and Gzara 2008)			x	x	
16	Do et al.	Propagation of EC to multiple product data views using history of product structure changes	(Do *et al.* 2002), (Do *et al.* 2008)	x			x	
17	ΔDSM	EC propagation due to requirement changes	(Morkos and Summers 2010)	x	x			
18	EC Propagator	Representation and propagation of EC information in collaborative product development using a neutral reference model	(Hwang *et al.* 2009)	x			x	
19	ECBOM	EC method based on information integration and data consistency using the bill of material	(Liu and Pan 2010)	x	x	x	x	
20	ECD-BOM	A distributed change control workflow for design network based on a specific product configuration	(Shiau and Li 2009), (Shiau and Wee 2008)	x	x	x	x	
21	EchoMag	Decision-making assistance in ECM process	(Habhouba *et al.* 2011), (Habhouba *et al.* 2006), (Habhouba *et al.* 2009)	x			x	
22	Feature Elasticity	Assessment of change impact on the relevant process plan	(McKay *et al.* 2003)			x	x	

No	Method/ reference name	Title or short description	Author(s) and year of respective publications	Handling of ECs			Computer tool	
				Earlier	More effective	More efficient	Pro-posed	Avail-able
23	Fei et al.	Model-driven and knowledge-based method	(Fei *et al.* 2011a), (Fei *et al.* 2011b), (Fei *et al.* 2010)	x	x		x	
24	Flanagan et al.	Change propagation through the link between functions and components	(Flanagan *et al.* 2003)	x	x			
25	Horvath et al.	Intelligent attribute definition for integrated decision assistance	(Horvath and Rudas 2007), (Horvath *et al.* 2005)	x			x	
26	House of Quality	Mapping of customer desires to company/ product capabilities	(Hauser and Clausing 1988)	x	x			x
27	ITA Phase II	Automatic EC analysis for incremental timing analysis	(Auch and Joosep 1984)	x	x		x	
28	Joshi et al.	Systematic decision support for ECM in PLM	(Joshi *et al.* 2005)	x	x	x	x	
29	Krishna-murthy & Law	Data management model for change control in collaborative design environments	(Krishnamurthy and Law 1995), (Krishnamurthy and Law 1996), (Krishnamurthy and Law 1997)	x			x	
30	KRITIK2	Functional model-based diagnosis in adaptive design	(Goel and Stroulia 1996)		x		x	
31	Lee et al.	Relative change impact analysis using analytic network process	(Lee *et al.* 2007), (Lee *et al.* 2010)		x			
32	Li et al.	ECM based on weighted complex networks	(Li *et al.* 2008)		x			
33	Liu et al.	Change propagation graph and process model based on a Petri net to analyse change implementation	(Liu *et al.* 2002)	x	x	x		
34	Ma, S. et al.	A framework for a knowledge-supported change impact analysis system	(Ma *et al.* 2003)	x	x	x	x	
35	Ma, Y. et al.	Change propagation algorithm in a unified feature modelling scheme	(Ma *et al.* 2008)	x	x	x	x	
36	Mehta et al.	EC impact prediction based on past changes and similarity analysis	(Mehta *et al.* 2010), (Yang *et al.* 2010)		x			
37	Mokhtar et al.	Information model for managing design changes in a collaborative environment	(Mokhtar *et al.* 1998)	x	x	x	x	
38	Ouertani	EC impact analysis in a multi technical information system context	(Ouertani 2004)	x	x		x	
39	Ou-Yang & Chang	Web-based query system that enables the user to refer to the constraint information and assembly information	(Ou-Yang and Chang 1999)	x	x		x	
40	PFEV Model	Product Feature Evolution Validation model aiming at controlling the information flow needed to support a product definition evolution	(Bouikni *et al.* 2006), (Bouikni *et al.* 2008)	x			x	
41	Qiu & Wong	Dynamic workflow change in PDM systems	(Qiu and Wong 2007)			x	x	
42	Raffaeli et al.	Modelling of possible change propagation path based on components and functional flows.	(Raffaeli *et al.* 2007)	x			x	
43	Reddi & Moon 1	Automatic identification of affected components based on change type and likeliness	(Reddi and Moon 2009)	x	x		x	
44	Reddi & Moon 2	A framework for ECM in enterprise resource planning using service-oriented architecture	(Reddi and Moon 2011a)	x	x		x	
45	Reddi & Moon 3	System dynamics modelling of ECM in a collaborative environment	(Reddi and Moon 2011b)			x		
46	RedesignIT	Model-based reasoning to generate and evaluate proposals of redesign plans	(Ollinger and Stahovich 2001), (Ollinger and Stahovich 2004)	x	x	x	x	
47	Roser et al.	Economic evaluation of design change options under uncertainty	(Roser *et al.* 2003)		x			
48	Rouibah & Caskey	ECM in concurrent engineering from a parameter perspective	(Rouibah and Caskey 2003), (Rouibah *et al.* 2007)	x	x	x	x	
49	Tseng et al.	Evaluating a design change and the distributed manufacturing operations in a collaborative manufacturing environment	(Tseng *et al.* 2008)	x	x	x		
50	VEC-Hub	Virtual Enterprise Collaboration Hub, an approach to enable collaborative ECM in the virtual/ extended enterprise	(Rosén and Almyren 2009)	x			x	
51	Wasmer et al.	An approach to shared, cross-organisational EC handling	(Wasmer *et al.* 2011)	x	x	x	x	
52	Wu et al.	Implementation and application of a CMII-based system for ECM	(Wu *et al.* 2010)	x			x	
53	Xue et al.	Evolutionary design database	(Xue *et al.* 2005)	x			x	
54	You & Chao	Propagation of design change between different CAD by using duplicate design procedures	(You and Chao 2009)	x			x	
Total number				**45**	**36**	**18**	**41**	**4**

3.6 Discussion of the state-of-the-art findings

3.6.1 Distribution of the number of publications over year

The distribution of the publication numbers in Figure 22 shows a discontinuous increase until 2007 with a peak of 50 publications in 2007 and a continuous decrease after 2007 with 28 publications in 2010 and 19 in the first three quarters of 2011. This reflects also the distribution in each of the two subgroups: journal articles and conference papers. From this distribution, it could be concluded that the interest in ECM research steadily increased until 2007, achieved its peak in 2007, and has been decreasing since then but still remains at a higher level compared to the period before 2000. A deeper analysis of the numbers of publications by source shows that 20 out of the 50 publications in 2007 came from ICED 2007 and were mainly submitted by European researchers. This conference took place in Paris and might have attracted many ECM papers partly also due to travelling convenience for the major European research groups. Just as the number of published conference papers for a given year depends on the parameters of the conferences, the number of journal articles depends on journal parameters such as the number of reviewers, the backlog, special issues, etc. Therefore, any conclusion from the distribution of the number of publications over time on the level of interest in ECM is difficult. However, the pattern suggests an overall increase of research interest in ECM which is without controversy. Wright’s review which was published in 1997 possibly contributed to this positive development leading to a significant increase of journal articles in 1999.

The number of conference papers is concentrated in the period after 2000 with zero conference papers between 1985 and 1994. This is due to the fact that the majority of considered publications until 1995 stem from the review by Wright (1997) which does not include any conference papers between 1985 and 1994. Although, Wright’s list of publications was completed by cross referencing of key publications and by the open search, no conference papers published in that period were found. Thus, it can be assumed that little work on ECM was published in conferences before 1995 and that ECM did not become established as a perennial topic within relevant conferences on engineering design until the early 2000s.

3.6.2 Distribution of the number of publications over categories

The overview of the categorisation results in Table 2 and accordingly in Figure 23 shows an irregular distribution of the total number of publication over categories. This can be traced back to mainly two reasons. First, the scope of the categories is different. For example, the categories *(A.1)*, *(A.2)*, *(A.3)*, and *(D.1)* which cover ECM related research from other specific research areas are wide-open, whereas the borders of the other categories are more stringent. Second, the research challenges within the categories are different. For example, while change classification is straightforward, change prediction and impact analysis still poses a huge challenge for research. *Authorisation,* for instance, is an important step but could be considered more as a gate at the end of the process step *Impact analysis* than a separate process step. The authorisation decision is based on the results of the impact analysis. Therefore, publications addressing authorisation primarily focus on impact analysis. There is no publication which in the first place addresses authorisation issues, such as, what is the authorisation procedure, who is involved in decision making, what procedures are required to authorise a change, when is which type of authorisation required, how do tools support authorisation, what information is required for decision-making. As a result, the category B.4.4 in Figure 23 is empty; Harhalakis (1986), and Rouibah and Caskey (2003) contribute to this category as a secondary focus (Hamraz *et al.* 2013a). However, to remain consistent with the well accepted ECM process proposed by Jarratt *et al.* (2004c), all six process steps are considered as separate categories within the framework.

Considering both of these factors, the profile discloses the following insights:

- Research in *(A) Pre-change stage* mainly focuses on *(A.3) Product-oriented* and *(A.2) Process-oriented* measures to reduce the number and impact of ECs and less on *(A.1) People-oriented* measures.
- Research in *(B) In-change stage* mainly focuses on *(B.4.3) Impact analysis*, *(B.4.6) Documentation and review* and *(B.3) ECM systems*, while *(B.1) Organisational issues* and *(B.4.5) Implementation* of ECs are infrequently addressed.
- Research in *(C) Post-change stage* mainly focuses on *(C.6) General sources and impacts*, impacts on *(C.4) Pre-manufacturing stage*, and *(C.1) Delays*. There is a lack of research on the impacts of ECs on *(C.3) Quality* and *(C.5) Manufacturing & post-manufacturing stage.*

The distribution of the number of journal articles and conference papers over year by category according to their primary contribution in Table 2 shows different patterns for the categories. While *(B.4.6) Documentation & review, (B.5) EC process*, and most of the post-change categories *(C.1-C.6)* have received continuous attention during the period from early 1980s to present, *(B.3) ECM systems, (B.4.3) Impact analysis, and (B.4.5) Implementation* were not addressed as late as the early 2000s.

3.6.3 ECM methods

From the categorised journal articles and conference papers, 54 unique ECM methods were identified. Of these, the majority are developed through a sequence of publications; CPM and the method from Chen & Li are the most widely published. The relationship between the methods and the guidelines they address is represented in the Euler diagram in Figure 24.

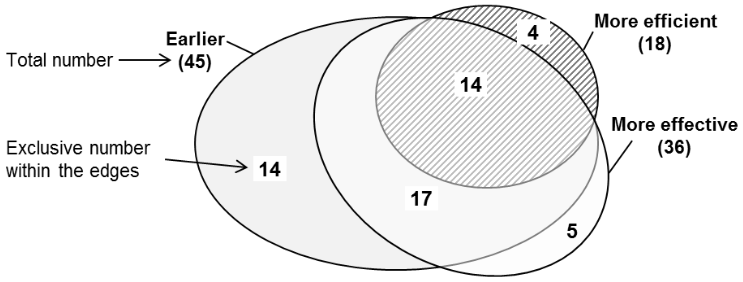


Figure 24: Euler diagram for the addressing of the three guidelines by the 54 ECM methods

Figure 24 indicates that most methods provide means to support earlier detection, faster handling, and improved communication of EC (i.e. *Earlier*: 45 methods, or 83%), while two-thirds address better assessment of change impacts for better decision making which changes to implement (i.e. *More effective*: 36 methods, or 67%). Only one-third addresses supporting the implementation planning of changes (i.e. *More efficient*: 18 methods, or 33%). The majority of the methods address more than one guideline (31 methods, or 57%); of these, 14 methods address all three guidelines and 17 methods address the two guidelines *Earlier* and *More effective*. From the 23 methods which address only one guideline, the majority address *Earlier* (14 methods) and less than one-quarter address either *More effective* (5 methods) or *More efficient* (4 methods).

Although computer tools were proposed for 41 methods, it was determined that the tools were actually available only for four of them – the method reported by Chen & Li, CPM, CPM-House-of-Quality, and House of Quality. For the other methods, a computer tool is either not explicitly reported (e.g. C-FAR), or is reported but not available. Reasons for unavailability include: the tool was implemented within a company and so is proprietary and confidential (e.g. the method from Rouibah & Caskey); the tool was not made accessible (e.g. RedesignIT); or the tool is no longer maintained (e.g. Cyber-Review).

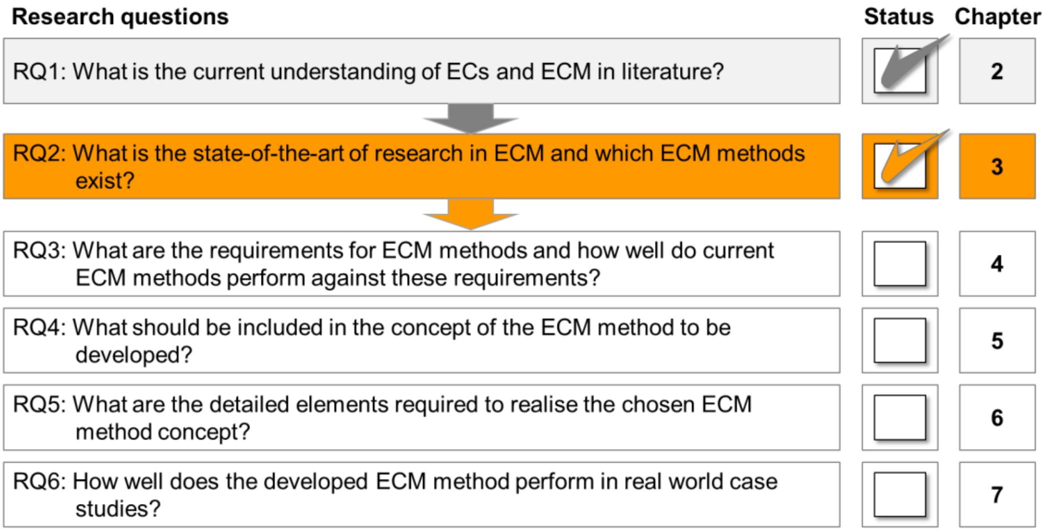
3.7 Chapter summary

This chapter has proposed a new, holistic and process-oriented categorisation framework for ECM literature. This framework visualises the big picture of the ECM research field and allows a comprehensive coverage and precise categorisation of publications in ECM and related areas. Drawing on an exhaustive systematic literature review which identified 384 journal articles and conference papers and 43 books, book sections, and other reports, the framework was used to categorise these publications and generate the current picture of research in ECM.

As depicted in Figure 23, this picture shows that major research areas are in *(A) Pre-change stage,* product- and process-oriented research to reduce the impact of ECs, in *(B) In-change stage,* impact analysis, documentation and review, and systems to ease the handling of ECs, and in *(C) Post-change stage*, general surveys on sources and impacts of ECs to learn for the future. In contrast, little research has been done in *(A) Pre-change stage* on people-oriented EC reduction measures, in *(B) In-change stage* on organisational issues and implementation of ECs, and in *(C) Post-change stage* on impact of ECs on quality and manufacturing & post-manufacturing stage.

Furthermore, the categorisation result was used to identify the current ECM methods and the guidelines addressed by them. Thereby, the 173 journal articles and conference papers listed in the categories *(B.3)* and *(B.4)* were considered and 54 methods were identified. The quantitative analysis of the addressed guidelines showed that the majority address *Earlier* and/ or *More effective* and only one-third *More efficient* and that only for four methods computer tools were actually available although for 41 methods such tools were proposed.

In conclusion, this chapter has answered the second research question. In combination, the findings from Chapters 2 and 3 support the need for an appropriate ECM method and direct the remainder of this research towards the development of such a method. A method can be developed in a similar way like an artefact, following the stages of requirements identification, conceptual design, detail design, and evaluation. To guide this research through these stages, four remaining research questions were formulated accordingly (Figure 25). These questions will be addressed consecutively in the following chapters.



Research questions	Status	Chapter
RQ1: What is the current understanding of ECs and ECM in literature?	☑	2
RQ2: What is the state-of-the-art of research in ECM and which ECM methods exist?	☑	3
RQ3: What are the requirements for ECM methods and how well do current ECM methods perform against these requirements?	☐	4
RQ4: What should be included in the concept of the ECM method to be developed?	☐	5
RQ5: What are the detailed elements required to realise the chosen ECM method concept?	☐	6
RQ6: How well does the developed ECM method perform in real world case studies?	☐	7

Figure 25: Research questions and status after Chapter 3

4 Requirements for and Competitive Assessment of ECM Methods

“Intelligence is the ability to adapt to change.”

(Stephen Hawking, British physicist, born 1942)

4.1 Chapter introduction

The insights gained from Chapter 2 showed that ECs and their propagation are crucial for complex designs and that a number of methods were proposed to support ECM. Chapter 3 identified 427 relevant publications in ECM through a systematic literature search and categorised them in the proposed framework to provide a state-of-the-art overview of research in ECM. This result was then used to identify current ECM methods and list their corresponding publications. In total, 54 ECM methods and the corresponding journal articles and conference papers that report them were identified. The findings from both chapters determined the course of this research towards the development of an ECM method. For guidance, four research questions were formulated.

This chapter addresses the third research question (RQ3: What are the requirements for ECM methods and how well do current ECM methods perform against these requirements?) by developing a set of requirements for ECM methods and assessing eight of the most promising ECM methods against these requirements. It is structured in three remaining sections. Section 4.2 develops a comprehensive list of requirements for ECM methods. Section 4.3 presents a comparative assessment of prominent current methods against this list of requirements. Section 4.4 summarises the chapter.

4.2 Identification of requirements for ECM methods

Systematic development of products, systems, or software starts with requirements analysis (Pahl *et al.* 2007). This crucial lifecycle phase should clarify the task, create a common understanding among all stakeholders, and determine the specific needs and conditions that the developed artefact has to fulfil. The degree to which the requirements are met by the developed artefact is one measure of success.

Despite the existence of numerous ECM methods in the literature, there is not much published on requirements for ECM methods. In fact, of the 173 journal articles and conference papers listed in the framework categories *B3 (ECM Systems)* and *B4 (ECM Methods & IT tools)* in Figure 23, only Lee *et al.* (2006) and Rouibah and Caskey (2003) appear to base their methods on an explicit analysis of requirements. Lee *et al.* (2006) studied the EC processes of a major Korean automobile company and determined their ECM requirements from the perspective of knowledge management and collaboration support. Rouibah and Caskey (2003) addressed requirements for multi-company ECM and grouped them into (1) *Support communication*, (2) *Involve all relevant parties*, (3) *Work toward consensus*, (4) *Control the process*, and (5) *Identify the scope of impact*. In the research literature other authors do discuss selected requirements but do not report a systematic analysis. For instance, some requirements are listed in Ph.D. theses such as Ariyo (2007), Ahmad (2011), Koh (2011).

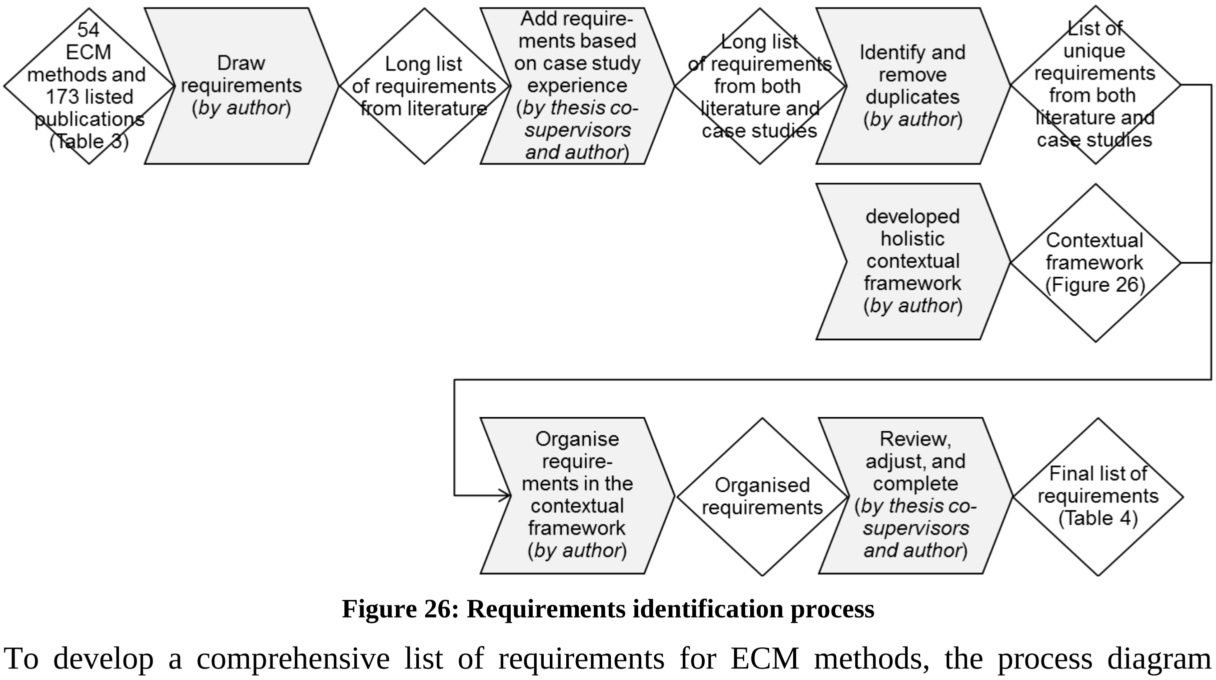


Figure 26: Requirements identification process

To develop a comprehensive list of requirements for ECM methods, the process diagram depicted in Figure 26 was followed. First, the author analysed the journal articles and conference papers listed in Table 3 in detail to draw requirements from literature. Key features of each method that the corresponding authors propose are important to its effective operation were identified, and corresponding requirements were drawn. Next, the thesis co-supervisors, Dr Nicholas H.M. Caldwell and Dr David C. Wynn, and the author added requirements that they thought are relevant based on their experience from past ECM related case studies to this list. Altogether, these case studies span over a period of ten years and included collaborative projects conducted at automotive, aerospace, oil, and telecommunication industry as partly reported elsewhere (e.g. Wynn (2007), Koh *et al.* (2012)). Then, the author studied the resulting long list of requirements from both literature and case studies to identify and remove duplicates and produce a list of unique requirements.

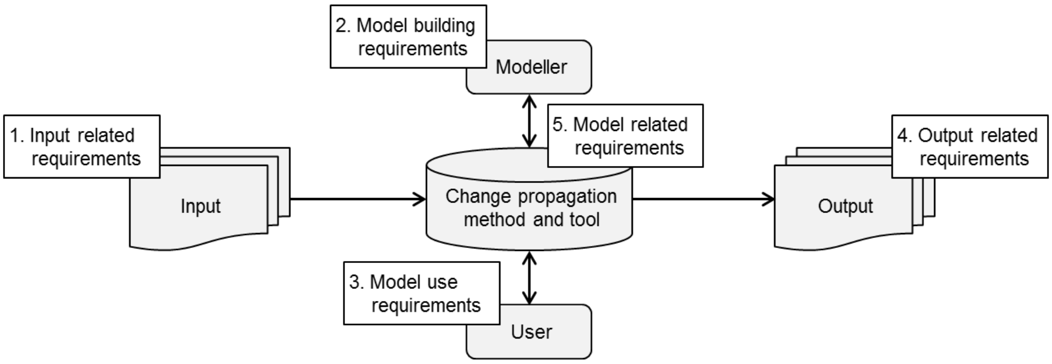


Figure 27: Contextual framework for identifying and organising requirements for ECM methods

Concurrently, the author developed a holistic contextual framework consisting of five requirement categories (Figure 27). In its centre, this framework considers the resulting ECM model and its capabilities. In its horizontal dimension, the framework accounts for the transformation function of ECM methods through the categories related to the method's input and output. In its vertical dimension, the framework considers the method's interactions with the modeller and user.

Subsequently, the author organised the list of unique requirements into these five categories. Finally, the two thesis co-supervisors and the author reviewed the list of organised requirements and further adjusted and completed it. This process resulted in 25 requirements, listed in Table 4.

Table 4: Requirements for an ECM method

No	Category	Requirement name	Description of required capability	Selected source(s) for rationale
1	1. Input related (scope/ feasibility)	Range of products covered	Allows manageable modelling of a variety of different products, from low to high complexity.	(Clarkson *et al.* 2004, Ollinger and Stahovich 2004, Chen *et al.* 2007)
2		Range of levels of decomposition supported	Allows modelling of the whole product on different levels of decomposition (i.e. system, component, part, attribute).	(Cohen *et al.* 2000, Ariyo *et al.* 2007a, Kocar and Akgunduz 2010)
3		Range of different changes covered	Allows modelling of changes from different kinds, i.e. domains, life cycle time, purpose, initiator, cause, target, and considers the change magnitude.	(Rutka *et al.* 2006, Ma *et al.* 2008, Reddi and Moon 2009)
4	2. Model building	Ease of model building	The model building procedure is easy, i.e. it can be done by any practitioner if an appropriate manual is provided.	Case study experience
5		Availability of information to build the model	The required information or knowledge can be easily collected from documents (i.e. drawings, specifications etc.) or experts (i.e. interviews etc.).	(Cohen *et al.* 2000, Clarkson *et al.* 2004, Kocar and Akgunduz 2010)

No	Category	Requirement name	Description of required capability	Selected source(s) for rationale
6		Accessibility of tools to build the model	The tools to create a model (i.e. DSM, Excel, other software programs) are available, openly accessible, or easily implementable.	Case study experience
7		Accuracy	The model captures all relevant dependencies explicitly and avoids hidden and implicit dependencies between product attributes.	(Goel and Stroulia 1996, Ollinger and Stahovich 2004, Ahmad *et al.* 2010a)
8		Consistency	The model-building approach supports consistency checks, ensuring that the model is internally consistent and consistent with other models.	(Xue *et al.* 2005, Do *et al.* 2008, Kocar and Akgunduz 2010)
9		Adaptability	A model of an existing product can be adapted to analyse a new product, i.e. existing models can be re-used easily.	(Goel and Stroulia 1996, Ma *et al.* 2008, Ahmad *et al.* 2010a)
10		Benefit-to-cost ratio of model building	The benefit of model building (i.e. knowledge creation, communication support etc.) outweighs the total cost of model building (i.e. material cost, personal cost).	Case study experience
11	3. Model use	Ease of model use	The use of the model is easy, i.e. it can be used by any designer if an appropriate manual is provided.	Case study experience
12		Accessibility of tools to use the model	Support tools to use the method (i.e. DSM, Excel, other software programs) are available, openly accessible, or easily implementable.	Case study experience
13		Practicality	The approach is applicable to a real situation and effective in use.	(Clarkson *et al.* 2004, Ollinger and Stahovich 2004, Chen *et al.* 2007)
14		Flexibility	The model can easily be changed / updated.	(Chen *et al.* 2007, Kocar and Akgunduz 2010)
15		Benefit-to-cost ratio of model use	The benefit of model use (i.e. prediction capability, communication support etc.) outweighs the total cost of model use (i.e. material cost, personal cost).	(Clarkson *et al.* 2004, Reddi and Moon 2009)
16	4. Output related (results)	Utility of results	Provide useful analysis for different users (i.e. at different levels of detail) and depict results clearly.	(Rouibah and Caskey 2003, Clarkson *et al.* 2004, Kocar and Akgunduz 2010)
17		Quantity of results	Provide sufficient and complete analyses.	(Rouibah and Caskey 2003, Chen *et al.* 2007, Bouikni *et al.* 2008)
18		Quality of results	Provide correct and accurate results (difficult to assess!).	Case study experience
19	5. Model related (capability / function-ality)	Product modelling capability	Descriptively model the product to represent and improve product understanding and support product improvement and communication.	(Ollinger and Stahovich 2004, Jarratt *et al.* 2004b, Lee *et al.* 2010)
20		Change modelling capability	Descriptively model change impacts.	(Rouibah and Caskey 2003, Ollinger and Stahovich 2004, Ma *et al.* 2008)
21		Change prediction capability	Predict changes caused by change propagation.	(Jarratt *et al.* 2004b, Kocar and Akgunduz 2010, Cheng and Chu 2011)
22		Change containment capability	Support causal change propagation analysis by capturing how and why changes propagate between different product attributes, to allow change control and containment.	(Ollinger and Stahovich 2004, Chen *et al.* 2007)
23		Solution finding capability	Enable development and testing of alternative solutions and support the solution selection process.	(Ollinger and Stahovich 2004, Chen *et al.* 2007, Koh and Clarkson 2009)
24		Numerical analysis capability	Allow numerical and probabilistic change prediction and risk analysis.	(Clarkson *et al.* 2004, Lee *et al.* 2010, Cheng and Chu 2011)
25		Compatibility	Support integration with other tools.	(Huang *et al.* 2001a, Habhouba *et al.* 2011, Wasmer *et al.* 2011)

The requirements are not ranked but merely grouped into the five categories. Altogether, these requirements ensure that the ECM method is useful to support the management of ECs in industry (i.e. utility), usable by modellers and designers in practice (i.e. usability), and affordable by companies in terms of benefit-to-cost (i.e. economic viability).

4.3 Comparative assessment of current ECM methods

The 25 requirements described above (Table 4) were used as criteria to rate a selection of most seminal existing ECM methods. To select the most promising ECM methods from the 54 identified in Chapter 3, the author followed three steps: Firstly, the methods that were reported before the year 2000 and not up-dated in 2000 or later were considered as (1) out-dated and excluded. Secondly, the methods that addressed only one of the proposed guidelines *Earlier*, *More effective*, *More efficient* and thus were (2) specialised on only one aspect of ECM were excluded. Thirdly, for the remaining methods, the corresponding publications listed in Table 3 were studied to exclude methods which: (3) were not sufficiently reported to allow for a detailed evaluation against the requirements, (4) were considered as adaptions of or showed similarities to original methods, or (5) were considered as not relevant for other reasons as specified below (Table 5).

Table 5: Selection procedure of the ECM methods

No	Method/ reference name	Reason for exclusion:					Selected
		(1) out-dated	(2) specialised on only one aspect of ECM	(3) not sufficiently reported	(4) adaptions of or similarities to:	(5) not relevant because:	
1	ADVICE						X
2	Ahmad et al.				CPM		
3	CECM		X				
4	C-FAR						X
5	Chen & Li						X
6	Chen et al.		X				
7	Cheng & Chu				CPM		
8	CIRA			X			
9	CMCEA	X					
10	CPA				CPM		
11	CPD			X			
12	CPM						X
13	CPM-House-of-Quality				CPM		
14	Cyber-Review		X				
15	DEPNET		X				
16	Do et al.		X				
17	ΔDSM			X			
18	EC Propagator		X				
19	ECBOM			X			
20	ECD-BOM			X			
21	EchoMag		X				
22	Feature Elasticity		X				
23	Fei et al.			X			
24	Flanagan et al.			X			
25	Horvath et al.		X				
26	House of Quality					not aimed primarily at ECM	
27	ITA Phase II	X					
28	Joshi et al.			X			
29	Krishnamurthy & Law	X					
30	KRITIK2	X					
31	Lee et al.		X				
32	Li et al.		X				
33	Liu et al.			X			
34	Ma, S. et al.			X			
35	Ma, Y. et al.						X
36	Mehta et al.		X				
37	Mokhtar et al.	X					
38	Ouertani			X			
39	Ou-Yang & Chang	X					
40	PFEV Model		X				

No	Method/ reference name	Reason for exclusion:					Selected
		(1) out-dated	(2) specialised on only one aspect of ECM	(3) not sufficiently reported	(4) adaptions of or similarities to:	(5) not relevant because:	
41	Qiu & Wong		X				
42	Raffaeli et al.		X				
43	Reddi & Moon 1						X
44	Reddi & Moon 2				Reddi & Moon 1		
45	Reddi & Moon 3		X				
46	RedesignIT						X
47	Roser et al.		X				
48	Rouibah & Caskey						X
49	Tseng et al.			X			
50	VEC-Hub		X				
51	Wasmer et al.			X			
52	Wu et al.		X				
53	Xue et al.		X				
54	You & Chao		X				
Total		**6**	**21**	**13**	**5**	**1**	**8**

This filtering procedure resulted in the selection of the following eight methods: *ADVICE, C-FAR, CPM, Redesign IT*, and the methods from *Chen & Li, Ma, Y. et al., Reddi & Moon 1,* and *Rouibah & Caskey*. These eight methods were thoroughly reviewed based on the available information which included all corresponding publications listed in Table 3. For CPM and the method from Chen & Li, the software or the Matlab-based codes and their manuals were considered alongside research publications describing them. For each of these methods, a detailed assessment table was prepared. To illustrate, the detailed assessment of CPM is shown in Table 6. The corresponding tables for the remaining seven methods can be found in the Appendix.

Table 6: Detailed assessment of CPM

No	Category	Requirement name	CPM score	Rationale for CPM score
1	1. Input related (scope/ feasibility)	Range of products covered	5	very broad; applied to a hairdryer, diesel engine, helicopter etc.; relative simplicity of technique makes it applicable to products of very high complexity
2		Range of levels of decomposition supported	2	only one level at a time which could be systems or components but not more detailed levels like attributes
3		Range of different changes covered	3	all kind of changes affecting components; changes to functions and behaviours must be translated to component changes; magnitude of changes not considered
4	2. Model building	Ease of model building	5	very easy and clear; two DSMs with direct likelihood and impact values need to be elicited
5		Availability of information to build the model	4	good; expert interviews; basic information; limited use of available documentation
6		Accessibility of tools to build the model	5	any tools to capture two matrices (DSMs) can be used
7		Accuracy	3	average; expert estimations without explicit rationale
8		Consistency	4	high; pairwise linkage building without any sources of inconsistencies
9		Adaptability	4	high; existing models can be used to a certain extent and need to be manually modified to adapt to other products
10		Benefit-to-cost ratio of model building	4	high benefit (change model; product model, communication support etc.) and low cost (only expert interviews but no buying or programming of tools needed)
11	3. Model use	Ease of model use	4	easy to use; run calculation, identify changed component, read imposed change risk to other components
12		Accessibility of tools to use the model	4	CAM tool and CPM module are freely available
13		Practicality	4	high; when a component changes, the model provides information about imposed risks on other components
14		Flexibility	3	average; linkage values need to be changed or defined for new components and calculations updated
15		Benefit-to-cost ratio of model use	4	high benefit (change prediction, communication support etc.) and low cost (low use effort and free software)
16	4. Output related (results)	Utility of results	4	high; risk profiles, critical components, depiction of change paths, etc.; clearly depicted; but no different levels of detail for different users
17		Quantity of results	4	high; combined likelihood, impact, risk, for different number of steps and for the whole product; different other analyses; but currently only for one change at a time
18		Quality of results		not assessable
19	5. Model related (capability / function-ality)	Product modelling capability	3	average; product model shows the links between components or systems; but at high level only without hierarchical decomposition and without capturing working mechanisms
20		Change modelling capability	4	good; change propagation along all possible links; but only at component level
21		Change prediction capability	3	average; based on estimated direct likelihood and impact values; considering all direct and indirect links; but limited accuracy and only on component level
22		Change containment capability	2	rather poor; no rationale of change propagation within the model; does not directly support control of propagation
23		Solution finding capability	2	rather poor; only predicts change paths and shows no solutions
24		Numerical analysis capability	5	very good; numerical linkage values and algorithm for change risk calculation
25		Compatibility	4	good; DSM-based results with import/export to xml and Excel files

Rating scale: 1 (poor) … 3 (average) … 5 (excellent)

The assessment scores of all eight methods are consolidated in Table 7; the rationales of these scores can be found in the Appendix. The quality of results (Requirement 18) was excluded from this analysis, because there is insufficient published information to assess it for any of the methods. For each category, the best-in-class benchmarks (i.e. best methods with regard to the given category) are highlighted.

Table 7: Rating results of ECM methods

No	Category	Criterion (i.e. Requirement name)	CPM	Chen & Li	Rede-sign IT	Ma, Y. et al.	Rouibah & Caskey	Reddi & Moon 1	C-FAR	ADVICE
1	1. Input related (scope/ feasibility)	Range of products covered	🟩 5	4	4	2	3	2	3	2
2		Range of levels of decomposition supported	2	3	2	2	3	3	🟩 4	🟩 4
3		Range of different changes covered	3	4	3	🟩 5	4	3	3	3
4	2. Model building	Ease of model building	🟩 5	3	3	2	2	3	2	2
5		Availability of information to build the model	🟩 4	3	3	2	3	3	3	3
6		Accessibility of tools to build the model	🟩 5	4	3	2	3	4	4	2
7		Accuracy	3	🟩 4	🟩 4	2	🟩 4	🟩 4	🟩 4	3
8		Consistency	🟩 4	3	3	2	3	3	3	🟩 4
9		Adaptability	🟩 4	🟩 4	🟩 4	2	3	2	🟩 4	3
10		Benefit-to-cost ratio of model building	🟩 4	3	3	2	3	3	2	2
11	3. Model use	Ease of model use	🟩 4	3	🟩 4	🟩 4	3	🟩 4	1	3
12		Accessibility of tools to use the model	🟩 4	🟩 4	1	2	1	2	2	1
13		Practicality	🟩 4	🟩 4	3	3	🟩 4	3	2	3
14		Flexibility	🟩 3	🟩 3	🟩 3	🟩 3	🟩 3	🟩 3	🟩 3	🟩 3
15		Benefit-to-cost ratio of model use	🟩 4	🟩 4	🟩 4	🟩 4	3	3	2	3
16	4. Output related (results)	Utility of results	🟩 4	🟩 4	3	3	3	3	2	3
17		Quantity of results	🟩 4	3	3	2	2	2	2	3
18		Quality of results (not assessable)								
19	5. Model related (capability / function-ality)	Product modelling capability	3	3	🟩 4	3	🟩 4	3	3	2
20		Change modelling capability	🟩 4	2	3	🟩 4	🟩 4	🟩 4	3	3
21		Change prediction capability	3	2	3	🟩 4	3	🟩 4	3	2
22		Change containment capability	2	🟩 5	🟩 5	4	3	3	3	2
23		Solution finding capability	2	🟩 5	4	4	3	2	3	1
24		Numerical analysis capability	🟩 5	2	2	1	1	1	🟩 5	3
25		Compatibility	🟩 4	3	2	3	3	3	3	3
Total number of best-in-class benchmarks			**17**	**9**	**7**	**6**	**5**	**5**	**5**	**3**
Unweighted average score			**3.7**	**3.4**	**3.2**	**2.8**	**3.0**	**2.9**	**2.9**	**2.6**

Rating scale: 1 (poor) … 3 (average) … 5 (excellent)	🟩 best-in-class benchmark

The rating outcome suggests that CPM (17 benchmarks) is superior compared to the other methods, followed by the method from Chen & Li (9 benchmarks), and RedesignIT (7 benchmarks). However, the benchmarks show that for some criteria other methods are better than CPM. Furthermore, it can be taken from the rating that for over half of the criteria the best mark of 5 is not achieved by any method. The unweighted average scores mostly underline the rating order but show smaller relative gaps between the methods.

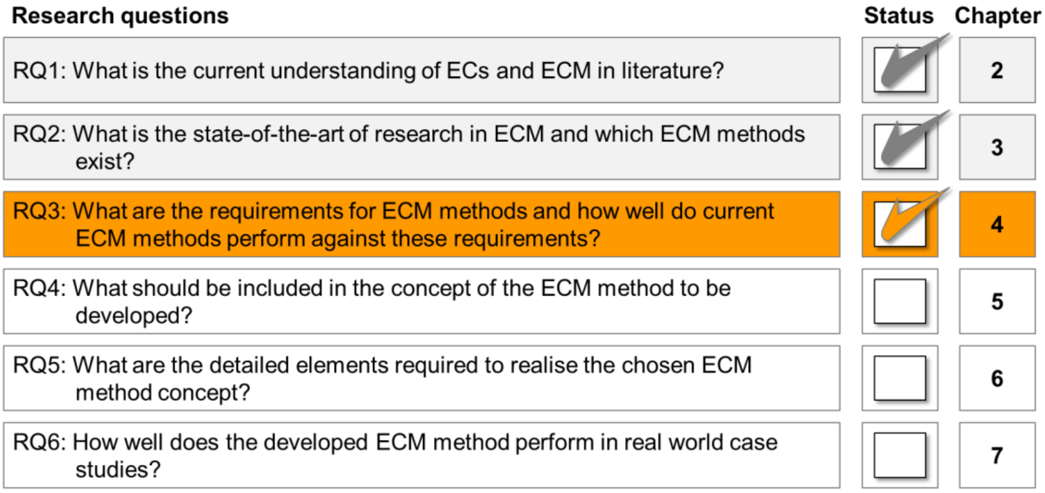
Acknowledging the difficulty of such a detailed rating under the condition of incomplete and unequal amount of available information for different methods, the results of this assessment are indicative rather than definitive. Furthermore, although care was taken to obtain an appropriate ranking, for instance, by comparing all methods directly to each other for one criterion at a time, it should be noted that this scoring approach involves a certain amount of unavoidable subjectivity and might be biased because it was conducted by only one person. For the use in this thesis, this comparison is sufficient. For other purposes, the assessment could be conducted by more evaluators and averaged for each criterion. Then, the criteria scores could be weighted according to the specific needs of the client to calculate overall scores. This might possibly lead to a different ranking.

4.4 Chapter summary

Drawing on the literature and industrial experience, this chapter has identified 25 requirements for ECM methods which focus on executing changes *Earlier*, *More effective*, and *More efficient*. These requirements were organised into the five categories related to: (1) input, (2) model building, (3) model use, (4) output, and (5) model. They include amongst others: range of covered products and changes, availability of information, accessibility of tools, and ease to build and use the model, utility of results, and different capabilities of the model itself.

Next, these requirements were used as criteria to assess current ECM methods. The rating of eight nominated methods revealed that CPM is overall the comparatively best method, but for some criteria, the benchmarks are set by other methods.

Thereby, this chapter has answered the third research question (Figure 28). A concept for an enhanced ECM method which addresses the identified requirements will be developed in the next chapter.



Research questions	Status	Chapter
RQ1: What is the current understanding of ECs and ECM in literature?	☑	2
RQ2: What is the state-of-the-art of research in ECM and which ECM methods exist?	☑	3
RQ3: What are the requirements for ECM methods and how well do current ECM methods perform against these requirements?	☑	4
RQ4: What should be included in the concept of the ECM method to be developed?	☐	5
RQ5: What are the detailed elements required to realise the chosen ECM method concept?	☐	6
RQ6: How well does the developed ECM method perform in real world case studies?	☐	7

Figure 28: Research questions and status after Chapter 4

5 Conceptual Design of the FBS Linkage Method

“Change the way you look at things
and the things you look at change.
(Wayne W. Dyer, American self-help advocate, born 1940)

5.1 Chapter introduction

This chapter addresses the fourth research question (RQ4: What should be included in the concept of the ECM method to be developed?) by developing the conceptual design of such a method.

The concept is designed following a benchmarking approach built on the comparative assessment in Chapter 4. In Section 5.2, the method to be improved is selected and its comparative weak points identified. Then, in Section 5.3, for those weak points, improvement suggestions are drawn from the best-in-class methods. Section 5.4 presents potential concepts for the implementation of the improvement suggestions to the CPM method, before one concept is selected in Section 5.5. Finally, the chapter is summarised in Section 5.6.

5.2 Method selection

The assessment in Section 4.3 clearly suggests selecting CPM as the comparatively best rated method with 17 best-in-class benchmarks. However, to improve on any method, the availability of information (*Requirement 5*) and the accessibility of tools to build (*Requirement 6*) and use the model (*Requirement 12*) are crucial. As CPM is at the same time the best-in-class method for those criteria, this did not pose any conflict and CPM was selected as the method to be improved. Next, the criteria for which other methods outperform CPM (i.e. competitive gaps) were determined from Table 7. There are seven such competitive gaps suggesting that by learning from the best-rated methods, CPM could be improved in terms of levels of decomposition (*Requirement 1*), coverage of different changes (*Requirement 2*), accuracy (*Requirement 7*), product modelling (*Requirement 19*), change prediction (*Requirement 21*), change containment (*Requirement 22*), and solution finding capabilities (*Requirement 23*).

5.3 Improvement suggestions

To address the seven identified competitive gaps, the corresponding best-in-class methods were analysed to draw improvement suggestions for CPM (Table 8).

Table 8: Competitive gaps and drawn improvement suggestions for CPM

No	Criterion (i.e. Requirement name)	Selected benchmark method(s)	Improvement suggestion for CPM	Rationale for improvement suggestion
2	Range of levels of decom-position supported	C-FAR ADVICE	Allow modelling the product and representing the results on different levels of detail at once and on more detailed levels.	This will allow building CPM models on different levels of detail (i.e. the whole product on systems level and one of its systems on component level) according to the intended use and available resources, as well as facilitate use of the models by people from different departments for high level or more in-depth decisions.
3	Range of different changes covered	Ma, Y. et al.	Capture product aspects other than components which might be the initial target of a change request, such as functions, behaviours, or structural attributes.	This will allow CPM to differentiate between and thus model more types of changes.
7	Accuracy	RedesignIT Rouibah & Caskey	Include rationales for the links between attributes or parameters into the model.	This will improve CPM by providing a systematic basis for deciding whether a connection exists or not, thus reducing possibility of mistakes while modelling.
19	Product modelling capability	RedesignIT Rouibah & Caskey	Model the working mechanisms of the product and include interfaces between domains describing different aspects of the design.	This will enhance the CPM product model to an explanatory and integrated model and improve the understanding of change implications.
21	Change prediction capability	Reddi & Moon I Ma, Y. et al.	Consider links between attributes and components explicitly in the model.	This will avoid the need to consider implicit links between components, which lead to hidden dependencies if not captured in CPM, and thus improve its prediction capability.
22	Change containment capability	Chen & Li RedesignIT	Model change implementation alternatives and support identification of decisions that create less change propagation.	This will improve CPM by allowing investigation of different change alternatives to select the best option.
23	Solution finding capability	Chen & Li	Support identification of solution plans and redesign strategies.	This will improve CPM by helping users to identify solutions to change requests, which is specifically helpful when it is not obvious which components to change.

5.4 Potential concepts for the implementation of the improvement suggestions to the CPM method

To collect ideas of how to implement the improvement suggestions in Table 8, the methods identified in Section 3.5 were analysed and a few ideas from the publications categorised in Section 3.4 were considered. By limiting the search for ideas to this list of categorised publications, only concepts that were already used in the context of ECM were considered. Moreover at this stage, it was considered as important to take a few different alternative ideas into account before selecting one; however, the list of identified ideas reflects the author's experience and is not exhaustive.

Some of these collected ideas were already part of CPM, for instance, the use of weighted complex networks (Li *et al.* 2008), or matrices (Cohen *et al.* 2000), and others were already tried on CPM, for instance, the integration of House of Quality (Koh *et al.* 2012), or the inclusion of change types (Lemmens *et al.* 2007). These ideas were not further considered.

Yet other ideas were new to CPM, namely, the use of concepts related to parameters (Rouibah and Caskey 2003), virtual reality (Aurich and Roessing 2007, Kocar and Akgunduz 2010), system dynamics (Reddi and Moon 2011b), axiomatic design (Suh 1998, Guenov and Barker 2005), product architecture (Ulrich 1995), and functional reasoning (FR) (Goel and Stroulia 1996, Van Beek *et al.* 2010). In the following subsections, these yet on CPM unexplored ideas will be briefly introduced, before they will be evaluated against the identified improvement suggestions from Table 8 to select the most promising concept in the next section.

5.4.1 Parameters

ECs affect engineering variables. In their parameter-based concurrent engineering, Rouibah and Caskey (2003, p. 23) refer to *"to the most elementary of these engineering variables as parameters"*, stating that they can refer to dimensions as well as forces and movements. This definition goes along with the more comprehensive definition in the Oxford English Dictionary: *"[Parameter in a technical context is] a numerical or other measurable factor forming one of a set that defines a system or sets the conditions of its operation"*.

Rouibah and Caskey (2003) captured the relationships between parameters and used them to model and analyse the impact of ECs. Incorporating such a parameter concept into CPM could enhance the CPM product model from the component level to the more detailed parameter level and potentially allow more accurate change analysis.

5.4.2 Virtual reality

"A virtual reality is defined as a real or simulated environment in which a perceiver experiences telepresence", where telepresence refers to any medium-induced (remote) sense of presence (Steuer 1992, p. 76). In engineering design, virtual reality can be applied to immerse the user into the virtual environment, allow him to interact with it, and run real time 3D simulations (Kan et al. 2001, Wiendahl et al. 2003).

Kocar and Akgunduz (2010) used virtual collaborative design environments and sequential pattern mining techniques to facilitate ECM. Their tool merges relevant graphical and parametric data into a virtual platform and allows engineers to raise, view, and accept or reject proposed changes in a graphically visualised environment. Similarly, Aurich and Roessing (2007) applied virtual reality to provide the user with a realistic visualisation and related information for change impact analysis. The incorporation of virtual reality technology into CPM could enhance its graphical capabilities.

5.4.3 System dynamics

System Dynamics (SD) is a technique which uses the system variables and their cause and effect relations to model complex systems as stock (representing states) and flow networks (Ford and Sterman 1998). SD modelling allows framing, simulating, and managing of systems with an emphasis on their dynamic behaviours. The technique is mostly used for modelling of processes with feedback loops. SD models of design process are very abstract and include only a few states and flows. For instance, Ford and Sterman (1998) used only five states to describe the overall product development process (Figure 29).

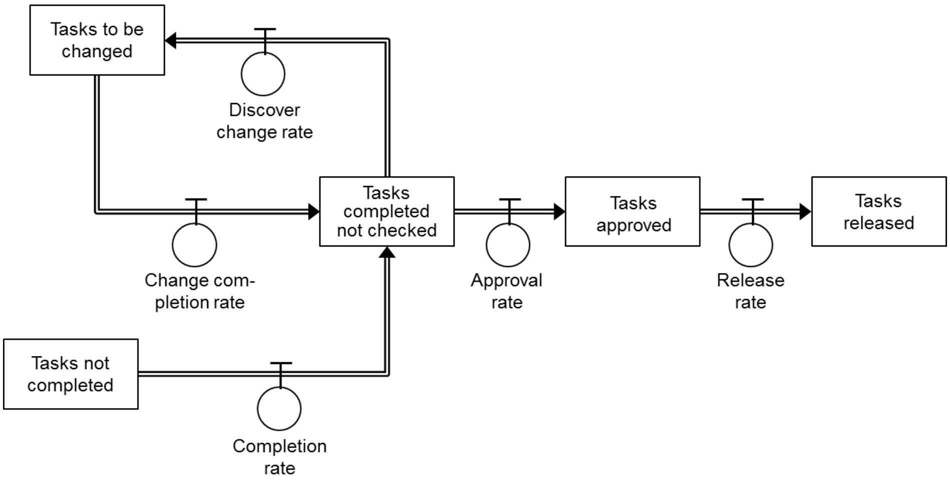


Figure 29: SD model of the overall product development process

Source: Adapted from Ford and Sterman (1998)

Reddi and Moon (2011b) developed SD models for the new product development processes including ECM processes across the supply chain and investigated the effect of the ECM process on the overall development lead time. The incorporation of SD models into CPM could enhance its capability for process lead time simulations and analysis.

5.4.4 Axiomatic design

In the axiomatic design theory, the design context is described based on the four domains: customer, functional, physical, and process domain (Suh 1998). Each of them contains a characteristic vector representing respectively customer needs, functional requirements, design parameters, and process variables. Suh (1998) suggested a general theory of systems using the last three of these domains as hierarchies to represent the system architecture:

- *"[Functional requirements (FRs) are] a minimum set of independent requirements that completely characterizes the functional needs of the product (or software, organizations, systems, etc.) in the functional domain"* (p. 205).
- Design parameters (DPs) are the key variables in *"the physical domain that characterize the design satisfying the specified FRs [functional requirements]"* (p. 205).
- Process variables (PVs) relate to the designing process domain that generates the specified product.

Guenov and Barker (2005) and Janthong (2011) decomposed systems based on the axiomatic design theory into the two hierarchies of FRs and DPs and applied DSMs to investigate the interdependencies between DPs; furthermore, Janthong (2011) used these dependencies to trace the change impacts among the DPs. The incorporation of the axiomatic design domains into CPM could allow change propagation analysis in greater detail considering the domains of FRs, DPs; it seems also to provide the possibility to establish a link from the change model to the design process domain.

5.4.5 Product architecture

Ulrich (1995, p. 419) defined product architecture as *"the scheme by which the function of a product is allocated to physical components"*. More formally, he specified the product architecture as (p. 420): *"(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; and (3) the specification of the interfaces between interacting components."*

The first clause refers to the functional structure of the product and Ulrich explained that *"The function of a product is what it does as opposed to what the physical characteristics of the product are"* (p. 420). Detail level functional structures *"embody more assumptions about the physical working principles on which the product is based"* (Ulrich 1995, p. 421). The second clause refers to the implementation of functional elements by physical elements (i.e. the components). This transformation of pre-defined product functions to alternative product layouts is according to Stone *et al.* (2000b) the core of the product architecture developing process. Ulrich (1995, p. 421) explained further that *"the mapping between functional elements and components may be one-to-one, many-to-one, or one-to-many."* The third clause refers to the specification of the connections of components. Interacting components are connected by interfaces to each other. These coupling-interfaces include geometric and non-contact connections. Components that do not interact with each other are de-coupled.

Finally, based on this framework, Ulrich (1995) developed a typology of different product architectures and investigated how the product architecture determines the impact of ECs. The incorporating of the product architecture concept into CPM could enhance CPM to consider the relations between form and function and combine change propagation analysis with product architecture decisions in earlier design phases.

5.4.6 FR frameworks

FR approaches model a product in the context of its functions, behaviours, and structures, including causal explanations of how the functions of a product are realised by behaviours which are exhibited by determined structures. FR was elaborated in Section 2.4.

Goel and Stroulia (1996) applied their SBF framework to analyse and support the diagnosis task when a design shows failures in the context of design modifications. Using the three layers of SBF, they defined three types of diagnosis tasks, correspondingly related to a failure in the device functions, behaviours, or structures and showed how their framework can be used to support the diagnostic search. Van Beek *et al.* (2010) used the FBSt framework to develop a modularisation scheme. They transferred the relations between the FBSt entities into a DSM and applied clustering algorithms to identify modules. Incorporating an FR scheme to CPM would enhance CPM to model the product in a greater detail by explicitly considering its structural, behavioural, and functional attributes and causal relations in the context of the product functions and working mechanisms.

5.5 Concept selection

To select the most promising of these concepts for the implementation of the improvement suggestions to the CPM, the six potential concepts presented above were rated against the seven identified competitive gaps of CPM in Table 8. For this rating, the author studied the corresponding publications and used a scale from 1 (poor) to 5 (excellent) to rate the potentials of these concepts with regard to implementing the improvement suggestions to CPM. It should be appreciated that this rating was conducted only by the author and thus could be biased. However, for the systematic comparison of the six concepts with regard to improving CPM and selection of one concept for this thesis, it is sufficient. The results of this rating including brief rationales for each score are summarised in Table 8.

Table 9: Rating of the concepts' potentials to address the improvement suggestions

No	Requirement name	Improvement suggestion for CPM	Rating score and brief rationale for:					
			FR frameworks	**Axiomatic design**	**Product architecture**	**Parameters**	**Virtual reality**	**System dynamics**
			(Goel and Stroulia 1996) (Van Beek *et al.* 2010)	**(Suh 1998) (Guenov and Barker 2005) (Janthong 2011)**	**(Ulrich 1995)**	**(Rouibah and Caskey 2003)**	**(Kocar and Akgunduz 2010) (Aurich and Roessing 2007)**	**(Reddi and Moon 2011b) (Ford and Sterman 1998)**
2	Range of levels of decomposition supported	Allow modelling the product and representing the results on different levels of detail at once and on more detailed levels.	5 hierarchical decomposition supported	5 hierarchical decomposition supported	5 hierarchical decomposition supported	1 parameters relate to the detailed levels only	1 hierarchies not supported	1 hierarchies not supported
3	Range of different changes covered	Capture product aspects other than components which might be the initial target of a change request, such as functions, behaviours, or structural attributes.	5 functional, behavioural, and structural attributes	4 FRs and DPs	3 functions and components	3 parameters may relate to functions and physical attributes	1 does not distinguish between different ECs	1 does not distinguish between different ECs
7	Accuracy	Include rationales for the links between attributes or parameters into the model.	5 causal attribute links systematically considered	5 causal link between DPs and FRs systematically considered	4 causality between components and functions present	3 causality for parameter links present, but parameters or links could be missed out	3 improved graphical representation may help to increase accuracy	2 causal stock and flow diagrams present but focus on process
19	Product modelling capability	Model the working mechanisms of the product and include interfaces between domains describing different aspects of the design.	4 working mechanisms considered; structural domain could be linked to processes	5 working mechanisms considered; customer needs and process variables linked	3 working mechanisms considered in the function-component scheme	3 working mechanisms only implicitly considered; parameters could be linked to other domains	4 improved graphical representation may help to understand working mechanisms and links to other domains	2 modelling of working mechanisms difficult; link to process domain present

No	**Require-ment name**	**Improvement suggestion for CPM**	**Rating score and brief rationale for:**					
			FR frameworks	**Axiomatic design**	**Product architecture**	**Parameters**	**Virtual reality**	**System dynamics**
			(Goel and Stroulia 1996) **(Van Beek *et al.* 2010)**	**(Suh 1998)** **(Guenov and Barker 2005)** **(Janthong 2011)**	**(Ulrich 1995)**	**(Rouibah and Caskey 2003)**	**(Kocar and Akgunduz 2010)** **(Aurich and Roessing 2007)**	**(Reddi and Moon 2011b)** **(Ford and Sterman 1998)**
21	Change pre-diction capability	Consider links between attributes and components explicitly in the model.	5 links between functional, behavioural, and structural attributes explicitly considered	4 links between FRs and DPs explicitly considered	4 links between functions and components explicitly considered	3 links between parameters considered	3 improved graphical representation may help with change prediction	1 abstract stock and flow models with emphasis on the process
22	Change contain-ment capability	Model change implementation alternatives and support identification of decisions that create less change propagation.	5 explanatory scheme shows how EC propagation can be reduced	5 axioms and architecture flow diagrams help reducing EC propagation	4 modulari-sation helps reducing EC propagation	3 parameter maps can be used to minimise the number of affected parameters	4 change alternatives could be virtually tested to reduce EC propagation	4 simulations could help to reduce change propagation
23	Solution finding capability	Support identification of solution plans and redesign strategies.	5 comprehend-sive scheme shows solution space	5 axioms and modules support finding solutions	4 modules and architecture support finding solutions	4 required parameters and related tasks could be identified	3 improved graphical representation may support finding solutions	4 simulations could support finding solutions based on change lead times
Unweighted average score			4.9	4.7	3.9	2.9	2.7	2.1

Rating scale: 1 (poor) … 3 (average) … 5 (excellent)

Of these new ideas, the incorporation of an FR scheme into CPM seemed to be the most promising as can be taken from the unweighted average scores in Table 9. Such an FR scheme would enhance the model with rationales for the links between product attributes, and hence, address *Requirements 7, 19*, and *22*; and it would capture more aspects of the product in the model, and thus, address *Requirement 3*. In particular, a three-layered FR scheme which distinguishes between functional, behavioural, and structural (FBS) attributes seemed to address also the rest of the suggestions. Each element of such an FBS scheme can be the initial target of a change request and a change to one element might propagate along the links to other elements. While the traditional CPM approach treats the dependencies between components as black boxes and quantifies them based on expert estimations without capturing their rationales, the incorporation of an FBS scheme would clarify those dependencies by decomposing them into causal attribute relations. This allows users of the FBS Linkage method to model changes at the more detailed level of attributes, while also improving their understanding of why and how changes propagate in the first place and enabling pro-active change management as will be detailed in Subsection 6.6.7.

To sum up, integrating an FBS scheme into the CPM approach promises the potential improvement suggestions as represented in the right hand side of Table 10.

Table 10: CPM benchmark improvement suggestions and potential improvements by an FBS scheme

No	Requirement name	Improvement suggestion for CPM		Potential improvement by incorporating an FBS scheme to CPM
2	Range of levels of decomposition supported	Allow modelling the product and representing the results on different levels of detail at once and on more detailed levels.	◀	FBS schemes support hierarchical decomposition and break down products up to the attribute level.
3	Range of different changes covered	Capture product aspects other than components which might be the initial target of a change request, such as functions, behaviours, or structural attributes.	◀	FBS schemes consider functional, behavioural, and structural attributes of the product.
7	Accuracy	Include rationales for the links between attributes or parameters into the model.	◀	FBS schemes provide rationales for the links between attributes.
19	Product modelling capability	Model the working mechanisms of the product and include interfaces between domains describing different aspects of the design.	◀	FBS schemes are explanatory models and their attributes provide interfaces which could be interlinked to other domains.
21	Change prediction capability	Consider links between attributes and components explicitly in the model.	◀	FBS schemes explicitly consider all relevant links required to fulfil the product's functions.
22	Change containment capability	Model change implementation alternatives and support identification of decisions that create less change propagation.	◀	FBS schemes explain how and why attributes are linked to each other and could be used to simulate alternative change decisions.
23	Solution finding capability	Support identification of solution plans and redesign strategies.	◀	FBS schemes can be used for synthesis and solution finding tasks.

This method is termed *FBS Linkage* and may proceed similarly to CPM but should incorporate an FBS scheme instead of a component dependency model as depicted in Figure 30. The detail design of this method is elaborated in the next chapter.

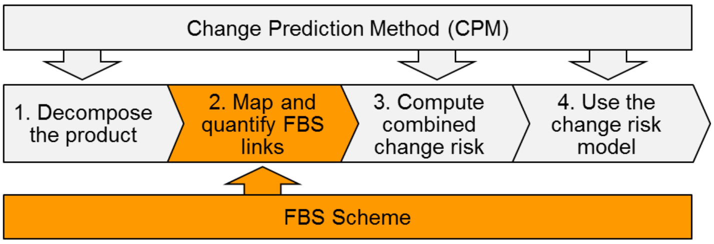
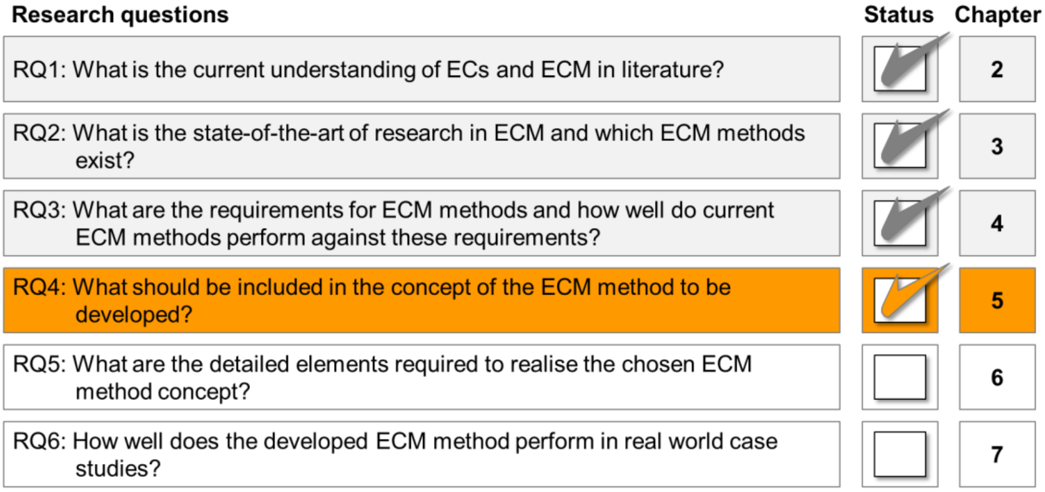


Figure 30: Concept of the FBS Linkage method

5.6 Chapter summary

In this chapter, a benchmarking approach was taken to develop the concept for an improved change propagation method - the FBS Linkage method. Drawing on the comparative assessment of Chapter 4, the CPM approach was selected as a starting point for the development of the concept. Subsequently, the benchmarks from other methods were investigated to determine how the CPM approach could be improved by learning from them while maintaining its own benchmarks. Then, the categorised publications and identified ECM methods were used to generate ideas for implementing the improvement suggestions to CPM. Six concepts that were yet unexplored on CPM were taken into further consideration and their potential to implement the improvement suggestions were rated. Based on this ranking, the concept for the FBS Linkage method was developed. This concept prescribes the integration of the CPM approach with a three-layered FR scheme.

Thereby, this chapter has answered the fourth research question (Figure 31). The proposed concept will be detailed in the next chapter.



Research questions	Status	Chapter
RQ1: What is the current understanding of ECs and ECM in literature?	☑	2
RQ2: What is the state-of-the-art of research in ECM and which ECM methods exist?	☑	3
RQ3: What are the requirements for ECM methods and how well do current ECM methods perform against these requirements?	☑	4
RQ4: What should be included in the concept of the ECM method to be developed?	☑	5
RQ5: What are the detailed elements required to realise the chosen ECM method concept?	☐	6
RQ6: How well does the developed ECM method perform in real world case studies?	☐	7

Figure 31: Research questions and status after Chapter 5

6 Detail Design of the FBS Linkage Method

"The world as we have created it is a process of our thinking.
It cannot be changed without changing our thinking."
(Albert Einstein, German physicist, 1879-1955)

6.1 Chapter introduction

This chapter addresses the fifth research question (RQ5: What are the detailed elements required to realise the chosen ECM method concept?) by presenting the detail design of the FBS Linkage method. The method's conceptual design suggests an integration of the CPM approach with an FBS scheme. This chapter elaborates that integration, specifies the FBS scheme, and develops and demonstrates the technique.

The chapter is structured into six remaining sections. Section 6.2 discusses the incorporation of an FBS scheme into CPM. Section 6.3 compares the ontologies of the three seminal FBS schemes in terms of their applicability for change propagation analysis. Based on that detailed comparison, Section 6.4 develops the FBS Linkage ontology and Section 6.5 discusses its application to develop an FBS Linkage scheme for a product. Section 6.6 demonstrates the FBS Linkage technique. Finally, Section 6.7 summarises the chapter.

6.2 Incorporation of an FBS scheme to CPM

CPM uses a model of the dependencies between component pairs to model change propagation and compute the overall risk of change propagation imposed on other components if one component changes. CPM assumes that a change to one component can only propagate to another component if they are directly linked to each other (i.e. direct change propagation) or if there is a path between them leading over several intermediary components (i.e. indirect change propagation). This assumption is essential, not only for CPM but for most existing propagation methods. It allows the use of network models to describe change propagation. According to Gero and Kannengiesser (2004, p. 374) *"A designer constructs connections between the function, behaviour and structure of a design object through experience. Specifically, the designer ascribes function to behaviour and derives behaviour from structure."* Such an FBS scheme may be represented as a multilayer network composed of functional, behavioural, and structural attributes, and the attribute connections can be used to describe how changes propagate between the network elements: A change to one FBS element might impact other elements if they are directly or indirectly related to each other. Thus, for an FBS scheme, it can be assumed analogous that:

ECs can only propagate between structural, behavioural, and functional elements along available links in the FBS scheme.

This assumption enables the integration of an FBS scheme into CPM by replacing the component network of CPM with an FBS network. As described in Subsection 2.3.1, the CPM technique proceeds with quantifying the component links in terms of likelihood and impact of change propagation. The links in the FBS network may be quantified similarly. Consequently, the Forward CPM algorithm may be applied to this numerical FBS network to compute the combined risk of change propagation.

In a similar way as the FBStr concept could be used to model the design process from early stages of design (Gero and Kannengiesser 2004), this method may be applied already in the conceptual stage, where information about functional requirements is available but the structure is incomplete; and the designer proceeds by linking functions to behaviours and behaviours to structures to determine the FBS network. Thus, in the early design phases, the FBS network is incomplete and evolves. For the method here, this means, in early design stages where the network is incomplete, change propagation can only be described within the already existing parts of the network. This allows the method to be used to assess the impact of adding new elements to the network on the existing elements. Apart from the CPM application, the FBS network opens the door to a number of possible applications to support designers at different phases of PD, from conceptual design, over embodiment design, to detail design and throughout the product life cycle. A few of these applications in the context of ECM will be discussed in Section 6.6. The discussion of possible applications outside of change management goes beyond the scope of this thesis.

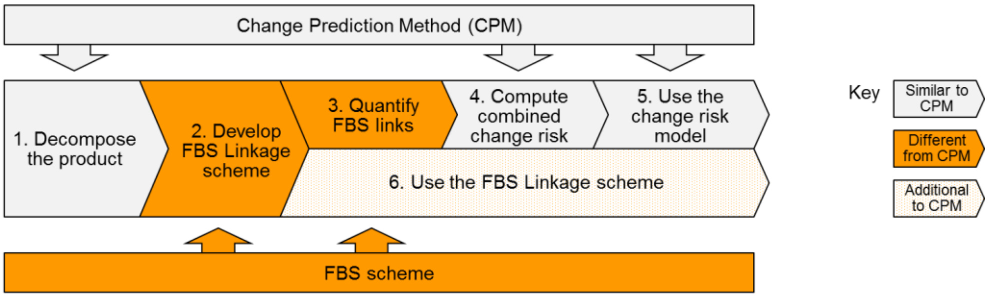


Figure 32: Stages of the FBS Linkage method

In overview, the FBS Linkage method proceeds in six stages as depicted in Figure 32, including three similar stages to CPM (i.e. *1. Decompose the product*, 4. *Compute combined change risk*, and 5. *Use the change risk model*), two modified stages (i.e. *2. Develop FBS Linkage scheme* and *3. Quantify FBS links* instead of the CPM step *Map and quantify component links*), and one additional stage (i.e. 6. *Use the FBS Linkage scheme*).

The core of the FBS Linkage method is the FBS Linkage scheme. To specify this scheme, first, the ontologies of the three seminal FBS schemes will be thoroughly reviewed and compared in the context of change propagation analysis in the next section. Then, a modified ontology for the FBS Linkage method will be developed in Section 6.4.

6.3 Comparison of the ontologies of SBF, FBSta, and FBStr

It is important to notice that although SBF, FBSta, and FBStr have many aspects in common, their purpose is different. While the SBF and FBSta schemes are focused on explaining the mechanisms of products, the FBStr scheme is more concerned with explaining the design process based on the function-behaviour-structure thinking. This difference reflects in their ontologies.

Table 11 includes a detailed comparison of these three schemes structured according to the three layers structure, behaviour, function, and the two joining spheres between structure and behaviour, and behaviour and function. This comparison shows that all three ontologies agree on causal links from structure over behaviour to function and avoid direct links from structure to function. Furthermore, they agree on the view of function as the teleology of the object. However, they incorporate different representation forms: SBF represents functions in state transition schema, FBSta in a *"to do"* form and FBStr in a more general *"verb object"* form. The differences for behaviour are more significant. SBF refers to behaviour as causal processes of artefacts (internal behaviours) that result in its functions, whereas behaviour in FBSta stands for output behaviours of an artefact of which its functions are an abstracted subset. Gero's FBStr, on the other hand, refers to behaviour as the properties of structural elements. Also in terms of structure they differ significantly. SBF represents structure by components, substances (i.e. material and abstract physical quantities), and relations between both, where component specifications contain, in addition to attributes, their primitive functions. FBSta represents structure as entities (referring to components and abstract physical quantities such as *"paper weight"*), their attributes, and relations. The notion of state in FBSta (where the term *state* comprises enduring structure plus temporary state) highlights the instantaneous character of structure and implies its changes of state through behaviours. FBStr on the other hand does not include abstract physical quantities in the structural description.

Table 11: Comparison of the SBF, FBSta, and FBStr ontologies

Ontology	**Structure-Behaviour-Function (SBF)**	**Function-Behaviour-State (FBSta)**	**Function-Behaviour-Structure (FBStr)**
Main publi-cations	• (Sembugamoorthy and Chandrasekaran 1986) • (Goel and Chandrasekaran 1989) • (Goel and Stroulia 1996) • (Goel *et al.* 2009)	• (Umeda *et al.* 1990) • (Umeda *et al.* 1996) • (Umeda and Tomiyama 1997) • (Van Beek *et al.* 2010)	• (Gero 1990) • (Gero *et al.* 1992) • (Qian and Gero 1996) • (Rosenman and Gero 1998) • (Gero and Kannengiesser 2004) • (Vermaas and Dorst 2007)
Function	**Key distinction:** state transition schema **Definition:** *“Functions in SBF describe the role that an Element plays in the overall operation of a device. They express the purpose or goal of the Element, whereas the Behavior describes how the purpose is accomplished”* (Goel *et al.* 2009, p. 26). Functions are represented as a schema that specifies their pre-conditions, post-conditions, the behaviour that accomplishes the function, and possibly conditions under which the specified behavior achieves the given function (Goel *et al.* 2009). **Example** (Goel *et al.* 2009, p. 24): • Function: transfer angular momentum • Pre-condition: angular momentum magnitude Li • Post-condition: angular momentum magnitude Lo • By behaviour: transfer angular momentum	**Key distinction:** *“to do”* form **Definition:** Function is *"a description of behavior abstracted by human through recognition of the behavior in order to utilize it. […] in general, [functions are] represented in the form of ‘to do something’”* (Umeda *et al.* 1990, p. 183). **Examples** (Umeda *et al.* 1996, p. 277): • to make a sound • to generate light	**Key distinction**: *“verb object”* form **Definition:** *“Function (F) variables: describe the teleology of the object, i.e. what it is for”* (Gero and Kannengiesser 2004, p. 374). *“A function may be a physical function, such as ‘providing sufficient space’, or a non-physical function such as ‘providing an ambience’”* (Rosenman and Gero 1998, p. 169, 170). **Examples** (Gero and Kannengiesser 2004, p. 381): The functions of a window are: • enhancing winter solar gain • controlling noise • providing view • providing daylight
Links betw. Function and Be-haviour	**Key distinction**: rational, one-to-one relation *“The representation of a function of a device also includes a pointer to the internal behavior of the device that results in the function”* (Goel and Stroulia 1996, p. 360). *“Each Element in an SBF Model has a Function, and each Function has a corresponding Behavior”* (Goel *et al.* 2009, p. 28).	**Key distinction**: rational, subjective (designer’s choice), many-to-many relation *“The relationships between functions and behaviors are subjective and many-to-many correspondent”* (Umeda *et al.* 1996, p. 276).	**Key distinction**: rational, subjective (designer’s choice), many-to-many relation *“Specifically, function is ascribed to behavior by establishing a teleological connection between the human’s goals and observable or measurable effects of the object”* (Gero and Kannengiesser 2007, p. 380). *“...one function may correspond to many behaviors and one behavior may be associated with more than one function”* (Qian and Gero 1996, p. 291).
Behaviour	**Key distinction:** internal behaviours/ sequence of state transitions **Definition:** *“The "B" in a SBF device model refers to the internal behaviors of the device that specify how the structure of the device delivers its functions, or, in general, its output behaviors”* (Goel and Stroulia 1996, p. 356). *“A behavior is represented as a sequence of states and transitions between them”* (Goel *et al.* 2009, p. 25). *“SBF models use an ontology of primitive functions based on the component–substance ontology, which enables a more precise specification of state transitions in a behaviour”* (Goel et al. 2009, p. 26). **Example** (Goel *et al.* 2009, p. 25):	**Key distinction**: output behaviours/ sequence of state transitions **Definition:** *“Introducing a discrete unit time, we define behavior as "sequential state transitions along time," and assume that physical phenomena determine behavior of an entity”* (Umeda *et al.* 1996, p. 276). **Examples** ” (Umeda *et al.* 1996, p. 276, 277): • hitting a bell • oscillating a string • a lamp lighting • a battery generating electricity	**Key distinction:** derivable attributes **Definition:** *“Behaviour (B) variables: describe the attributes that are derived or expected to be derived from the structure (S) variables of the object, i.e. what it does”* (Gero and Kannengiesser 2004, p. 374). *“A behaviour is thus a description of the object’s actions or processes in given circumstances”* (Rosenman and Gero 1998, p. 169). **Examples** (Gero and Kannengiesser 2004, p. 381**)**: The behaviours of a glass are: • thermal conduction • light transmission • direct solar gain

Ontology	**Structure-Behaviour-Function (SBF)**	**Function-Behaviour-State (FBSta)**	**Function-Behaviour-Structure (FBStr)**
	• Behaviour: transfer angular momentum • State 1: momentum at gyroscope with magnitude M_input • Transition by using function: *“allow angular momentum of linkage gyroscope-worm wheel”* • State 2: momentum at pivot with magnitude L_ww		
Links betw. Behaviour and Structure (State)	**Key distinction**: causal, objective (by physical laws) Many-to-many relation. *“Each component plays a functional role in a state transition in one or more internal behaviors of the device; […] A component may also be affected by some state transition”* (Goel and Stroulia 1996, p. 379). *“Causal explanations for state transitions may include physical laws, mathematical equations, functions of its subsystems, structural constraints, other behaviors, or a state or transition in another behaviour”* (Goel *et al.* 2009, p. 25).	**Key distinction**: causal, objective (by physical laws), In general, many-to-many relation. Within one view/aspect: one (behaviour)-to-many (states) relation *“However, a transition from a state to the next state [i.e. a behaviour] does not occur at random but is governed by some principles; viz. physical laws“* (Umeda *et al.* 1990, p. 183). *“However, representations of behavior may differ depending on the physical situations of the current interest. […] To represent this difference, we introduce aspects. An aspect is a collection of all relevant entities, attributes, relations, and physical phenomena of the current interest”* (Umeda *et al.* 1996, p. 276).	**Key distinction**: causal, objective (by physical laws) Many-to-many relation. *“Behavior is causally connected to structure, that is, it can be derived from structure using physical laws or heuristics”* (Gero and Kannengiesser 2007, p. 380). *“Similarly [to the links between functions and behaviors], behavior can be derived from more than one structure”* (Qian and Gero 1996, p. 291).
Structure or state	**Key distinction:** components, substances (i.e. physical quantities), and relations **Definition:** *“In SBF models, structure is represented in terms of components, the substances contained in the components, and connections among the components. The specification of a component includes its functional abstractions”* (Goel *et al.* 2009, p. 24). *“Each component has one or more primitive functions relative to the substances: allow, move, pump, create, destroy, or expel”* (Goel and Stroulia 1996, p. 358). *“The specification of a substance includes its properties”* (Goel *et al.* 2009, p. 24). **Examples** (Goel *et al.* 2009, p. 31): • Components: gyroscope, worm wheel, pivot • Substance: angular momentum • Connections: contains, connected	**Key distinction:** defined state of entities (components, physical quantities), their attributes, and relations **Definition:** The state of an entity is defined by *“a set of entities, a set of attributes, and a set of relations”* amongst them (Umeda *et al.* 1990, p. 182). An entity could be a component, system, or product, its attribute any property which can be observed by scientific means, and a relation any link between entities, attributes, or relations (Umeda *et al.* 1990). The notion of state implies *“changes of state”* through behaviours “ (Umeda *et al.* 1990, p. 183). **Examples** (Umeda *et al.* 1990, p. 182): • Entities: paper weight, paper • Relation: "on", i.e. the paper weight is on the paper. • Attributes of paper: weight, volume, density, which are also related to each other.	**Key distinction:** elements (components), structural attributes, and relations **Definition:** *“The structure specifies what elements the design is composed of, what the attributes of the elements are, and how they are related”*, i.e. what it is (Qian and Gero 1996, p. 291). *“These structural properties are those which a designer directly manipulates in order to generate a physical solution to an abstract problem. Thus, while designers take many things into consideration in the course of designing, ultimately what they do is select structural variables and assign to them values representing material properties, shape descriptions, dimensions, location and connectivity”* (Rosenman and Gero 1998, p. 169). Elements could be assemblies, components, or parts. *“An element has many properties, or attributes, for example, color, shape, material, and so on. […] If the elements are physical, the relationship between them is a physical interconnection using topological or geometrical data”* (Qian and Gero 1996, p. 292). **Examples** (Gero and Kannengiesser 2004, p. 381**)**: • Elements: glass, frame • Attributes: glazing length, type of coating, type of glass • Relation: glass and frame are geometrically interlinked.

Having conducted this detailed comparison, the question to be answered is which ontology to adapt for the FBS Linkage model. Many of these requirements can be addressed by using any one of the three ontologies discussed above as the basis for the change propagation model. For instance, all three ontologies represent the functions, behaviours, and structure of products explicitly and model causal relations between them while avoiding hidden or implicit dependencies. They allow capturing ECs which (initially) might affect any product attribute. However, all three ontologies focus on a very granulated level of detail; while they are very useful for reasoning purposes which go beyond the analysis of change propagation, they are hardly applicable for complex products where change propagation is more relevant. Furthermore, the ontologies define the attributes of all three layers and elaborate their inter-layer links, but they do not specify the links between attributes of the same layer (i.e. intra-layer links). Thus, they do not provide all information needed to build a complete product network which could be used for change propagation modelling. Finally, the effort of developing the ontologies is relatively high as all attributes have to be individually identified, described, and interlinked. Though the number of structural attributes is limited, there is a high number of behavioural attributes. This is especially true for the state-transition based ontologies SBF and FBSta which represent behaviours as a sequence of state transitions. In order to meet the requirements of a change propagation method listed in Section 4.2, a modified ontology has to be developed for the FBS Linkage model. This is the subject of the next section.

6.4 The FBS Linkage ontology

Drawing on the detailed comparison of the three seminal FBS schemes, a new ontology for the FBS Linkage method was developed. This is composed of eleven assumptions and represented in Table 12, using the same scheme as for the above comparison. Contrasting this ontology with the three seminal ontologies discussed above shows that, in general, the FBS Linkage ontology is most closely related to the FBStr ontology as it focuses on product properties rather than on state transitions. However, the FBS Linkage model specifies, enriches, and modifies the FBStr ontology in order to make it more applicable to complex products and usable for change propagation analysis. The specifications comprise a listing and narrowing down of the elements and links of each layer. The enrichments comprise the use and integration of the concepts from Pahl et al. (2007), McMahon (1994), and Hirtz et al. (2002) as means to identify and define these elements and links. The modifications comprise a focus on physical or technical functions described by input/output relations of flows rather than general *“verb object”* functions which might refer to non-technical functions (e.g.

aesthetic functions) and are considered as more subjective. In particular, the reconciled functional basis reported by Hirtz et al. (2002) was adopted for the functional layer, because it supports the development of systematic and unambiguous functional block diagrams by providing a comprehensive dictionary of functions and flows. This ontology helps reconcile different notions of function, which otherwise can lead to inconsistencies while modelling the functional structure of an existing design (Eckert *et al.* 2011).

Assumption 11 is a prerequisite for the FBS Linkage method which models a product's structural and behavioural layers at different levels of decomposition and its functional layer at the product level. The idea of product decomposition into smaller parts is based on a common principle of engineering to break down complex problems into smaller parts that are more easily manageable. Product decomposition is widely accepted and manifested in most other methods (e.g. CPM and other component-based DSMs) and strategies (e.g. modular design, product platform based design, and concurrent design).

Assumption 9 is closely linked to the concepts of *design properties* from Hubka and Eder (1996) and *design attributes* from McMahon (1994). In general, there is an appropriate number of independent types of structural or behavioural attributes. With reference to Hubka and Eder's *elementary design properties (i.e. form, dimensions, materials, surface)* and *general design properties (i.e. strength, stiffness, corrosion, pollution, hardness, noise emissions, etc.)* (Hubka and Eder 1996, p. 112) and McMahon's *explicit attributes "[which] must be must be explicitly defined for the artefact to be made"* and *implicit attributes "which describe the characteristics and behaviour of the artefact subjected to the external effects"* (McMahon 1994, p. 198), it is reasonable to assume that a fixed set of structural and behavioural attribute types may be determined for inclusion in a model, although the number of types may vary from case to case. If fewer attribute types than this are defined, the attributes are more likely to be insufficiently distinct and thus dependent; if more attribute types than this are defined, the attributes are more likely to be part of a higher level attribute and thus dependent. For instance, if only the two structural attribute types *Dimensions* and *Contents* were defined, it may not be clear to which of these two groups attributes such as *Form*, *Shape*, and *Surface* belong and this could lead to dependencies between *Dimensions* and *Contents*. On the other hand, if the *Dimensions* attribute was divided into *Axial dimensions* (length, width, height) and *Radial dimensions*, the radius of a cylinder could determine its width and this could lead again to dependencies between them.

Table 12: The FBS Linkage ontology

Ontology	FBS Linkage model
Main publi-cations	The FBS Linkage model is based on Gero's FBStr ontology and integrates concepts from: • (Pahl *et al.* 2007) • (McMahon 1994) • (Hirtz *et al.* 2002), (Stone and Wood 2000)
Function	**Key distinction**: operations interlinked by flows **Definition:** Function describes what the product is for. It specifies the (1) operations of the product and their (2) interrelations. **1. Functional elements:** Functions can be decomposed from product function to subfunctions at several levels of hierarchy down to a level where they can be linked to the behaviours which realise them (Pahl *et al.* 2007). They are defined as follows (Stone and Wood 2000, p. 359, 360): *"Product function: the general input/output relationship of a product having the purpose of performing an overall task, typically stated in verb-object form. Subfunction: a description of part of a product's overall task (product function), stated in verb-object form. Subfunctions are decomposed from the product function and represent the more elementary tasks of the product."* These lowest level functions are termed functional elements. **2. Functional links:** Functional interrelations might exist between functional elements in form of flows of material, energy, and information (Rodenacker 1971, Pahl *et al.* 2007). **Examples** for a hairdryer (Section 6.6): • Product function: produce and control hot air • Subfunctions (i.e. functional elements): import gas, guide gas, heat gas, focus and release gas • Functional links: air, electricity, thermal energy etc.
Function - behaviour links	**Key distinction**: rational, subjective (designer's choice), many-to-many relation **3. Rationality of function-behaviour links:** *"Specifically, function is ascribed to behavior by establishing a teleological connection between the human's goals and observable or measurable effects of the object"* (Gero and Kannengiesser 2007, p. 380). The links from behavioural attributes to functional elements depend on the designer's goals, experience, and knowledge. Thus, the links from the behavioural layer to the functional layer are rational and subjective. **4. (n:m)-Cardinality of function-behaviour links:** The relation between functional and behavioural elements is of type n:m (i.e. many-to-many). Hence, one functional element may depend on one or many behavioural elements (of different components), and one behavioural element may influence one or many functional elements. **Example** for a hairdryer (Section 6.6): • The 'focus and release gas' function is linked to the mechanical and aerodynamic behaviours of the fan and aerodynamic behaviours of the casing
Beha-viour	**Key distinction:** implicit attributes encompassing physical properties interlinked by product behavioural requirements **Definition:** Behaviour describes what the product does, i.e. how it reacts to external influences due to physical laws. It specifies (1) behavioural attributes of the constituent artefacts and their (2) behavioural interrelations. **5. Behavioural elements:** Behavioural attributes are *"[…] implicit attributes which describe the characteristics and behaviour of the artefact subjected to the external effects L. The implicit attributes describe the functional performance of the artefact, including such parameters as strength and durability. The term is used here, because the attributes are considered to be implicit in the design of the artefact. They may be estimated from the explicit attributes and the external effects. They may also, in some circumstances, be regarded as relationships between the explicit attributes and the external effects"* (McMahon 1994, p. 198). A behavioural attribute can encompass a group of physical properties, dependent on the type of product and level of detail. As behaviours are the mechanisms by which functions are achieved, these attribute types enable both the functions and the flows between them. Therefore, they are closely related to the types of flows between functions as defined by Hirtz et al. (2002) and Stone and Wood (2000). Behavioural element refers to a behavioural attribute of a specific constituent artefact, e.g. thermal behaviour

Ontology	FBS Linkage model
	of the casing. **6. Behavioural links:** Behavioural interrelations might exist between behavioural elements of the same attribute (e.g. thermal behaviour of component 1 and thermal behaviour of component 2) across constituent artefacts of a product due to the product behavioural requirements or proximity of the elements. For example, the product strength depends on the strength of its components or the thermal behaviour of a wire and its coating depend on each other. Ideally, there are no behavioural links between behavioural elements of different attributes (e.g. no link between thermal behaviour and mechanical behaviour). However, this is usually not the case for such behaviours as thermal and electrical. **Examples** for a hairdryer (Section 6.6): • (High level) behavioural attributes: mechanical (strength, inertia, elasticity, etc.), thermal (conduction, temperature change, absorption, resistance, etc.), electrical (conduction, resistance, charging, etc.), Chemical (affinity, reaction rate, radioactivity, etc.) • Behavioural elements: mechanical behaviour of the motor • Behavioural links: mechanical behaviour of the motor is linked to mechanical behaviour of the casing
Behaviour-structure (state) links	**Key distinction**: causal, objective (by physical laws), many-to-many relation **7. Causality of behaviour-structure links:** Behavioural attributes (i.e. implicit attributes) are realised by structural attributes (i.e. explicit attributes) and derivable by means of a physical theory from the structure of the artefact and possibly some properties of the environmental conditions (adapted from Gero (1990) and McMahon (1994)). Thus, the links from the structural layer to the behavioural layer are causal and objective. **8. (n:m)-Cardinality of behaviour-structure links:** The relation between behavioural and structural elements is of type n:m (i.e. many-to-many). Thus, within a component, a behavioural element may depend on one or many structural elements of different structural attributes, and a structural element may influence one or many behavioural elements of different behavioural attributes. **Examples** for a hairdryer (Section 6.6): • Aerodynamic behaviour of the fan is linked to its geometry and surface attributes • Mechanical behaviour of the casing is linked to its geometry and material attributes
Structure	**Key distinction:** constituent artefacts, explicit attributes, and relations **Definition:** Structure describes what the product consist of. It specifies what (1) constituent artefacts the design is composed of, what (2) the structural attributes of these artefacts are, and how they are (3) structurally related (adapted from Qian and Gero (1996)). **9. Structural elements:** Structural attributes are *"[…] explicit attributes describing the design, such as its dimensional parameters, the values of the properties of the materials from which the artefact is constructed, etc. They are termed explicit attributes here, because they must be explicitly defined for the artefact to be made"* (McMahon 1994, p. 198). Structural attributes are grouped into geometry (dimensions, shape descriptions), material (type, volume, density, and other explicit properties of material), surface (surface finish, texture, and micro dimensions of surface), colour (type, tone, intensity, and reflectance), controller (codes, microchips, relays). Structural element refers to a specific structural attribute of a specific constituent artefact, e.g. the material of the casing. **10. Structural links:** Structural interrelations might exist between structural elements of the same attribute (e.g. material of component 1 and material of component 2) across constituent artefacts of a product due to the product structural requirements. For example, the geometry requirement of the product interlinks the geometries of its constituent artefacts. Ideally, there are no structural links between structural elements of different attributes (e.g. no link between material and geometry). **11. Constituent artefacts/ Product decomposition:** A product can be decomposed into its constituent artefacts at different levels of detail. Constituent artefacts may refer to systems, assemblies, components, or parts, dependent on the selected level of detail. **Examples** for a hairdryer (Section 6.6): • Constituent artefacts (here components): fan, motor, heating unit, casing, control unit, power supply • Structural attributes: geometry, material, surface, colour, controller • Structural elements: geometry of the fan, material of the fan • Structural links: geometry of the fan is linked to geometry of the casing

The five structural attributes listed represent generic attributes which are applicable for most artefacts. However, the list might need to be adapted to model specific class of artefacts. Strictly speaking, the structural attributes are not independent; for example, the *Material* of a component might determine its *Surface finish*. However, the dependencies between structural elements of different attributes (e.g. *Material* ↔ *Surface finish*) can be neglected compared to the dependencies between structural elements of the same attribute across components (e.g. *Material* of *Component 1* ↔ *Material* of *Component 2*).

The restriction in Assumption 10 is a logical consequence of Assumption 9; the five types of structural elements cannot influence each other in the structural layer because they are considered as (structurally) independent.

Assumption 7 and 8 are drawn from Gero's FBStr model. As the structural layer is linked to the behavioural layer by causality, the links from structural elements to behavioural elements are (causally) deterministic. Thus, a change to a structural element will always have an impact on all behavioural elements which depend on it. On the other hand, due to the *(n:m)*-relation, a change to a behavioural element may be realised by change(s) to different possible structural elements. Thus, the links from behavioural elements backwards to structural elements are "*possibilistic*" and depend on the designer's decisions.

Assumptions 5 and 6, and 1 and 2 are similar to Assumption 9 and 10. Assumptions 3 and 4 are similar to the Assumptions 7 and 8.

6.5 Developing an FBS Linkage scheme

Based on the FBS Linkage ontology described above, an FBS scheme can be developed for the design to be analysed following the five steps depicted in Figure 33.

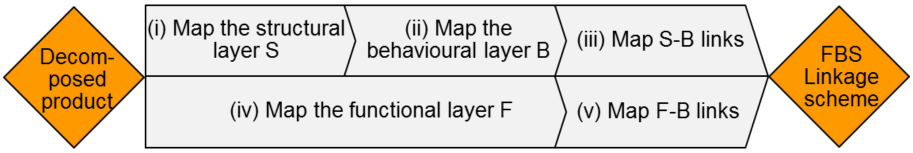


Figure 33: Step-by-step developing of an FBS Linkage scheme

For a given decomposed product, (i) structural and (ii) behavioural attributes can be defined and their elements linked to each other within each layer. For the structural layer, a number of ideally independent attributes such as *Material*, *Geometry*, *Surface*, *Colour*, and *Controller* (i.e. transistors, chips, microprocessors) can be considered. For the behavioural layer, different types of preferably independent behaviours such as *Mechanical*, *Thermal*, and *Electrical* should be identified. If those structural or behavioural attributes are not independent, their relations should also be captured. This requires more effort and leads to a more complex network than would otherwise be the case.

Then, (iii) the structural elements that determine the component behaviours must be linked to each other. Because the relation between structure and behaviour is determined by physical laws that apply to all components, the mapping between structural and behavioural attributes can be developed independently from the components. However, for some components certain links might be irrelevant for EC propagation and can be omitted, e.g. the influence of the structural attribute *Colour* on *Thermal* behaviour is often insignificant compared to the influence of *Material* on *Thermal* behaviour.

In parallel, (iv) the functional layer can be mapped as a functional block diagram composed of functions interlinked by flows of energy, material, and signal based on the reconciled functional basis from Hirtz et al. (2002). The functional layer considers the whole product and has a separate hierarchical structure, independently from the level of decomposition of the product into systems, components, or parts.

Finally, (v) to obtain the function-behaviour links, the functions can be assigned to components that realise them and then specified to responsible component behaviours.

The result is a product linkage model – *the FBS Linkage scheme*. This scheme can be represented as a network or as a corresponding multidomain matrix (MDM). As illustrated in Figure 34, the FBS Linkage network is composed of structural, behavioural, and functional elements which are linked to each other within and between the layers. The characteristic network parts are tagged by the respective ontology assumptions on the right hand side of the figure.

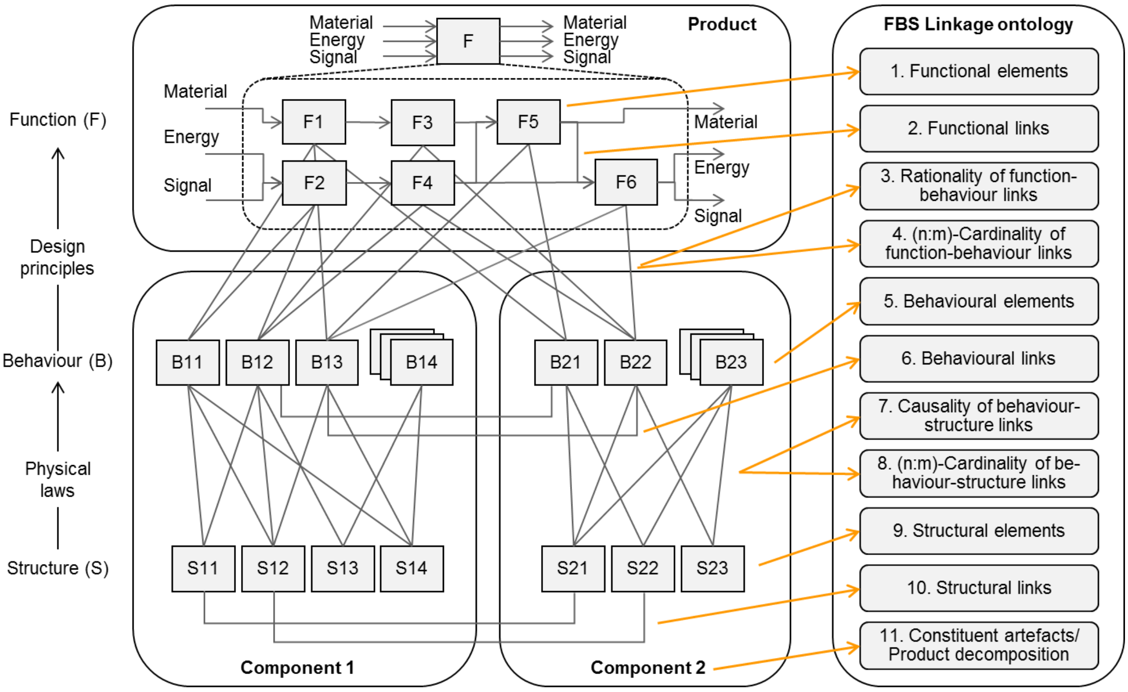


Figure 34: FBS Linkage network and the corresponding ontology assumptions

MDMs are block matrices composed of one DSM for each domain in the diagonal blocks and domain mapping matrices (DMMs) for inter-domain relations off the diagonal blocks. For more background on MDMs, the reader is referred to Lindemann and Maurer (2007), Maurer (2007), Lindemann *et al.* (2009). In particular, the FBS Linkage MDM is a block tridiagonal matrix composed of a function, a behaviour, and a structure DSM on the main diagonal, and a function-behaviour, a behaviour-function, a behaviour-structure, and a structure-behaviour DMM on the adjacent upper and lower diagonals correspondingly (Figure 35).

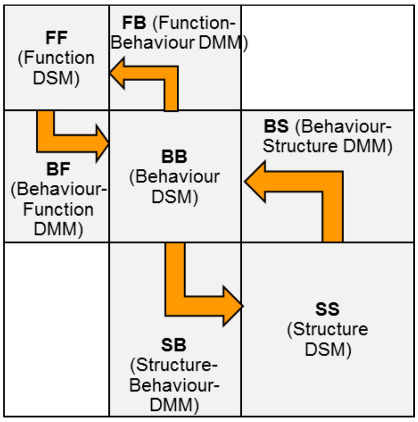


Figure 35: FBS Linkage MDM

The FBS Linkage scheme can be developed at different levels of product decomposition, i.e. for the whole product, or its systems, components, or parts. All three layers may include hierarchical structures breaking down potentially large attributes into a number of smaller attributes as suggested by (Umeda *et al.* 1990) and (Goel and Bhatta 2004). The higher the degree of decomposition the more information about the product can be stored and the more precisely change propagation can be modelled.

In practice, the level of detail should be chosen to suit the anticipated application of the model. For example, if the purpose of the model is to support management decisions related to price estimations and overall project planning of a requested design modification, a less detailed model would be sufficient. Such decisions are relevant, for instance, when customers ask for a modified version of a product model. To compete in the bidding process, quick high level assessments of the change effort and required delivery time are needed. However, if the model should be used by the designers to analyse ECs and support their day-to-day decisions, a more detailed model is required. For instance, a component designer might want to know which specific attributes of his component are affected by a change.

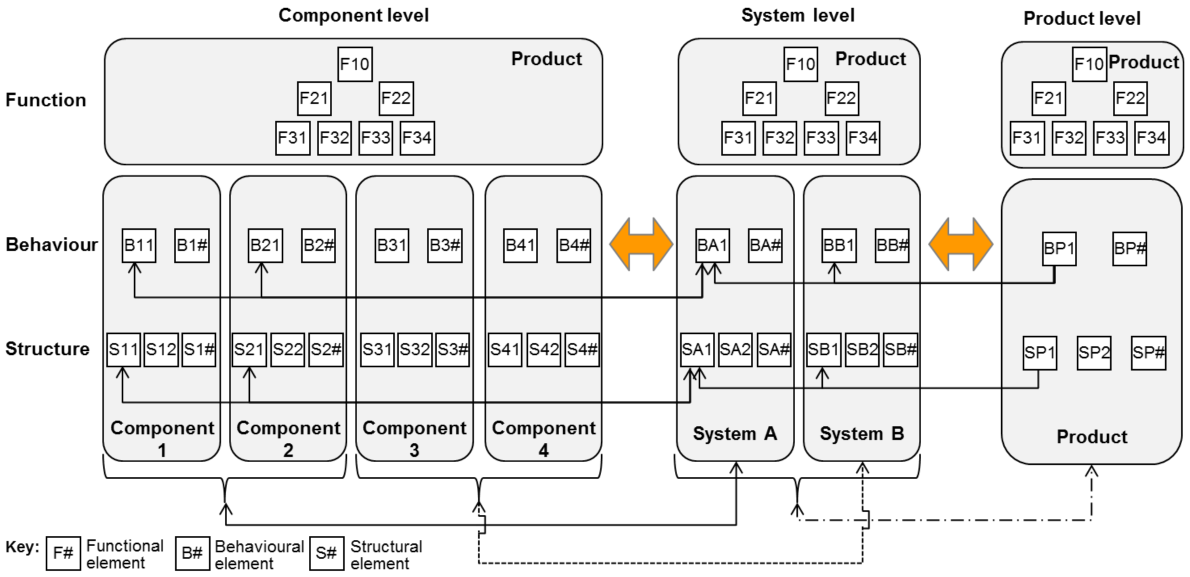


Figure 36: FBS Linkage network for different levels of decomposition

Note: Only selected links are shown.

All models are consistent (Figure 36); the models at lower level of decomposition can be generated by collapsing the more detailed models; the latter can be generated by detailing the abstract high level models. The component-level model includes a network of component attributes and allows change analysis between components, whereas the system-level model includes a less-detailed network of system attributes and only allows change analysis between systems.

The network above is clustered based on components. Alternatively, it can be clustered based on attributes. Accordingly, it can be represented in a component-clustered (Figure 37a) or attribute-clustered MDM (Figure 37b). These two views group and thus highlight different linkage types and help reveal specific aspects of the design. The component-clustered view shows in how many ways two components are interlinked between the diagonal DSMs, whereas the attribute-clustered view highlights the component links for each attribute within the diagonal DSMs.

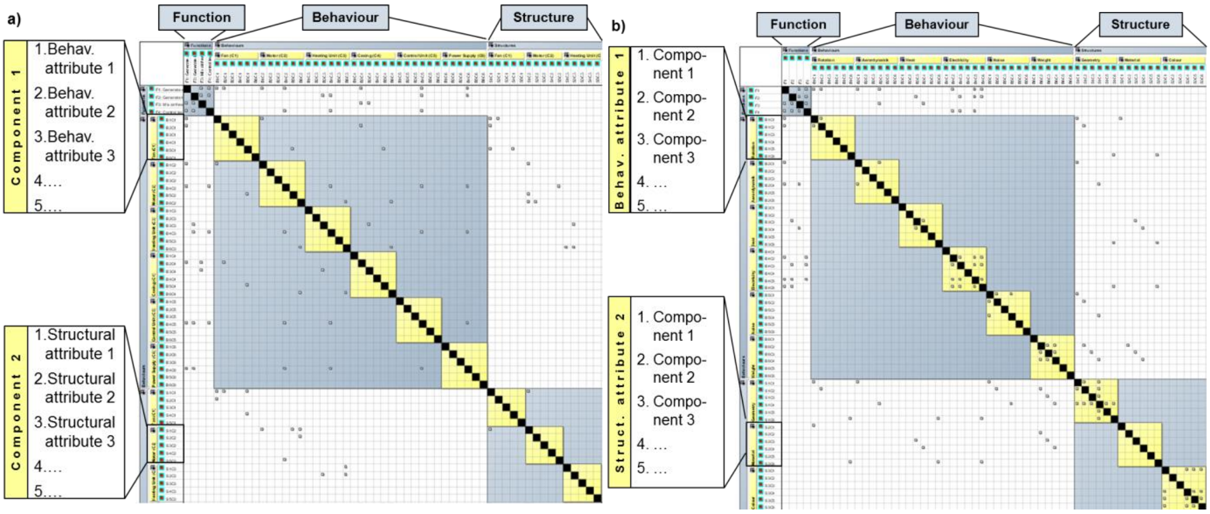


Figure 37: FBS Linkage MDM – (a) component-clustered, (b) attribute-clustered

6.6 Demonstration of the FBS Linkage technique

The inclusion of the FBS Linkage scheme steps (Figure 33) into the method flow diagram (Figure 32) results in the detailed FBS Linkage technique in Figure 38. In the following subsections, this technique will be elaborated and demonstrated using a hairdryer as an illustrative example.

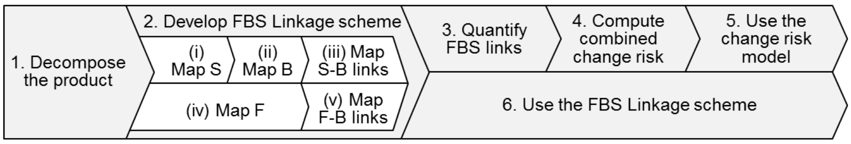


Figure 38: Detailed FBS Linkage technique

6.6.1 Decompose the product

Depending on the desired level of detail, a product can be decomposed into its systems, assemblies, components, parts, or a mix of those, if, for instance, some systems need to be modelled in greater depth than others. The hairdryer was decomposed into six components as depicted in Figure 39.

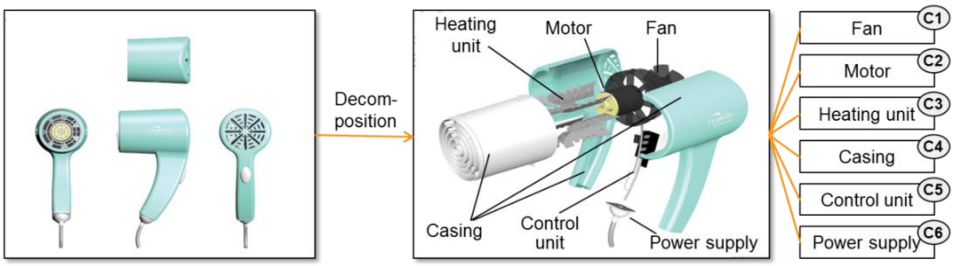


Figure 39: Decomposition of the hairdryer

Source: Hairdryer design adapted from Shimin (2006)

6.6.2 Develop FBS Linkage scheme

(i) Map the structural layer S: The structural layer is composed of components, their structural attributes, and structural interrelations. For each of the six hairdryer components, five structural attributes (Table 12) were defined, namely: *Geometry*, *Material*, *Colour*, *Surface*, and *Controller*, leading to 5*6=30 structural elements (Figure 40).

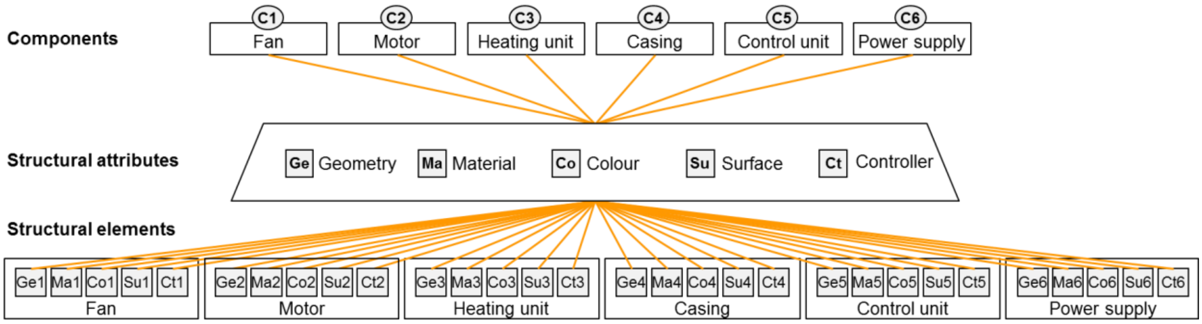
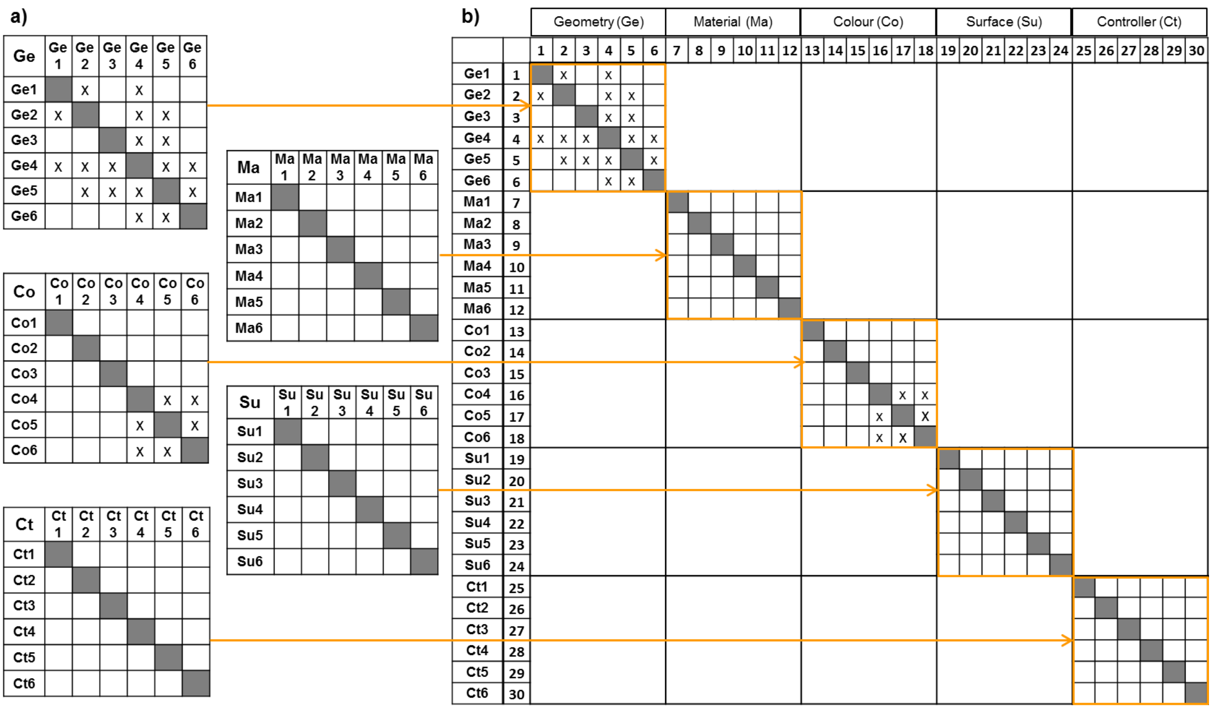


Figure 40: Structural attributes and elements of the hairdryer

The structural links can be captured independently using separate DSMs for each structural attribute (Figure 41a), where *"x"* indicates the existence of a link, and then summarised into a block matrix (Figure 41b). For the hairdryer, links between its components within the attributes *Geometry* and *Colour* were identified. The *Material*, *Surface*, and *Controller* elements are structurally not linked to each other.



a)

Ge	Ge 1	Ge 2	Ge 3	Ge 4	Ge 5	Ge 6
Ge1	■	x		x		
Ge2	x	■		x	x	
Ge3			■	x	x	
Ge4	x	x	x	■	x	x
Ge5		x	x	x	■	x
Ge6				x	x	■

Ma	Ma 1	Ma 2	Ma 3	Ma 4	Ma 5	Ma 6
Ma1	■					
Ma2		■				
Ma3			■			
Ma4				■		
Ma5					■	
Ma6						■

Co	Co 1	Co 2	Co 3	Co 4	Co 5	Co 6
Co1	■					
Co2		■				
Co3			■			
Co4				■	x	x
Co5				x	■	x
Co6				x	x	■

Su	Su 1	Su 2	Su 3	Su 4	Su 5	Su 6
Su1	■					
Su2		■				
Su3			■			
Su4				■		
Su5					■	
Su6						■

Ct	Ct 1	Ct 2	Ct 3	Ct 4	Ct 5	Ct 6
Ct1	■					
Ct2		■				
Ct3			■			
Ct4				■		
Ct5					■	
Ct6						■

b)

		Geometry (Ge)						Material (Ma)						Colour (Co)						Surface (Su)						Controller (Ct)					
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Ge1	1	■	x		x																												
Ge2	2	x	■		x	x																											
Ge3	3			■	x	x																												
Ge4	4	x	x	x	■	x	x																								
Ge5	5		x	x	x	■	x																								
Ge6	6				x	x	■																								
Ma1	7							■																							
Ma2	8								■																						
Ma3	9									■																					
Ma4	10										■																				
Ma5	11											■																			
Ma6	12												■																		
Co1	13													■																	
Co2	14														■																
Co3	15															■															
Co4	16																■	x	x												
Co5	17																x	■	x												
Co6	18																x	x	■												
Su1	19																			■											
Su2	20																				■										
Su3	21																					■									
Su4	22																						■								
Su5	23																							■							
Su6	24																								■						
Ct1	25																									■					
Ct2	26																										■				
Ct3	27																											■			
Ct4	28																												■		
Ct5	29																													■	
Ct6	30																														■

Figure 41: (a) Structural attribute DSMs and (b) structure DSM of the hairdryer

Assuming that the structural attributes are independent from each other on the structural level, the off-diagonal blocks in Figure 41b remain empty. This implies that, in the case where there were no functional and behavioural dependencies, those attributes could be independently determined and any combination would be possible. For instance, while the geometry of interlocking parts must be interdependent, and the materials of those parts may be interdependent, any suitable set of materials could be combined with any suitable set of geometries. However, when behaviours and functions are taken into account, it is clear that structural attributes usually cannot be determined independently. For instance, the weight of a component is determined by both material and geometry, so these two structural attributes must be considered in combination during the design process.

If structural attributes are not independent on the structural level, for instance, if the material of a component influences important properties of its surface, their interrelations could be captured in the corresponding off-diagonal blocks in Figure 41b. This increases the number of dependencies in the model and correspondingly increases the change propagation risk calculated using Forward CPM. Thus, dependent on the definition of the structural attributes, the resulting risk profile might change. This issue concerns the level of detail chosen while model-building (Figure 36), rather than the structure of the design itself.

(ii) Map the behavioural layer B: The behavioural layer can be modelled following a similar procedure. This layer is composed of component behavioural attributes (i.e. behavioural elements) and their behavioural interrelations. For each of the six hairdryer components, four relevant behavioural attributes (Table 12) were defined, namely: *Mechanical*, *Aerodynamic*, *Thermal*, and *Electrical* behaviours, leading to 6*4=24 behavioural elements. (Figure 42). For simplicity, these behaviours were assumed to be independent in the hairdryer model. Especially, for the *Thermal* and *Electrical* behaviours, which are usually interdependent, this simplification could be refined by adding links to the matrix fields between the *Thermal* and *Electrical* matrix blocks.

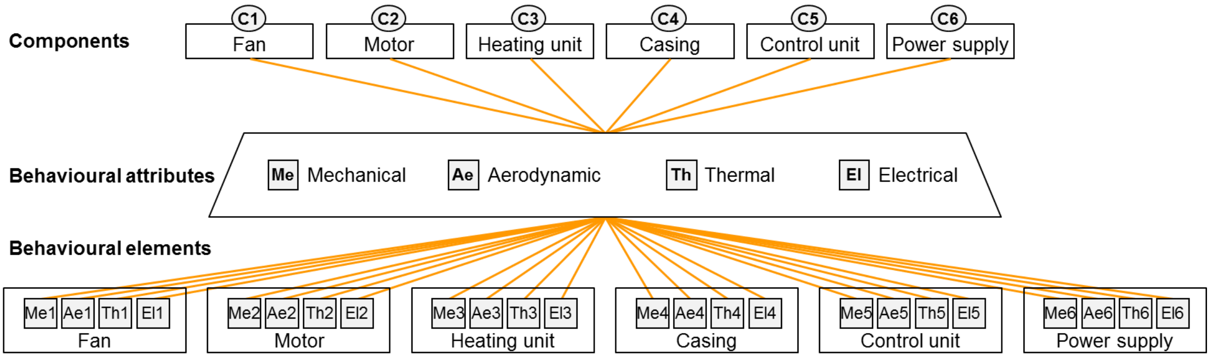
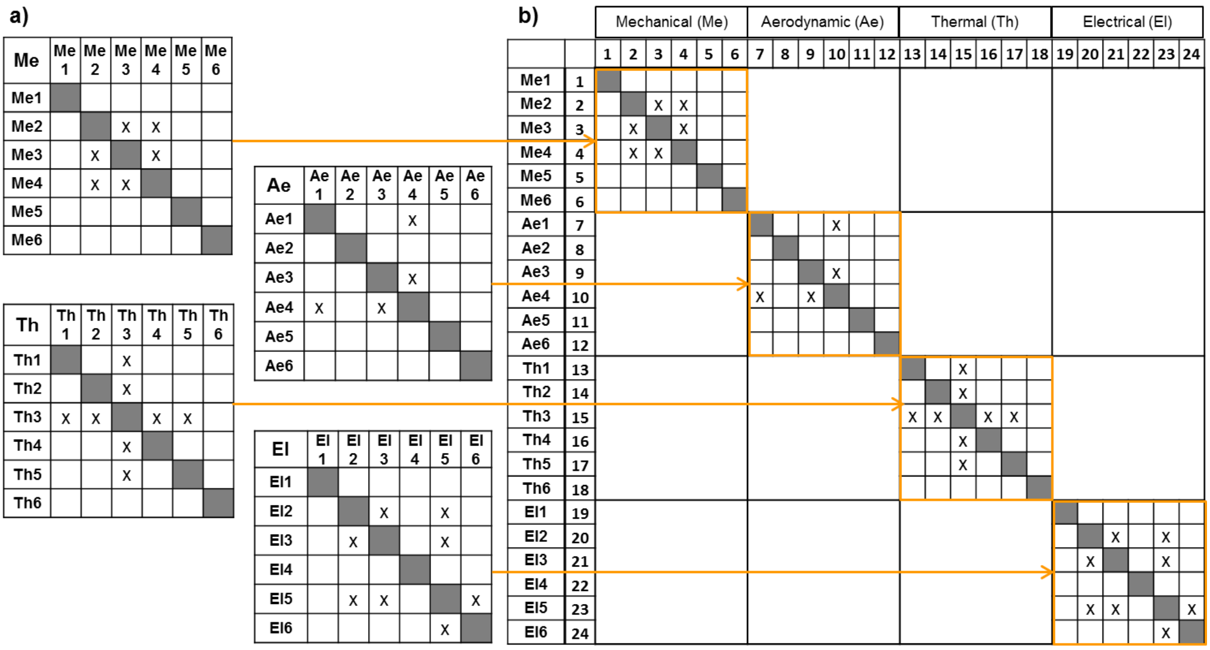


Figure 42: Behavioural attributes and behavioural elements of the hairdryer



Me	Me 1	Me 2	Me 3	Me 4	Me 5	Me 6
Me1	■					
Me2		■	X	X		
Me3		X	■	X		
Me4		X	X	■		
Me5					■	
Me6						■

Ae	Ae 1	Ae 2	Ae 3	Ae 4	Ae 5	Ae 6
Ae1	■			X		
Ae2		■				
Ae3			■	X		
Ae4	X		X	■		
Ae5					■	
Ae6						■

Th	Th 1	Th 2	Th 3	Th 4	Th 5	Th 6
Th1	■		X			
Th2		■	X			
Th3	X	X	■	X	X	
Th4			X	■		
Th5			X		■	
Th6						■

El	El 1	El 2	El 3	El 4	El 5	El 6
El1	■					
El2		■	X		X	
El3		X	■		X	
El4				■		
El5		X	X		■	X
El6					X	■

		Mechanical (Me)						Aerodynamic (Ae)						Thermal (Th)						Electrical (El)					
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Me1	1	■																							
Me2	2		■	X	X																				
Me3	3		X	■	X																				
Me4	4		X	X	■																				
Me5	5					■																			
Me6	6						■																		
Ae1	7							■			X														
Ae2	8								■																
Ae3	9									■	X														
Ae4	10							X		X	■														
Ae5	11											■													
Ae6	12												■												
Th1	13													■		X									
Th2	14														■	X									
Th3	15													X	X	■	X	X							
Th4	16															X	■								
Th5	17															X		■							
Th6	18																		■						
El1	19																			■					
El2	20																				■	X		X	
El3	21																				X	■		X	
El4	22																						■		
El5	23																				X	X		■	X
El6	24																							X	■

Figure 43: (a) Behavioural attribute DSMs and (b) behaviour DSM of the hairdryer

Similarly to the structural links, the behavioural links can be captured first in separate attribute DSMs (Figure 43a) and then summarised into a behaviour DSM (Figure 43b). For the hairdryer, links between the behavioural elements of all four behavioural attributes were identified (Figure 43).

(iii) Map the structure-behaviour (S-B) links: The links between structural and behavioural attributes are determined by physical laws, and thus, for the most part independent from the components. For instance, *Aerodynamic* behaviour depends on the *Geometry* and *Surface* attributes but not on *Material* or *Colour* attributes. The strength of the links (i.e. likelihood and impact of change propagation), on the other hand, may differ according to the components. The links used for all the hairdryer components are depicted in Figure 44a. They were transferred into the SB and BS DMMs (Figure 44b).

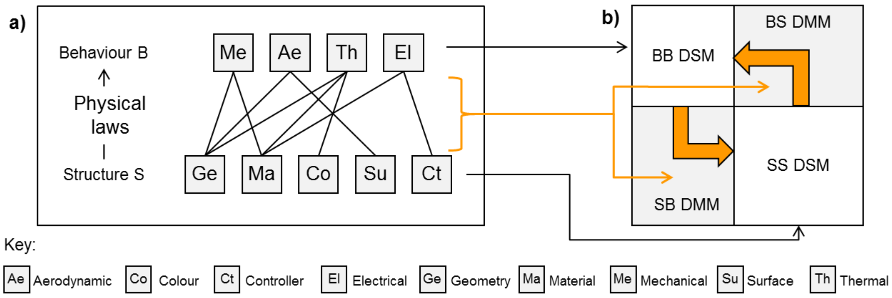


Figure 44: (a) Structure-behaviour links and (b) structure-behaviour DMM of the hairdryer

(iv) Map the functional layer F: The functional layer of products can be modelled using the reconciled functional basis suggested by Hirtz et al. (2002). For the hairdryer, eleven subfunctions were identified and interlinked by flows of signal, electricity, air, thermal energy, rotational energy, and acoustic energy (Figure 45).

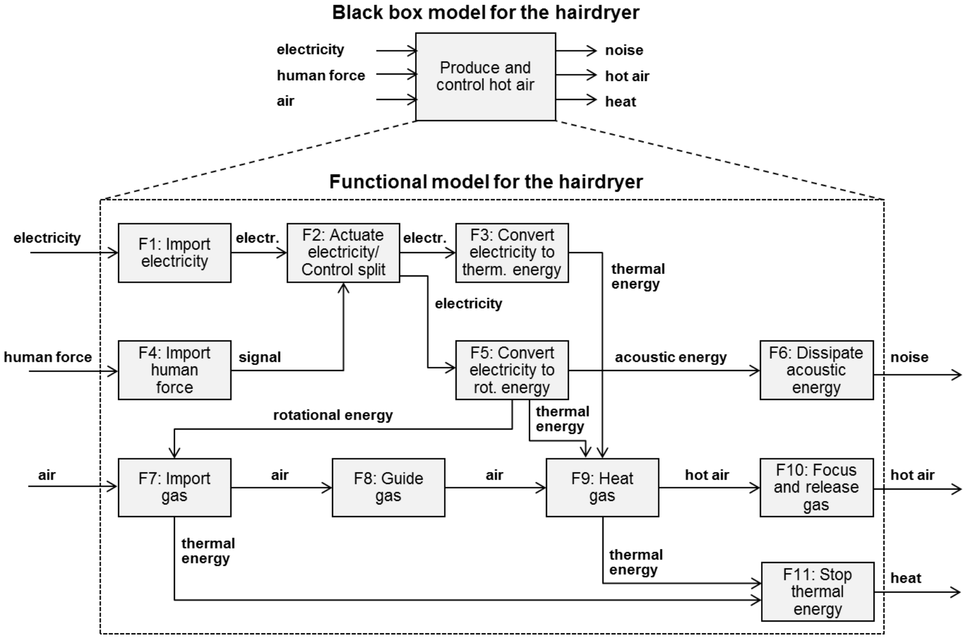


Figure 45: Functional elements and links of the hairdryer

This functional model was developed independently from the model existing in the functional basis repository as used by Caldwell (2009). It corresponds to the former to a great extent but includes fewer subfunctions as it subsumes the transfer subfunctions, which are less relevant for change propagation analysis, to the functions which send or receive the transferred flow.

Although the functional links in this network are represented as directed to indicate the flows, for change propagation and thus within the FBS Linkage model, they were considered to be undirected. In consequence, changes can propagate in both directions irrespective of the flow orientations. This is reasonable, because a change to a given function might affect both its input and output. For instance, a change to *Convert electricity to rotational energy (F5)* which aims at increasing the rotational energy might impact not only its successor function *Import gas (F7)* – because the higher rotational energy might increase the volume of imported gas – but also its predecessor function *Actuate electricity/ Control split (F2)* – because more electrical energy would likely be required.

(v) Map the function-behaviour (F-B) links: In order to develop the links between functional and behavioural elements, first the links from functional elements to components were identified. Then, these links were specified into undirected functional element - behavioural element links (Figure 46) and transferred into the BF and FB DMMs (Figure 47).

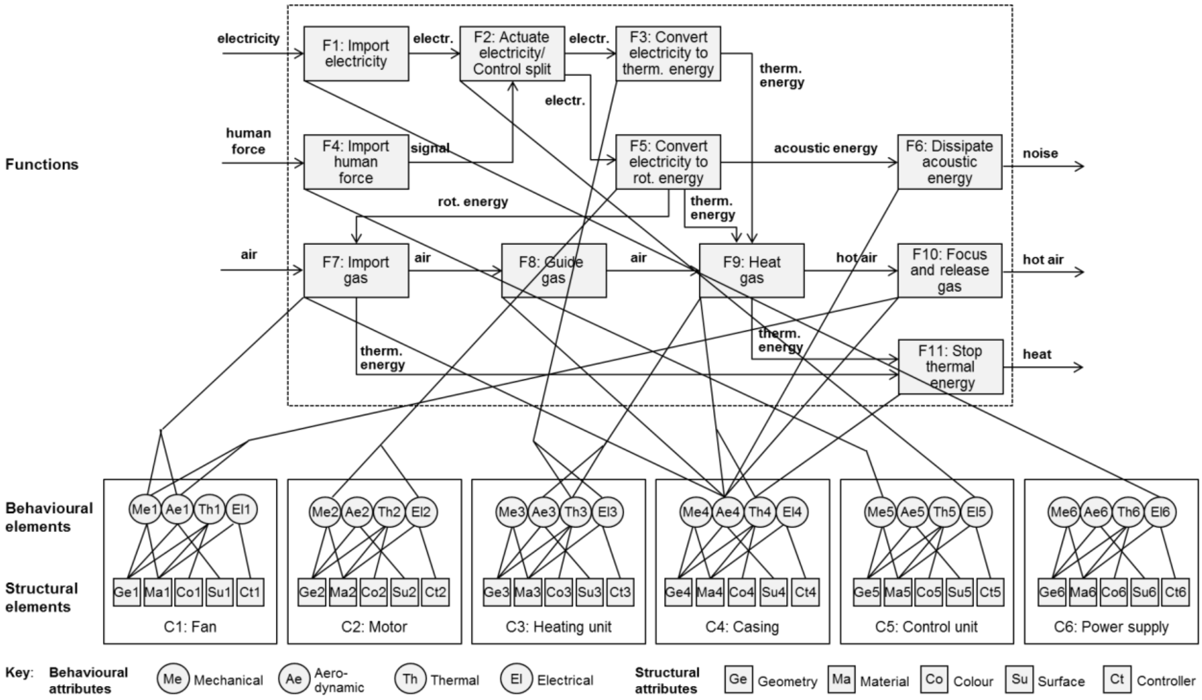


Figure 46: FBS Linkage network of the hairdryer

Although this model appears complex, the network was constructed through a straightforward logical process once the components and functional block diagram had been identified. The line of reasoning can be illustrated considering, for instance, the *Focus and release gas* function *(F10)*. This was mapped to its implementing components, *Fan (C1)* and *Casing (C4)*. Each component was then considered to determine the behavioural attributes involved in the function under consideration. In the case of the *Fan*, for example, its *Mechanical (Me1)* and *Aerodynamic (Ae1)* behaviour are involved in the *Focus and release gas* function *(F10)*, while its *Thermal (Th1)* and *Electrical (El1)* behaviours are not. This shows how the FBS Linkage method improves upon CPM from the point of view of *Requirement 7* (Accuracy), because it requires making the nature of the links explicit during model-building.

Finally, after having identified all elements and links of the hairdryer, the FBS Linkage scheme can be put together and represented as a MDM (Figure 47) or network (Figure 48). The three layers and the different attributes are highlighted in the MDM. It can be seen that there are no links between any two different structural attributes within the SS DSM or any two different behavioural attributes within the BB DSM as they were assumed to be independent from each other. Furthermore, because the links between structural and behavioural elements were defined on an attribute level, equally for all components, they appear in diagonals in the SB and BS DMMs. This network and MDM show how the FBS Linkage method improves upon CPM from the point of view of *Requirement 19* (Product modelling capability), because it models the working mechanisms of the hairdryer in significantly greater detail.

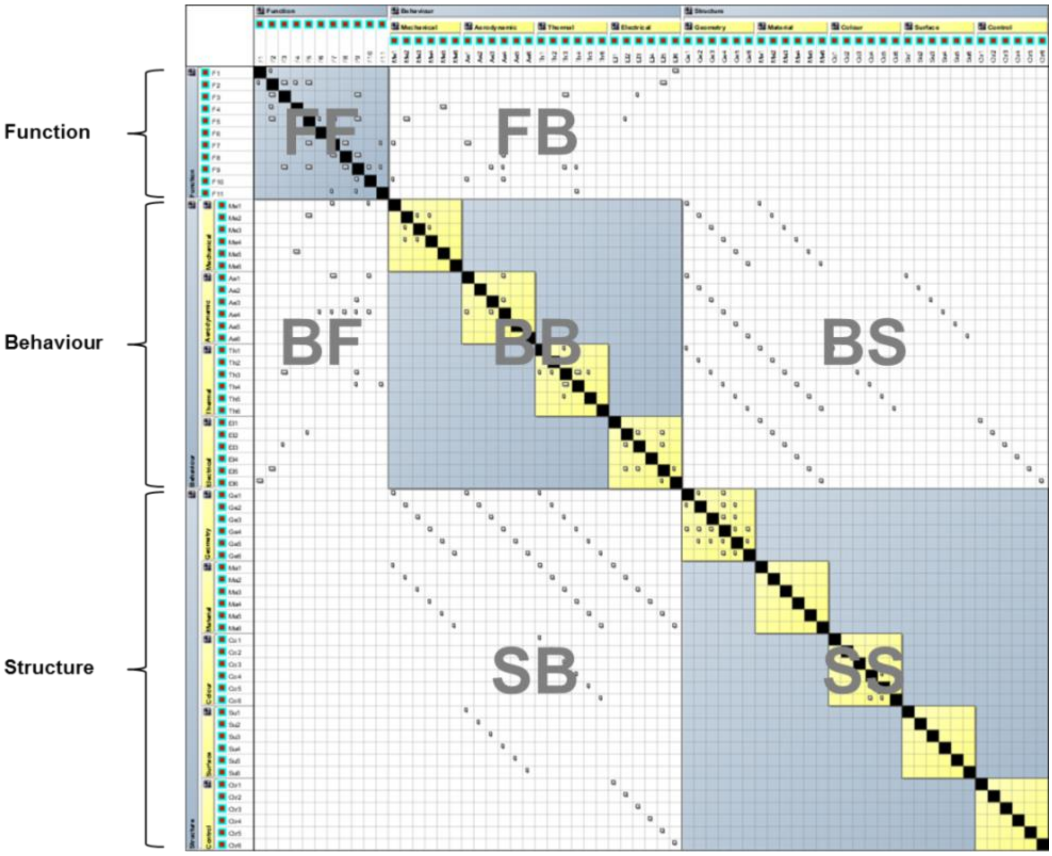


Figure 47: FBS Linkage MDM of the hairdryer in CAM

6.6.3 Quantify FBS links

Similarly to CPM, the direct FBS links can be quantified by likelihood and impact of change propagation. While the original CPM approach only captures the links between components, and subsumes all types of interactions (i.e. structural, behavioural, and functional) into a single number, the FBS links are more detailed and specific. The existence of a link between any two elements may be explained based on reasoning in the context of the product's functions and working mechanisms. In principle, at least some of the impact and likelihood values might be possible to calculate directly. For instance, the dependency between *Material* and *Thermal behaviour* might be described using mathematical equations which relate their parameters to each other. Where such calculations are possible and feasible with a reasonable amount of effort, objective values can replace the estimations, and this will improve the model's fidelity. An algorithm to achieve this under some circumstances is discussed in (Hamraz *et al.* 2013b). However, maintaining the probabilistic character of CPM is generally appropriate. The probabilistic approach reduces the complexity and effort of model building, because estimated linkage values are much easier to obtain than the results of deterministic calculations.

In general, each link between two elements could be quantified individually and separately for each direction. This would require each cell which contains an *"x"* in the FBS Linkage MDM in Figure 47 to be quantified separately. However, to minimise this tedious task of quantifying the available links one by one, three shortcuts can be taken: (1) the values of many links can be assumed as symmetric; (2) the links between the structural and behavioural elements which are mostly independent from the components can be quantified collectively first and then changed for exceptions; and (3) some other links can be quantified by standard values if they have not been specified yet, e.g. 0.5 for likelihood and 0.3 for impact.

The remaining links can be quantified using three different values, e.g. 0.3 for low, 0.5 for medium, and 0.8 for high. To estimate these values, the relations between directly linked attributes can be investigated for generic changes. The network representation is more useful for this step. For the hairdryer for instance, if the diameter of the *Fan (C1)* is increased, it will require the *Casing (C4)* diameter to be increased accordingly to house the bigger *Fan*, whereas a decrease of the same diameter will not propagate to the *Casing*. Assuming that 50% of the generic change cases require an increase and 50% a decrease of the *Fan* diameter, it can be concluded that the likelihood of change propagation from the *Geometry* attribute of the *Fan (Ge1)* to the *Geometry* attribute of the *Casing (Ge4)* is 0.5. The impact of change propagation for this link is low (0.3) as in case of actual propagation, not the whole *Casing* has to be re-designed but only the corresponding diameter.

The likelihood values for the hairdryer are represented in the network in Figure 48, where the intra-layer links for the structural and behavioural layers are omitted to preserve graphical clarity.

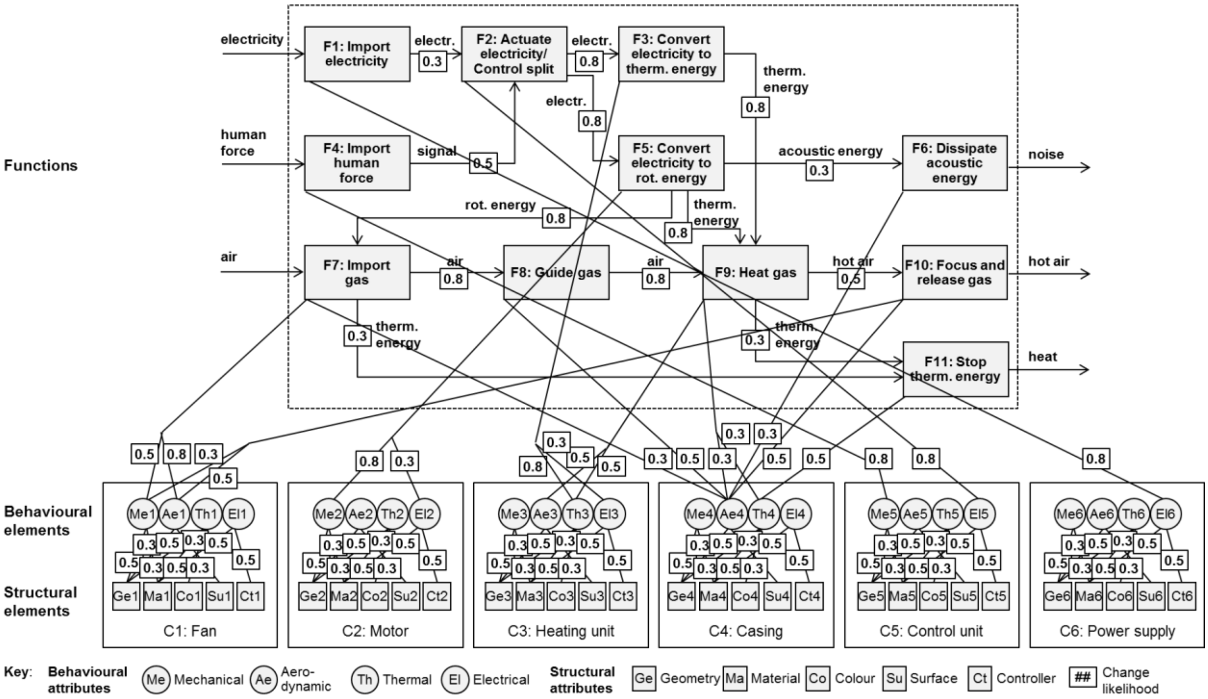
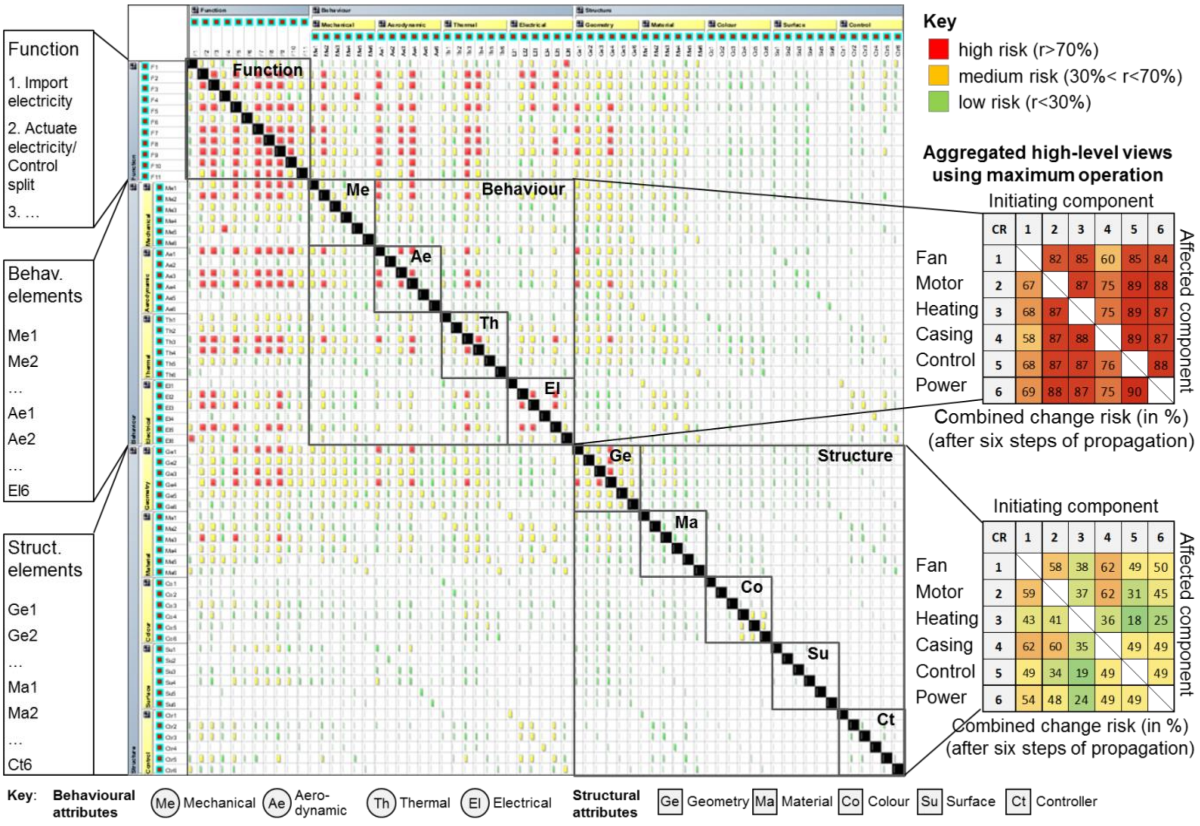


Figure 48: FBS Linkage network of the hairdryer quantified by change likelihood

6.6.4 Compute combined change risk

As with the CPM approach, the Forward CPM algorithm can be applied to the numerical FBS Linkage scheme including direct likelihood and impact values of change propagation to calculate a combined risk matrix. So far, the Forward CPM algorithm has been discussed only in the context of single-domain networks, i.e. DSMs (Keller 2007). As all elements in an FBS scheme are equal in terms of receiving and forwarding changes, this multi-layer network obeys the same rules as a single-layer network. Thus, the Forward CPM algorithm can be applied to the MDM in the same way. However, because the FBS network consists of three layers that are connected in series, at least four steps of change propagation are required to consider indirect change propagation between two structural or two functional elements across all other layers (e.g. *S1*→*B1*→*F1*→*B2*→*S2*). This is two steps more than in the single-layered CPM network (e.g. *C1*→*C2*→*C3*). Therefore, five or six steps of change propagation should be considered for the FBS Linkage model, two steps more than Clarkson *et al.* (2004) used for CPM.

As result for the hairdryer, the combined risk MDM shown in Figure 49 was generated after six steps of change propagation. This MDM includes risk values for all different element pairs. It can be collapsed or aggregated in different ways to generate specific high level views of change propagation. For example, the blocks within the structural and behavioural layers can be aggregated to generate a component-component change risk plot, similar to the result of CPM (see e.g. Keller *et al.* 2009).



	CR	1	2	3	4	5	6
Fan	1		82	85	60	85	84
Motor	2	67		87	75	89	88
Heating	3	68	87		75	89	87
Casing	4	58	87	88		89	87
Control	5	68	87	87	76		88
Power	6	69	88	87	75	90	

	CR	1	2	3	4	5	6
Fan	1		58	38	62	49	50
Motor	2	59		37	62	31	45
Heating	3	43	41		36	18	25
Casing	4	62	60	35		49	49
Control	5	49	34	19	49		49
Power	6	54	48	24	49	49	

Figure 49: Combined risk MDM for the hairdryer (attribute-clustered)

While the MDM incorporates the detailed FBS information useful for tracing specific change paths, these collapsed views provide a high-level overview. For instance, the component-component DSM indicates the overall propensity of each component to receive or transmit change. This example indicates how the FBS Linkage method can be used to produce results on different levels of detail, and thus, improves upon CPM from the point of view of *Requirement 2* (Range of levels of decomposition supported).

Different operations (e.g. arithmetic average, arithmetic sum, intersection, maximum, etc) can be used to obtain these aggregated values from the individual values dependent on the risk affinity of the user, which may be influenced by guidelines for risk estimation issued by the company. However, from a risk management perspective, the maximum operation makes sense, because it reflects the worst case scenario which a risk manager often has to consider. For the hairdryer such views were generated using the maximum operation, i.e. the maximum of all structural element linkage values was determined for the corresponding component linkage value, as depicted in the right hand side of Figure 49.

6.6.5 Use the change risk model

The FBS risk matrix is more detailed than the CPM risk matrix, in that it includes calculated risk values not only between components but between their structural and behavioural attributes and the product’s functions. To inform high-level judgements, these values can be aggregated (e.g. into risks for propagation between components, subsystems, etc.) or collapsed to represent different views on how change can propagate (e.g. between attributes, across layers, etc.). Similarly to CPM, the risk values can be used by different design stakeholders for various purposes. For instance, the risk matrix could be applied to predict change risks when a change or variant is requested. This could be used amongst others by the sales engineers to estimate the cost of a variant when they bid for a contract (Simons 2000). Other purposes include the identification of change multipliers, carriers, and absorbers as proposed by Eckert et al. (2004) and prioritisation of components or elements according to their imposed risk as proposed by Ariyo et al. (2007b).

6.6.6 Use the FBS Linkage scheme

The FBS Linkage scheme shows how the product's structure is organised to exhibit actual behaviours which realise its functions. The model can be applied to reason about changes for the purpose of solution development and change containment. For instance, when a function has to be changed, tracing links in the FBS network allows identification of the different behaviours which realise this function and, in turn, the structural elements which exhibit those behaviours. Studying the network thus helps to identify the elements that could be involved in a change. At the same time, it can be used to investigate which elements should be manipulated to accommodate the functional change most effectively. These benefits will be explained in the next subsection through an illustrative example.

6.6.7 Example use case

Consider the situation in which a designer has to increase the power of a hairdryer design from 1200W to 1400W. This change request is not directly targeted to any specific component but to the functional layer of the hairdryer. Using the FBS Linkage network, the initial change target can be located at the *Import electricity (F1)* function – this function may need to be changed to import the additional 200W. This may require accordingly changes to the *Electical (El6)* behaviour of the power supply and consequently to its *Geometry (Ge6)* and *Controller (Ct6)* attributes. This indicates how the FBS Linkage method improves upon CPM from the point of view of *Requirement 3* (Range of different changes covered), because it allows evaluation of changes that are initiated in any product attribute or link.

If the change request is not further specified, the designer has the choice how to split this additional power between the *Fan (C1)* to produce more air and the *Heating unit (C3)* to produce more heat. His decision determines the change effect on the function *Actuate electricity/ Control split (F2)* and its propagation to other attributes consequently. This demonstrates how the FBS Linkage method improves upon CPM from the point of view of *Requirement 22* (Change containment capability) because it can be used to identify different alternatives for the implementation of a change and select the most suitable one to reduce the effects of change propagation. Let us assume that the designer decides to use the additional power entirely to increase the heating and thus changes *F2* accordingly. Using the FBS Linkage network, this change can then be propagated to the functions *Convert electricity to thermal energy (F3)* and *Heat gas (F9)* (Figure 50); both might need to be changed to accommodate the higher power level.

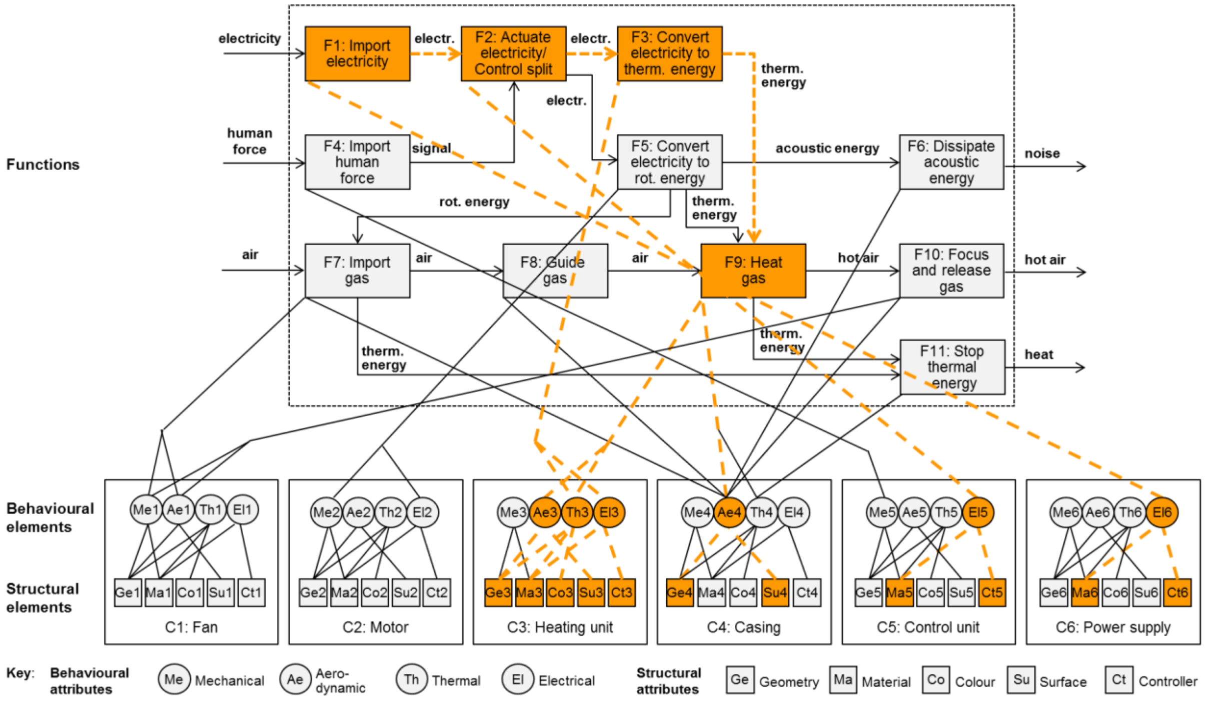


Figure 50: Hairdryer example change case

Actual implementation of changes requires manipulation of explicit parameters in the design (i.e. structural attributes). Changes that target the product's functions have to be traced back to the responsible behaviours, and those behaviours, in turn, to the structural attributes that trigger them. To determine how the change above might be implemented, the designer can trace the linkages in the FBS Linkage model to determine the structural attributes that must be manipulated. In this case the functional flow connection suggests that *F3* or its input flow might require a change. More specifically, it can be deduced that the electricity input of *F3* should be increased to produce more thermal energy. To accommodate this change to *F3*, the *Electrical (El3)* and *Thermal (Th3)* behaviours of the *Heating unit (C3)* which realise *F3* may require changes accordingly, if they cannot support the higher electricity input. These behaviours, in turn, are determined by the structural attributes of the *Heating unit* which can be identified by following a similar procedure.

This example shows how a concrete change plan can be developed for an abstract change request and highlights the FBS Linkage method's improvement upon basic CPM from the point of view of *Requirement 23* (Solution finding capability). The reasoning-based and explanatory FBS model supports the designer in finding the implementation levers and developing solutions to change requests.

Most change requests can be implemented through different alternatives. For instance, if *Th3* needs to be changed to support the higher conversion of electricity into thermal energy, it might be implemented by modifying the *Heating unit's Geometry (Ge3)*, improving its *Material (Ma3)*, or changing its *Colour (Co3)*. To determine which option is preferable, the designer may investigate the links between those structural attributes and other attributes. The FBS Linkage model shows that *Ge3* is interconnected to *Ge4* and *Ge5*, while *Ma3* and *Co3* are not (Figure 41). Alternatively, the combined risk MDM from Figure 49 might be used to compare the imposed risk profiles of these attributes. This suggests that the imposed change risk of *Ge3* is higher than *Ma3* or *Co3*. Therefore, if the cost of these alternatives is equal, it is better to accommodate the change by using a better *Material* or a different *Colour*.

This example demonstrates how the FBS Linkage method improves upon basic CPM from the point of view of *Requirement 22* (Change containment capability) because it shows the different alternatives for the implementation of a given change and supports the selection of the best alternative.

Furthermore, tracing the links in the network suggests that some other functions such as *Heat gas (F9)*, *Actuate electricity/ control split (F2)*, and *Import electricity (F1)*, and their inputs might require changes. Those functions are realised by the behavioural attributes of the *Heating unit (C3)*, *Casing (C4)*, *Control unit (C5)* and *Power supply (C6)* which would then be investigated accordingly. The systematic basis and comprehensive product model of the FBS Linkage method ensure that the implications of a change on other functions and components are not overlooked, indicating how the FBS Linkage method improves upon CPM from the point of view of *Requirement 21* (Change prediction capability).

This hypothetical case might appear to imply that the chain of affected attributes is endless, but in practice the propagation chain will come to a halt after a few steps because some attributes will be able to tolerate changes and some others are frozen. The former absorb changes and stop the propagation chain. Frozen attributes cannot be changed; when these nodes are identified while tracing changes through the FBS linkage network, the change must be stopped at that point or redirected, such that it is implemented by changing some other attributes. Further discussion on design freeze and its effect on change propagation paths can be found in (Eger *et al.* 2005).

6.7 Chapter summary

This chapter has presented the detail design of the FBS Linkage method. A comparative review of the three seminal FBS ontologies showed that all three have shortcomings in terms of EC modelling. Consequently, a modified ontology for the FBS Linkage model was developed and its application to generate an FBS scheme for a given design was detailed. Subsequently, the FBS Linkage technique was elaborated using a hairdryer example for demonstration. This technique proceeds in six steps to model a product design as a network of its structural, behavioural, and functional elements and to use their relations to describe change propagation.

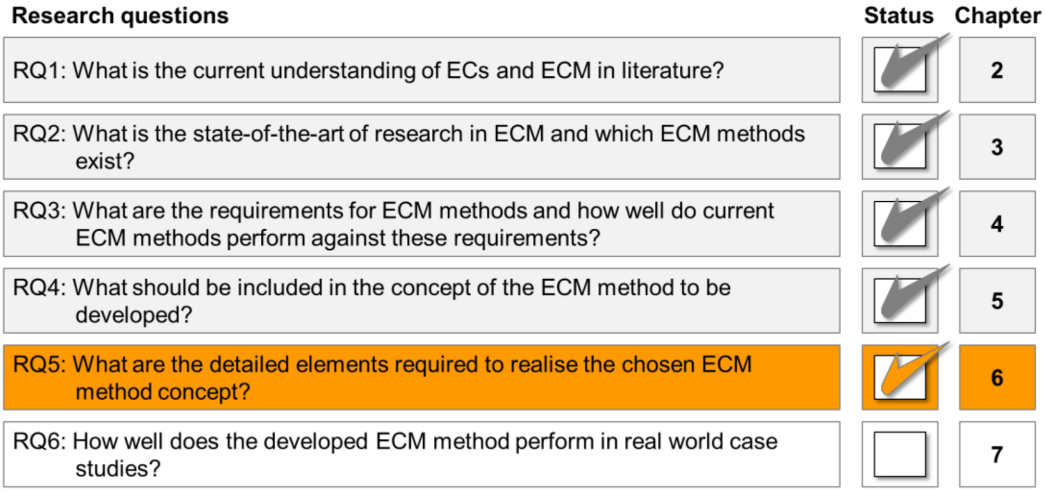
Throughout its application to the hairdryer example, it was shown that the FBS Linkage method improves on CPM with regard to the identified requirements where CPM has competitive gaps (Table 13).

Table 13: Addressed improvement suggestions by FBS Linkage model

No	Requirement name	Improvement suggestion for CPM	Implementation in FBS Linkage method		Thesis section
2	Range of levels of hierarchical decomposition supported	Allow modelling the product and representing the results on different levels of detail at once and on more detailed levels.	√	FBS Linkage method is based on a detailed model including different types of design attributes. This allows results to be aggregated to different levels of detail.	6.6.4
3	Range of different changes covered	Capture other product aspects which might be the initial target of a change request, such as functions, behaviours, structural attributes.	√	FBS Linkage method explicitly considers functional, behavioural, and structural attributes of the product and allows evaluation of changes that are initiated in any product attribute or link.	6.6.7
7	Accuracy	Include rationales for the links between attributes or parameters into the model.	√	FBS links can be explained in the context of the product functions and working mechanisms. The method makes the nature of the links explicit during model-building, which helps avoid overlooking propagation paths.	6.6.2
19	Product modelling capability	Model the working mechanisms of the product and include interfaces between domains describing different aspects of the design.	√	FBS Linkage scheme explains how the product realises its functions; thus it models the working mechanisms of the hairdryer in significantly greater detail than CPM.	6.6.2
21	Change prediction capability	Consider links between attributes and components explicitly in the model.	√	The systematic basis and comprehensive product model of the FBS Linkage method ensure that the implications of a change on other functions and components are not overlooked.	6.6.7
22	Change containment capability	Model change implementation alternatives and support identification of decisions that create less change propagation.	√	Tracing the FBS linkage model suggests different alternatives for implementation of a given change and supports selection of the best alternative.	6.6.7
23	Solution finding capability	Support identification of solution plans and redesign strategies.	√	The FBS model captures reasoning behind the design and thus supports finding implementation options and developing solutions to change requests.	6.6.7

The FBS Linkage method allows representing the product at more detailed and different levels of decomposition *(Requirement 2)*, enables modelling of changes to different aspects of the product *(Requirement 3)*, systematically models the product in the context of its functions and working mechanisms, thus, improving accuracy *(Requirement 7)*, product modelling *(Requirement 19)*, and change prediction capability (*Requirement 21)*, and allows reasoning about change propagation, thereby, supporting change containment *(Requirement 22)* and solution development *(Requirement 23)*.

Thereby, this chapter has answered the fifth research question (Figure 51). An evaluation of these criteria to see how well they are addressed by the FBS Linkage model will be presented through industrial case studies in the next chapter.



Research questions	Status	Chapter
RQ1: What is the current understanding of ECs and ECM in literature?	☑	2
RQ2: What is the state-of-the-art of research in ECM and which ECM methods exist?	☑	3
RQ3: What are the requirements for ECM methods and how well do current ECM methods perform against these requirements?	☑	4
RQ4: What should be included in the concept of the ECM method to be developed?	☑	5
RQ5: What are the detailed elements required to realise the chosen ECM method concept?	☑	6
RQ6: How well does the developed ECM method perform in real world case studies?	☐	7

Figure 51: Research questions and status after Chapter 6

7 Applications and Evaluation of the FBS Linkage Method

"The secret of change is to focus all of your energy,
not on fighting the old, but on building the new."
(Socrates, Greek Athenian philosopher, BC 469-399)

7.1 Chapter introduction

This chapter addresses the sixth research question (RQ6: How well does the developed ECM method perform in real world case studies?) by presenting two case studies and an evaluation of the FBS Linkage method. Sections 7.2 and 7.3 report the method's application to a diesel engine and a scanning electron microscope (SEM). Section 7.4 presents the evaluation of the method and Section 7.5 summarises the chapter.

7.2 Diesel engine case study

In the author's group, case studies with diesel engines were carried out in the past to understand the propagation of ECs. Those studies have generated knowledge about the diesel engine, in particular, about its decomposition, linkage types and values between its components, and change propagation risk analysis based on that. As part of the on-going development of CPM, connectivity models capturing component-component relations in terms of likelihood and impact of change propagation were developed (see e.g. Jarratt *et al.* 2004a). Those models primarily focused on the structural layer while considering other dependencies only implicitly.

The engine modelled here is Perkins' VistaD diesel engine as partly discussed in (Jarratt *et al.* 2004a, Keller *et al.* 2009). The definition of different types of links in the existing CPM model helped map and quantify the structural and behavioural layers of the FBS linkage model. The functional layer and the inter-layer links were developed additionally with support from Tom W. Ridgman, a diesel engine expert from the IfM (Institute for Manufacturing) at the University of Cambridge. Mr Ridgman has worked in the automotive industry for 20 years, in a variety of roles in new product development, manufacturing strategy and operations, including more than 5 years in the diesel engine product development of Perkins.

The FBS Linkage model for the diesel engine was built following the steps described in Section 6.6.

7.2.1 Decompose the product

The diesel engine was decomposed into 42 components, 12 of which were considered as core components and received more attention during model building (Figure 52).

Core components

1 Cylinder Head Assembly
2 Cylinder Block Assembly
3 Piston Rings Gudgeon Pin
4 Conn Rod
5 Crankshaft Main Bearings
6 Valve Train
7 Cam Shaft
8 Push Rods
9 High Pressure Fuel Pipes
10 Electric Control Module
11 Fuel Pump
12 Fuel Injection Assembly

Non-core components

13 Adapter Plate / Flywheel Housing
14 Flywheel Ring Gear
15 Starter Motor
16 Sump
17 Oil Filler
18 Engine Breather
19 Oil Pump
20 Oil Filter
21 Oil Cooler
22 Crank Pulley Damper Belt
23 Fan Drive
24 Fan Extension
25 Coolant Pump
26 Alternator Bracket
27 Belt Driven Auxiliary (Hydraulic Pump)
28 Gear Train
29 Gear Driven Auxiliary (Compressor)
30 Timing Case
31 Balancer
32 Turbocharger
33 Aircharge Cooler
34 Air Intake
35 Air Filter
36 Exhaust Manifold
37 Low Pressure Fuel System
38 Fuel Filter
39 Starting Aid
40 Lifting Eyes
41 Wiring Harness
42 Radiator

Figure 52: Product decomposition of the diesel engine

Source: Engine photo is used by courtesy of Perkins Engines Company Limited.

7.2.2 Develop FBS Linkage scheme

(i) Map the structural layer S: The four structural attributes *Geometry (Ge)*, *Material (Ma)*, *Surface (Su)*, and *Controller (Ct)* were used to define (42*4=) 168 structural elements (Figure 53). The *Colour* attribute was left out because it is only of minor significance for the engine design. Although *Controller* is only relevant for a few components, it was kept for all components to preserve consistency in the scheme.

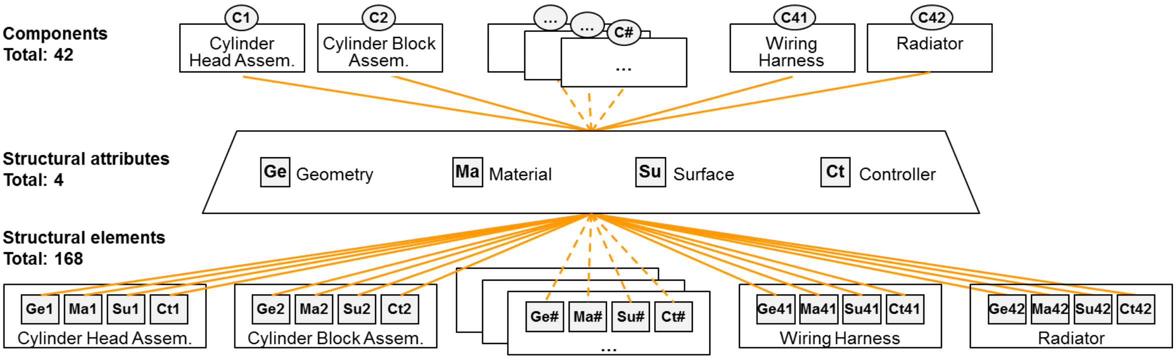
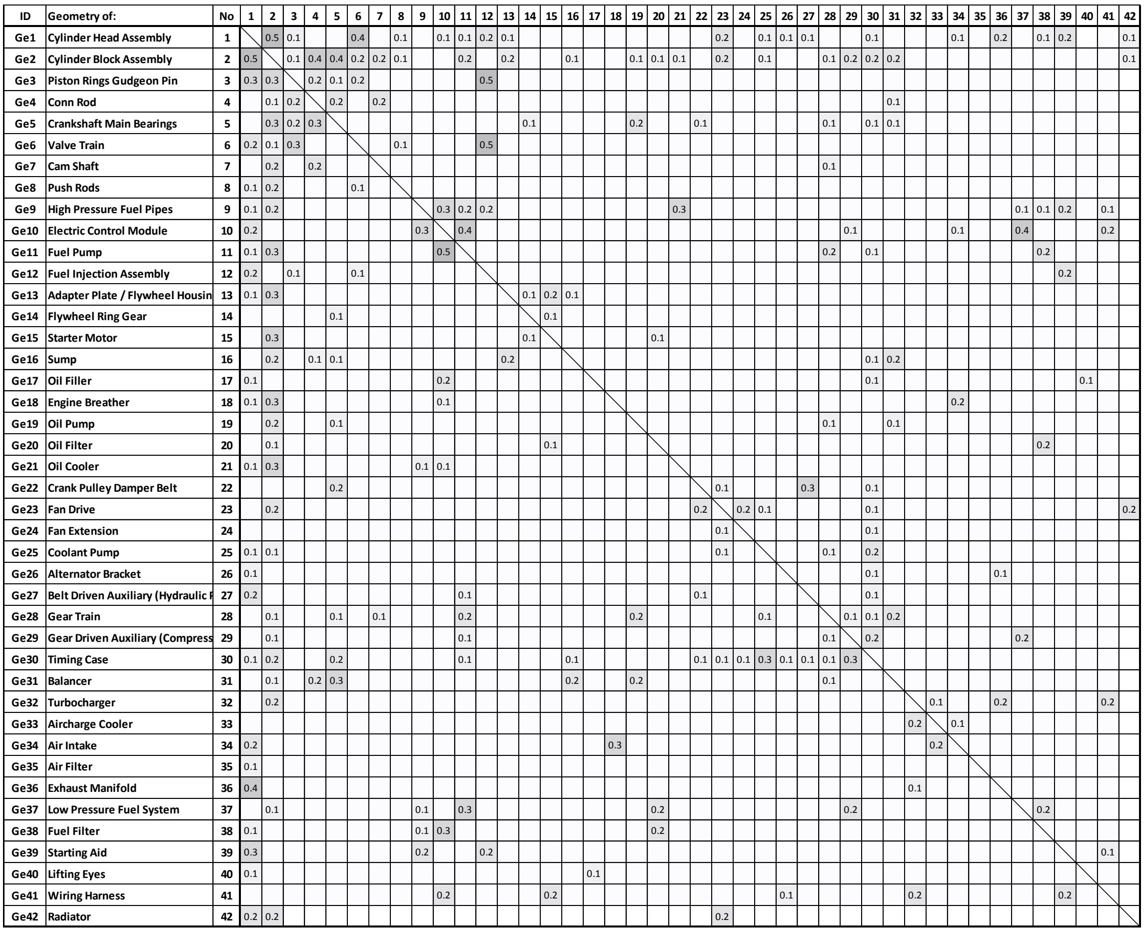


Figure 53: Defining structural elements for the diesel engine

The structural links between these 168 elements were first captured in structural attribute DSMs and then put together into a structure DSM. The majority of the structural links are symmetric and come from *Geometry* (Figure 54).



ID	Geometry of:	No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Ge1	Cylinder Head Assembly	1		0.5	0.1			0.4		0.1		0.1	0.1	0.2	0.1										0.2		0.1	0.1	0.1			0.1				0.1		0.2		0.1	0.2			0.1
Ge2	Cylinder Block Assembly	2	0.5		0.1	0.4	0.4	0.2	0.2	0.1			0.2		0.2			0.1			0.1	0.1	0.1		0.2		0.1			0.1	0.2	0.2	0.2											0.1
Ge3	Piston Rings Gudgeon Pin	3	0.3	0.3		0.2	0.1	0.2						0.5																														
Ge4	Conn Rod	4		0.1	0.2		0.2		0.2																								0.1											
Ge5	Crankshaft Main Bearings	5		0.3	0.2	0.3										0.1					0.2			0.1						0.1		0.1	0.1											
Ge6	Valve Train	6	0.2	0.1	0.3					0.1				0.5																														
Ge7	Cam Shaft	7		0.2		0.2																								0.1														
Ge8	Push Rods	8	0.1	0.2				0.1																																				
Ge9	High Pressure Fuel Pipes	9	0.1	0.2								0.3	0.2	0.2									0.3																0.1	0.1	0.2		0.1	
Ge10	Electric Control Module	10	0.2								0.3		0.4																		0.1					0.1			0.4				0.2	
Ge11	Fuel Pump	11	0.1	0.3								0.5																		0.2		0.1								0.2				
Ge12	Fuel Injection Assembly	12	0.2		0.1			0.1																																	0.2			
Ge13	Adapter Plate / Flywheel Housin	13	0.1	0.3												0.1	0.2	0.1																										
Ge14	Flywheel Ring Gear	14					0.1										0.1																											
Ge15	Starter Motor	15		0.3												0.1						0.1																						
Ge16	Sump	16		0.2		0.1	0.1								0.2																	0.1	0.2											
Ge17	Oil Filler	17	0.1									0.2																				0.1										0.1		
Ge18	Engine Breather	18	0.1	0.3								0.1																								0.2								
Ge19	Oil Pump	19		0.2			0.1																							0.1			0.1											
Ge20	Oil Filter	20		0.1													0.1																							0.2				
Ge21	Oil Cooler	21	0.1	0.3							0.1	0.1																																
Ge22	Crank Pulley Damper Belt	22					0.2																		0.1				0.3			0.1												
Ge23	Fan Drive	23		0.2																				0.2		0.2	0.1					0.1												0.2
Ge24	Fan Extension	24																							0.1							0.1												
Ge25	Coolant Pump	25	0.1	0.1																					0.1					0.1		0.2												
Ge26	Alternator Bracket	26	0.1																													0.1						0.1						
Ge27	Belt Driven Auxiliary (Hydraulic P	27	0.2										0.1											0.1								0.1												
Ge28	Gear Train	28		0.1			0.1		0.1				0.2								0.2						0.1				0.1	0.1	0.2											
Ge29	Gear Driven Auxiliary (Compress	29		0.1									0.1																	0.1		0.2							0.2					
Ge30	Timing Case	30	0.1	0.2			0.2						0.1					0.1						0.1	0.1	0.1	0.3	0.1	0.1	0.1	0.3													
Ge31	Balancer	31		0.1		0.2	0.3											0.2			0.2									0.1														
Ge32	Turbocharger	32		0.2																															0.1			0.2					0.2	
Ge33	Aircharge Cooler	33																																0.2		0.1								
Ge34	Air Intake	34	0.2																	0.3															0.2									
Ge35	Air Filter	35	0.1																																									
Ge36	Exhaust Manifold	36	0.4																															0.1										
Ge37	Low Pressure Fuel System	37		0.1							0.1		0.3									0.2									0.2									0.2				
Ge38	Fuel Filter	38	0.1								0.1	0.3										0.2																						
Ge39	Starting Aid	39	0.3								0.2			0.2																													0.1	
Ge40	Lifting Eyes	40	0.1																0.1																									
Ge41	Wiring Harness	41										0.2					0.2											0.1						0.2							0.2			
Ge42	Radiator	42	0.2	0.2																					0.2																			

Figure 54: Geometry attribute DSM including change likelihood values for the diesel engine

(i) Map the behavioural layer B: Similarly to the structural elements, (42*3=) 126 behavioural elements were defined using the three behavioural attributes: *Mechanical (Me), Electrical (El),* and *Thermal (Th)* (Figure 55). Again, the *Electrical* behaviour of many components is not relevant and their corresponding elements could be left out but were kept for consistency reasons.

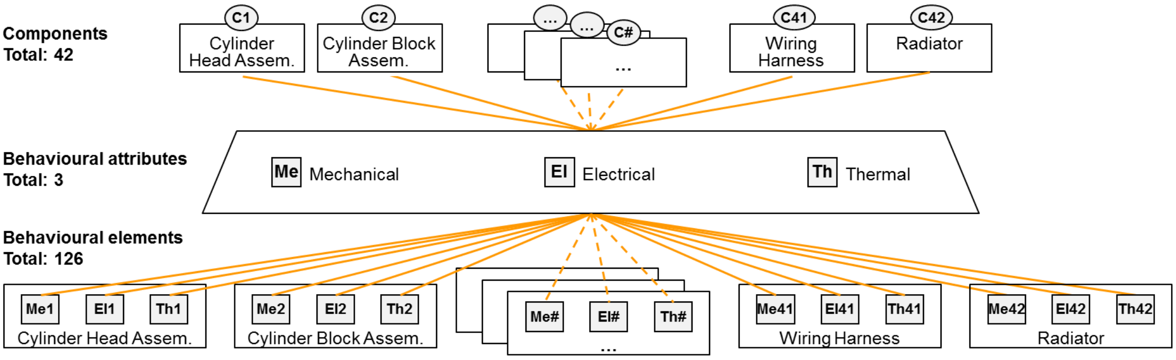
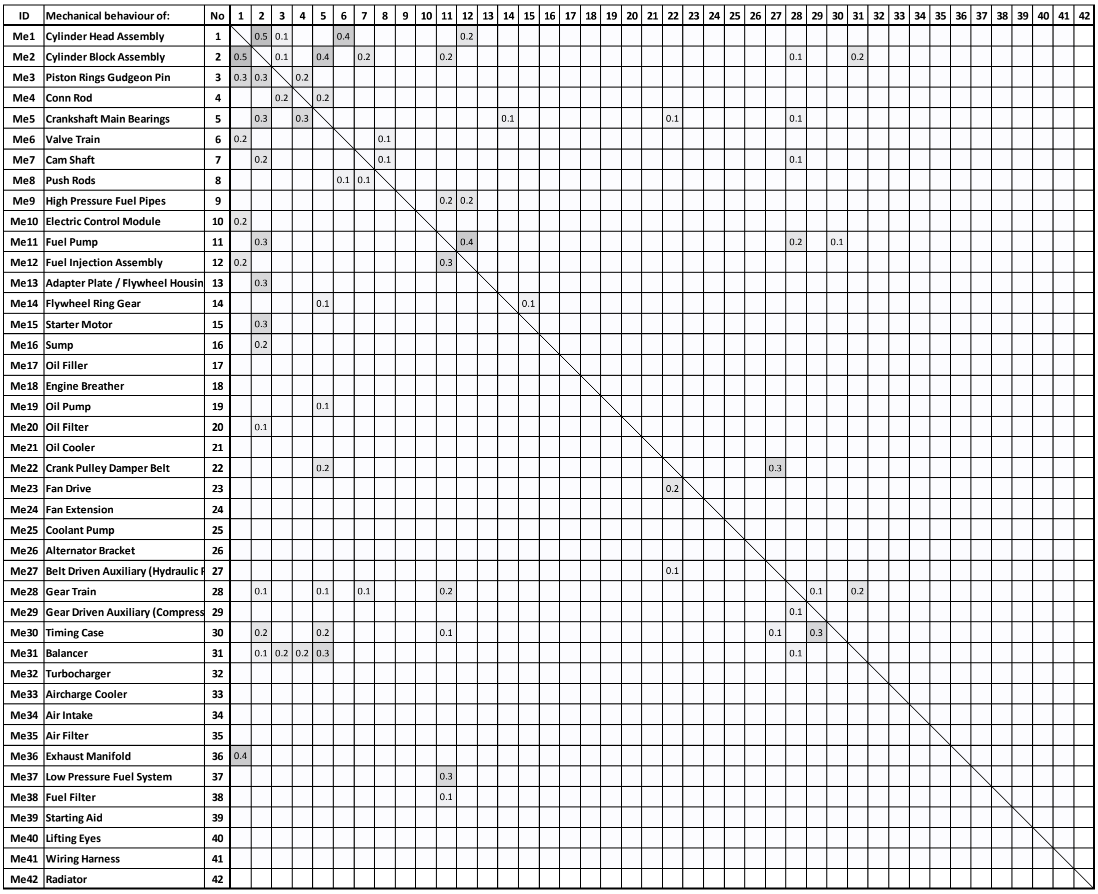


Figure 55: Defining behavioural elements for the diesel engine

The behavioural links between these 126 elements were first captured in behavioural attribute DSMs and then put together into a behaviour DSM. The *Mechanical* behaviour DSM represented in Figure 56 is the densest behavioural attribute DSM; however, it is less populated than the *Geometry* DSM in Figure 54 because there are less mechanical dependencies between the components than spatial.



ID	Mechanical behaviour of:	No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Me1	Cylinder Head Assembly	1		0.5	0.1			0.4						0.2																														
Me2	Cylinder Block Assembly	2	0.5		0.1		0.4		0.2				0.2																	0.1			0.2											
Me3	Piston Rings Gudgeon Pin	3	0.3	0.3		0.2																																						
Me4	Conn Rod	4			0.2		0.2																																					
Me5	Crankshaft Main Bearings	5		0.3		0.3										0.1								0.1						0.1														
Me6	Valve Train	6	0.2							0.1																																		
Me7	Cam Shaft	7		0.2						0.1																				0.1														
Me8	Push Rods	8						0.1	0.1																																			
Me9	High Pressure Fuel Pipes	9											0.2	0.2																														
Me10	Electric Control Module	10	0.2																																									
Me11	Fuel Pump	11		0.3										0.4																0.2		0.1												
Me12	Fuel Injection Assembly	12	0.2										0.3																															
Me13	Adapter Plate / Flywheel Housin	13		0.3																																								
Me14	Flywheel Ring Gear	14					0.1										0.1																											
Me15	Starter Motor	15		0.3																																								
Me16	Sump	16		0.2																																								
Me17	Oil Filler	17																																										
Me18	Engine Breather	18																																										
Me19	Oil Pump	19					0.1																																					
Me20	Oil Filter	20		0.1																																								
Me21	Oil Cooler	21																																										
Me22	Crank Pulley Damper Belt	22					0.2																						0.3															
Me23	Fan Drive	23																						0.2																				
Me24	Fan Extension	24																																										
Me25	Coolant Pump	25																																										
Me26	Alternator Bracket	26																																										
Me27	Belt Driven Auxiliary (Hydraulic	27																						0.1																				
Me28	Gear Train	28		0.1			0.1		0.1				0.2																		0.1		0.2											
Me29	Gear Driven Auxiliary (Compress	29																												0.1														
Me30	Timing Case	30		0.2			0.2						0.1																0.1		0.3													
Me31	Balancer	31		0.1	0.2	0.2	0.3																							0.1														
Me32	Turbocharger	32																																										
Me33	Aircharge Cooler	33																																										
Me34	Air Intake	34																																										
Me35	Air Filter	35																																										
Me36	Exhaust Manifold	36	0.4																																									
Me37	Low Pressure Fuel System	37											0.3																															
Me38	Fuel Filter	38											0.1																															
Me39	Starting Aid	39																																										
Me40	Lifting Eyes	40																																										
Me41	Wiring Harness	41																																										
Me42	Radiator	42																																										

Figure 56: Mechanical attribute DSM including change likelihood values for the diesel engine

(iii) Map the structure-behaviour (S-B) links: The links between the structural and behavioural elements were identified collectively and symmetrically for all corresponding elements using the attribute relations depicted in Figure 57. If the attribute link was not relevant on the element level, it was removed subsequently.

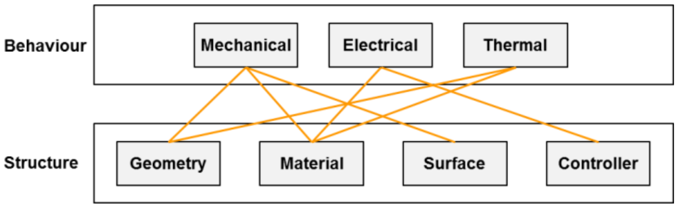


Figure 57: Defining the links between the structural and behavioural attributes of the diesel engine

(iv) Map the functional layer F: The functional model of the diesel engine was developed by applying the reconciled functional basis from Hirtz et al. (2002) to detail the four diesel strokes. 40 subfunctions were identified and linked to each other by flows of material, energy, and signal (Figure 58).

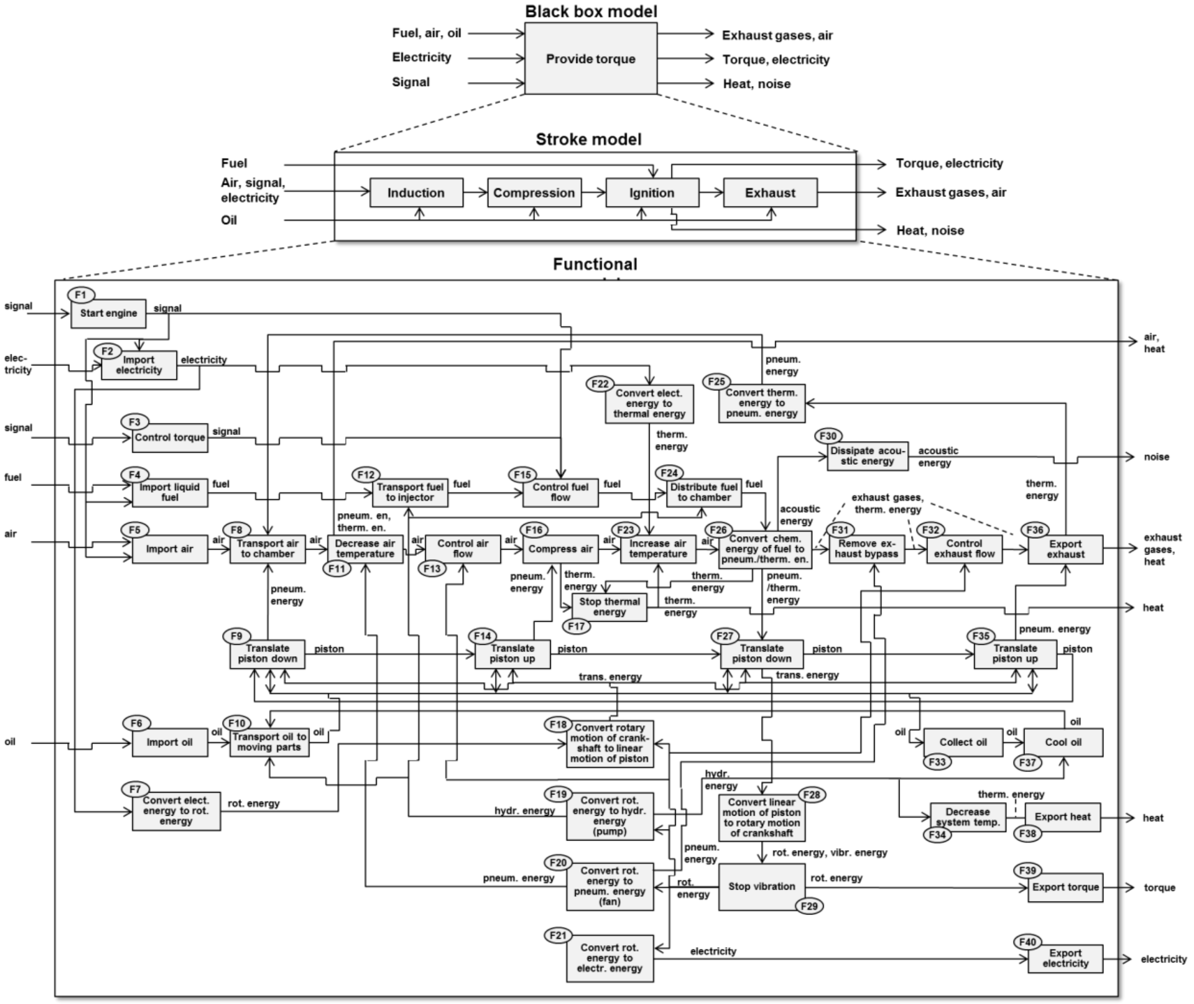


Figure 58: Functional elements and links of the diesel engine

Fuel, air, oil, exhaust gases, and piston were used as material flows. The flows of energy were differentiated into thermal, electrical, rotational, translational, pneumatic, hydraulic, acoustic, and vibrational. Signal includes the interaction with the engine user in order to start the engine and control its speed. Although the functional block diagram in Figure 58 is directed it was considered to be undirected for change propagation and thus within the FBS Linkage model as previously explained for the hairdryer. Consequently, the functional layer DSM is symmetric (Figure 59).

The functional model follows most of the proposed functions and flows from the reconciled functional basis. However, in some cases it was decided to be more and in other cases less precise. For example, on one hand, while Hirtz et al. (2002) use general functions such as *Import liquid*, it was decided to use here a more precise function description such as *Import fuel* to locate subfunctions. On the other hand, functions such as *Start engine (F1)* are kept less detailed than suggested by the reconciled functional basis because their elementary level is less relevant for the change model of the diesel engine.

A key characteristic of the functional model of the diesel engine is its cycles. This is represented by the up and down movement of the piston as a material flow through the subfunctions *F9*, *F14*, *F27*, and *F35*. The subfunctions *F1*, *F2*, *F7*, and *F22* are only required in the starting phase of the engine and not involved in the cycles. The subfunctions *F6*, *F10*, *F33*, and *F37* are responsible for the lubrication of the whole system, and especially, of the piston.

(v) Map the function-behaviour (F-B) links: The functional elements (subfunctions) were first linked to the components and then further specified into undirected links between functional and behavioural elements as shown in Table 14.

Finally, all links and elements were put together to complete the FBS Linkage scheme for the diesel engine.

Table 14: Mapping of the function-behaviour links of the diesel engine

No	Subfunction	No of component for:		
		Thermal behaviour	Electrical behaviour	Mechanical behaviour
1	Start engine		10,41	
2	Import electricity		41	
3	Control torque		10,41	
4	Import liquid fuel			37,38
5	Import air			34,35
6	Import oil			17
7	Convert elect. energy to rot. energy		15	13,14
8	Transport air to chamber	32,34		32,34
9	Translate piston down			1,2,3,4,5
10	Transport oil to moving parts			19,20
11	Decrease air temperature	33		
12	Transport fuel to injector	9		9
13	Control air flow		10,41	6,7,8,22,28,30
14	Translate piston up	1,2,3		1,2,3,4,5
15	Control fuel flow		10,41	6,7,22,28,30
16	Compress air	1,2,3,8		1,2,3,8
17	Stop therm. energy	1,2,3,8		
18	Convert rotary motion of crankshaft to linear motion of piston			3,4,5
19	Convert rot. energy to hydr. energy			19,22,25,27,30
20	Convert rot. energy to pneum. energy			22,23,24,29,30
21	Convert rot. energy to electr. Energy		26	22,26,30
22	Convert elect. energy to therm. energy		39	
23	Increase air temperature	1,2,3		
24	Distribute fuel to chamber		12	12
25	Convert therm. energy to pneum. energy	32		32
26	Convert chem. energy of fuel to pneum./ therm. energy	1,2,3		1,2,3
27	Translate piston down	1,2,3		1,2,3,4,5
28	Convert linear motion of piston to rotary motion of crankshaft			3,4,5
29	Stop vibration			30, 31
30	Dissipate acoustic energy			1,2
31	Remove exhaust bypass	18		18
32	Control exhaust flow	8	10	6,7,8,22,28,30
33	Collect oil	16		16
34	Decrease system temperature	25		25
35	Translate piston up	1,2,3		1,2,3,4,5
36	Export exhaust	32,36		32,36
37	Cool oil	21		21
38	Export Heat	42		42
39	Export torque			13,14,28
40	Export electricity		41	

No	Component
1	Cylinder Head Assembly
2	Cylinder Block Assembly
3	Piston Rings Gudgeon Pin
4	Conn Rod
5	Crankshaft Main Bearings
6	Valve train
7	Cam Shaft
8	Push rods
9	High Pressure Fuel Pipes
10	Electric Control Module
11	Fuel Pump
12	Fuel Injection Assembly
13	Adapter Plate / Flywheel Housing
14	Flywheel Ring Gear
15	Starter Motor
16	Sump
17	Oil Filler
18	Engine Breather
19	Oil Pump
20	Oil Filter
21	Oil Cooler
22	Crank Pulley Damper Belt
23	Fan Drive
24	Fan Extension
25	Coolant Pump
26	Alternator Bracket
27	Belt Driven Auxiliary (hydraulic pump)
28	Gear Train
29	Gear Driven Auxiliary (compressor)
30	Timing Case
31	Balancer
32	Turbocharger
33	Aircharge Cooler
34	Air Intake
35	Air Filter
36	Exhaust Manifold
37	Low Pressure Fuel System
38	Fuel Filter
39	Starting Aid
40	Lifting Eyes
41	Wiring Harness
42	Radiator

7.2.3 Quantify FBS links

The intralayer links between structural and behavioural elements were quantified drawing on the linkage types and values defined in the CPM model from Jarratt *et al.* (2004a). The likelihood values for *Geometry* are represented in Figure 54 and for *Mechanical* behaviour in Figure 56. The intralayer links between functional elements were quantified under the symmetry assumption using a change impact value of 0.1 for all links and one of the three different values for change likelihood, namely: 0.3 for low, 0.5 for medium, and 0.8 for high as represented in Figure 59. All interlayer links were defined using 0.5 for change likelihood and 0.1 for change impact.

ID	Function name	No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
F1	Start engine	1		0.3		0.3	0.3										0.3																									
F2	Import electricity	2	0.3						0.3															0.3																		
F3	Control torque	3															0.3																									
F4	Import liquid fuel	4	0.3											0.3																												
F5	Import air	5	0.3							0.3																																
F6	Import oil	6										0.3																														
F7	Convert elect. energy to rot. ene	7		0.3																0.3																						
F8	Transport air to chamber	8					0.3				0.3		0.3														0.3															
F9	Translate piston down	9								0.3		0.3				0.5				0.5															0.3		0.5					
F10	Transport oil to moving parts	10						0.3			0.3					0.3					0.3								0.3								0.3		0.3			
F11	Decrease air temparature	11								0.3					0.3							0.3																				
F12	Transport fuel to injector	12				0.3											0.3				0.3																					
F13	Control air flow	13											0.3					0.3													0.3											
F14	Translate piston up	14									0.5	0.3						0.5		0.5									0.5						0.3							
F15	Control fuel flow	15	0.3		0.3									0.3												0.3																
F16	Compress air	16													0.3	0.5			0.5						0.5																	
F17	Stop therm. energy	17																0.5							0.3			0.5														
F18	Convert rotary motion of cranksh	18							0.3		0.5					0.5													0.5		0.3						0.5					
F19	Convert rot. energy to hydr. ene	19										0.3		0.3												0.3					0.3					0.3			0.3			
F20	Convert rot. energy to pneum. e	20											0.3																		0.3		0.3									
F21	Convert rot. energy to electr. En	21																													0.3											0.3
F22	Convert elect. energy to therm.	22		0.3																					0.3																	
F23	Increase air temparature	23																0.5	0.3					0.3				0.8														
F24	Distribute fuel to chamber	24															0.3				0.3							0.8														
F25	Convert therm. energy to pneum	25								0.3																												0.3				
F26	Convert chem. energy of fuel to	26																	0.5						0.8	0.8			0.8			0.3	0.3									
F27	Translate piston down	27										0.3				0.5				0.5								0.8		0.8					0.3		0.5					
F28	Convert linear motion of piston	28																											0.8		0.3											
F29	Stop vibration	29													0.3					0.3	0.3	0.3	0.3							0.3				0.3							0.3	
F30	Dissipate acoustic energy	30																										0.3														
F31	Remove exhaust bypass	31																				0.3						0.3						0.3								
F32	Control exhaust flow	32																													0.3		0.3					0.3				
F33	Collect oil	33									0.3					0.3													0.3								0.3		0.3			
F34	Decrease system temperature	34																			0.3																			0.3		
F35	Translate piston up	35									0.5	0.3								0.5									0.5						0.3			0.3				
F36	Export exhaust	36																									0.3							0.3			0.3					
F37	Cool oil	37										0.3									0.3														0.3							
F38	Export Heat	38																																		0.3						
F39	Export torque	39																													0.3											
F40	Export electricity	40																					0.3																			

Figure 59: Function DSM including likelihood values of change propagation for the diesel engine

7.2.4 Compute combined change risk

The likelihood and the impact FBS Linkage MDMs were transferred into CAM, where the Forward CPM algorithm was applied to them to calculate the combined change risks considering six steps of propagation. The detailed results are represented in the risk MDM in Figure 60. The shading colour indicates the risk value: the darker (redder) the cells the higher the risk. Although, the diagram resolution is too low for reading the details, the screenshot indicates the density distribution of the MDM.

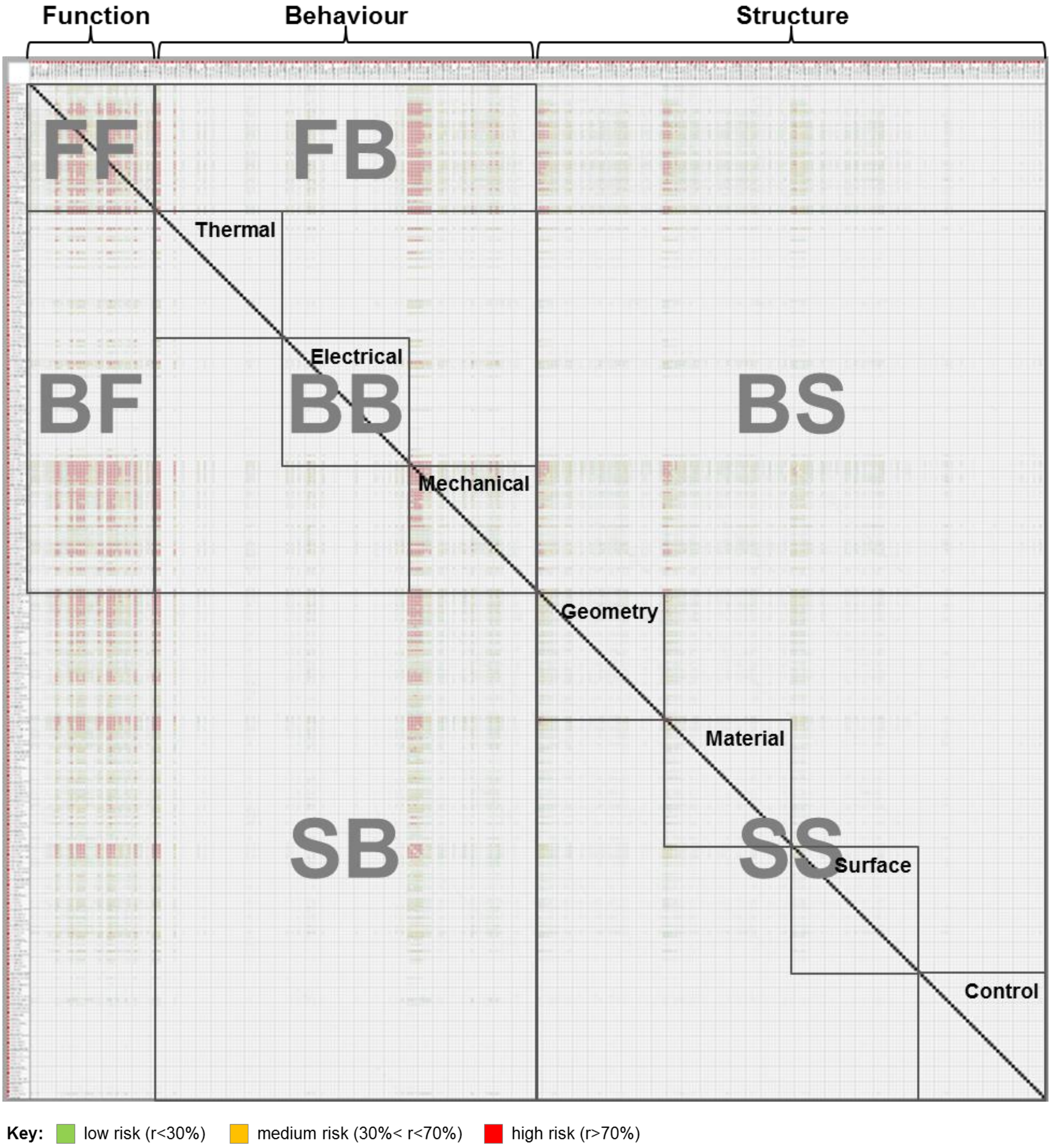
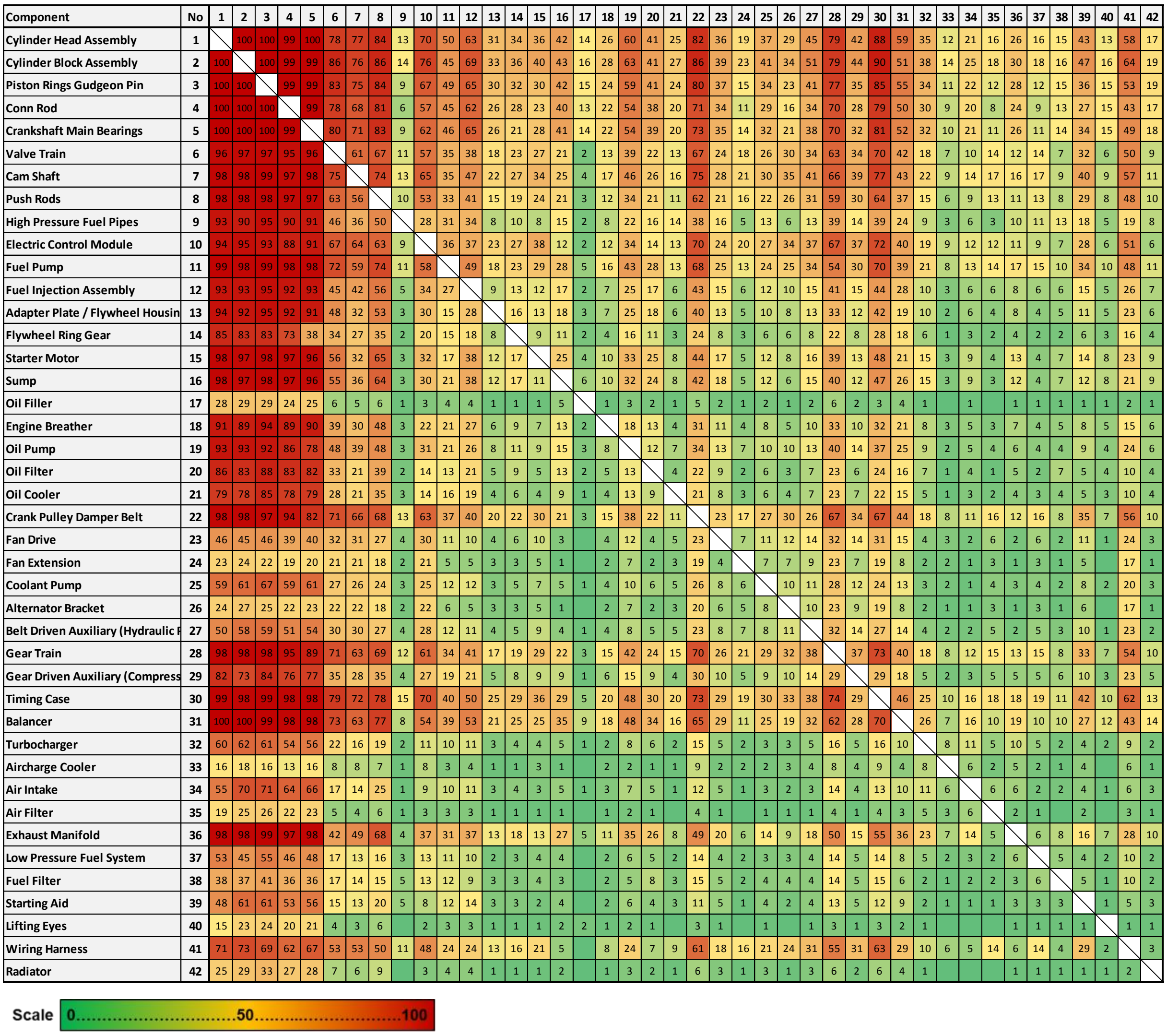


Figure 60: Combined risk MDM for the diesel engine

7.2.5 Use the change risk model

The combined risk MDM in Figure 60 shows the dependencies between the functional, behavioural, and structural layers in multiple attribute dimensions. It is more populated than the direct likelihood or impact MDMs and has only a few empty cells.

A comparison of the DSMs along the diagonal of this MDM shows that the function DSM (FF) has the highest density. This means that the functions are highly integrated and interdependent. This is expected and can be explained because most functions are part of one of the four diesel engine strokes. A change to one function impacts the corresponding stroke, which in turn is most likely to impact the other strokes. For instance, an increase of the induction volume would affect the compression, ignition, and exhaust strokes. The second densest risk DSM is the *Mechanical* behaviour DSM. This suggests that the components' mechanical behaviours are highly interdependent. This is reasonable because the diesel engine works mainly mechanically, and thus, the mechanical stress of its components is high. Consequently, changes affecting mechanical behaviours of one component impose high risk to other components. In a more detailed model, the mechanical behaviours could be further subdivided into static load, dynamic load, aerodynamic behaviour, etc. to investigate these relations more rigorously.



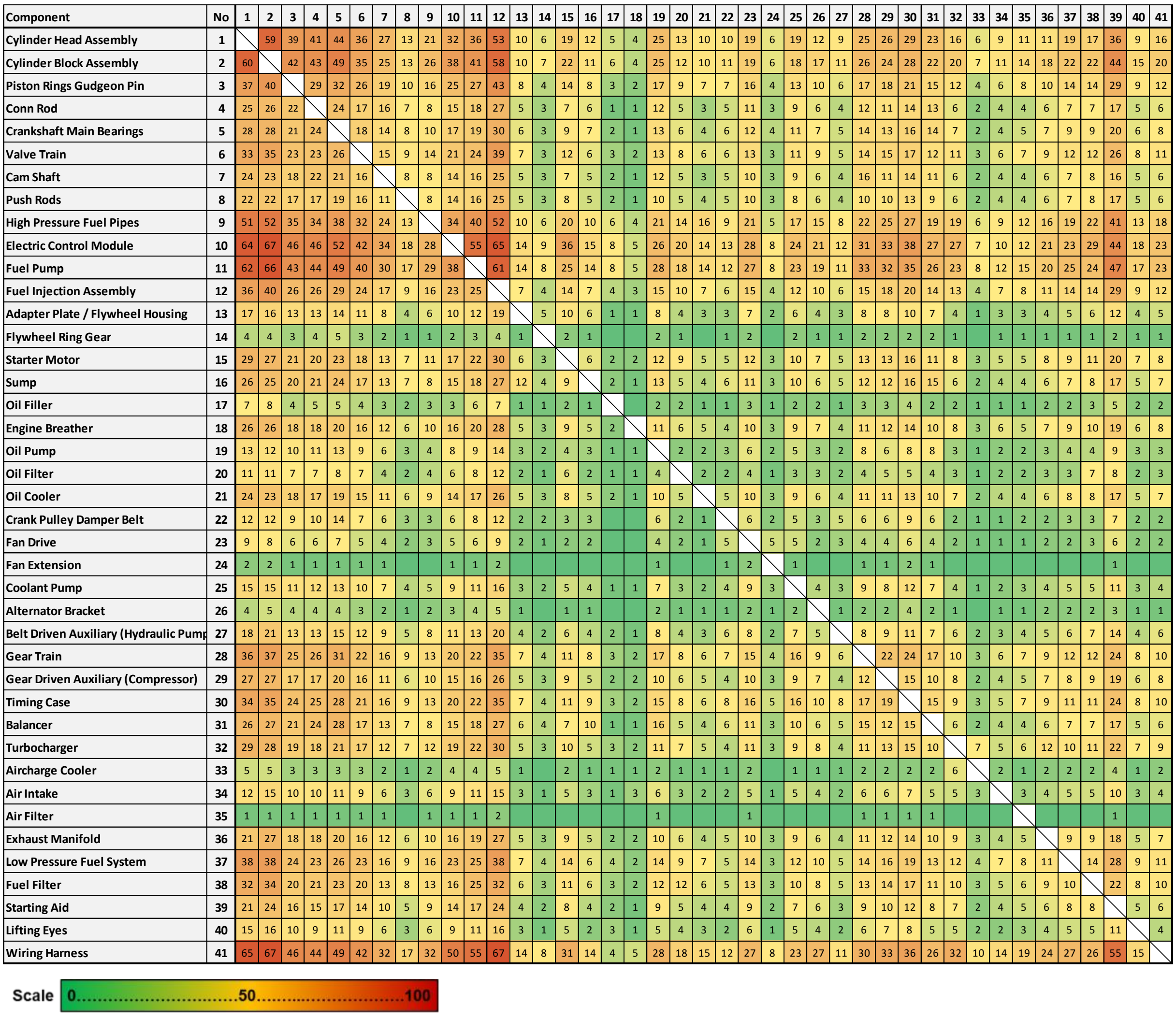
Component	No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Cylinder Head Assembly	1		100	100	99	100	78	77	84	13	70	50	63	31	34	36	42	14	26	60	41	25	82	36	19	37	29	45	79	42	88	59	35	12	21	16	26	16	15	43	13	58	17
Cylinder Block Assembly	2	100		100	99	99	86	76	86	14	76	45	69	33	36	40	43	16	28	63	41	27	86	39	23	41	34	51	79	44	90	51	38	14	25	18	30	18	16	47	16	64	19
Piston Rings Gudgeon Pin	3	100	100		99	99	83	75	84	9	67	49	65	30	32	30	42	15	24	59	41	24	80	37	15	34	23	41	77	35	85	55	34	11	22	12	28	12	15	36	15	53	19
Conn Rod	4	100	100	100		99	78	68	81	6	57	45	62	26	28	23	40	13	22	54	38	20	71	34	11	29	16	34	70	28	79	50	30	9	20	8	24	9	13	27	15	43	17
Crankshaft Main Bearings	5	100	100	100	99		80	71	83	9	62	46	65	26	21	28	41	14	22	54	39	20	73	35	14	32	21	38	70	32	81	52	32	10	21	11	26	11	14	34	15	49	18
Valve Train	6	96	97	97	95	96		61	67	11	57	35	38	18	23	27	21	2	13	39	22	13	67	24	18	26	30	34	63	34	70	42	18	7	10	14	12	14	7	32	6	50	9
Cam Shaft	7	98	98	99	97	98	75		74	13	65	35	47	22	27	34	25	4	17	46	26	16	75	28	21	30	35	41	66	39	77	43	22	9	14	17	16	17	9	40	9	57	11
Push Rods	8	98	98	98	97	97	63	56		10	53	33	41	15	19	24	21	3	12	34	21	11	62	21	16	22	26	31	59	30	64	37	15	6	9	13	11	13	8	29	8	48	10
High Pressure Fuel Pipes	9	93	90	95	90	91	46	36	50		28	31	34	8	10	8	15	2	8	22	16	14	38	16	5	13	6	13	39	14	39	24	9	3	6	3	10	11	13	18	5	19	8
Electric Control Module	10	94	95	93	88	91	67	64	63	9		36	37	23	27	38	12	2	12	34	14	13	70	24	20	27	34	37	67	37	72	40	19	9	12	12	11	9	7	28	6	51	6
Fuel Pump	11	99	98	99	98	98	72	59	74	11	58		49	18	23	29	28	5	16	43	28	13	68	25	13	24	25	34	54	30	70	39	21	8	13	14	17	15	10	34	10	48	11
Fuel Injection Assembly	12	93	93	95	92	93	45	42	56	5	34	27		9	13	12	17	2	7	25	17	6	43	15	6	12	10	15	41	15	44	28	10	3	6	6	8	6	6	15	5	26	7
Adapter Plate / Flywheel Housin	13	94	92	95	92	91	48	32	53	3	30	15	28		16	13	18	3	7	25	18	6	40	13	5	10	8	13	33	12	42	19	10	2	6	4	8	4	5	11	5	23	6
Flywheel Ring Gear	14	85	83	83	73	38	34	27	35	2	20	15	18	8		9	11	2	4	16	11	3	24	8	3	6	6	8	22	8	28	18	6	1	3	2	4	2	2	6	3	16	4
Starter Motor	15	98	97	98	97	96	56	32	65	3	32	17	38	12	17		25	4	10	33	25	8	44	17	5	12	8	16	39	13	48	21	15	3	9	4	13	4	7	14	8	23	9
Sump	16	98	97	98	97	96	55	36	64	3	30	21	38	12	17	11		6	10	32	24	8	42	18	5	12	6	15	40	12	47	26	15	3	9	3	12	4	7	12	8	21	9
Oil Filler	17	28	29	29	24	25	6	5	6	1	3	4	4	1	1	1	5		1	3	2	1	5	2	1	2	1	2	6	2	3	4	1		1		1	1	1	1	1	2	1
Engine Breather	18	91	89	94	89	90	39	30	48	3	22	21	27	6	9	7	13	2		18	13	4	31	11	4	8	5	10	33	10	32	21	8	3	5	3	7	4	5	8	5	15	6
Oil Pump	19	93	93	92	86	78	48	39	48	3	31	21	26	8	11	9	15	3	8		12	7	34	13	7	10	10	13	40	14	37	25	9	2	5	4	6	4	4	9	4	24	6
Oil Filter	20	86	83	88	83	82	33	21	39	2	14	13	21	5	9	5	13	2	5	13		4	22	9	2	6	3	7	23	6	24	16	7	1	4	1	5	2	7	5	4	10	4
Oil Cooler	21	79	78	85	78	79	28	21	35	3	14	16	19	4	6	4	9	1	4	13	9		21	8	3	6	4	7	23	7	22	15	5	1	3	2	4	3	4	5	3	10	4
Crank Pulley Damper Belt	22	98	98	97	94	82	71	66	68	13	63	37	40	20	22	30	21	3	15	38	22	11		23	17	27	30	26	67	34	67	44	18	8	11	16	12	16	8	35	7	56	10
Fan Drive	23	46	45	46	39	40	32	31	27	4	30	11	10	4	6	10	3		4	12	4	5	23		7	11	12	14	32	14	31	15	4	3	2	6	2	6	2	11	1	24	3
Fan Extension	24	23	24	22	19	20	21	21	18	2	21	5	5	3	3	5	1		2	7	2	3	19	4		7	7	9	23	7	19	8	2	2	1	3	1	3	1	5		17	1
Coolant Pump	25	59	61	67	59	61	27	26	24	3	25	12	12	3	5	7	5	1	4	10	6	5	26	8	6		10	11	28	12	24	13	3	2	1	4	3	4	2	8	2	20	3
Alternator Bracket	26	24	27	25	22	23	22	22	18	2	22	6	5	3	3	5	1		2	7	2	3	20	6	5	8		10	23	9	19	8	2	1	1	3	1	3	1	6		17	1
Belt Driven Auxiliary (Hydraulic	27	50	58	59	51	54	30	30	27	4	28	12	11	4	5	9	4	1	4	8	5	5	23	8	7	8	11		32	14	27	14	4	2	2	5	2	5	3	10	1	23	2
Gear Train	28	98	98	98	95	89	71	63	69	12	61	34	41	17	19	29	22	3	15	42	24	15	70	26	21	29	32	38		37	73	40	18	8	12	15	13	15	8	33	7	54	10
Gear Driven Auxiliary (Compress	29	82	73	84	76	77	35	28	35	4	27	19	21	5	8	9	9	1	6	15	9	4	30	10	5	9	10	14	29		29	18	5	2	3	5	5	5	6	10	3	23	5
Timing Case	30	99	98	99	98	98	79	72	78	15	70	40	50	25	29	36	29	5	20	48	30	20	73	29	19	30	33	38	74	29		46	25	10	16	18	18	19	11	42	10	62	13
Balancer	31	100	100	99	98	98	73	63	77	8	54	39	53	21	25	25	35	9	18	48	34	16	65	29	11	25	19	32	62	28	70		26	7	16	10	19	10	10	27	12	43	14
Turbocharger	32	60	62	61	54	56	22	16	19	2	11	10	11	3	4	4	5	1	2	8	6	2	15	5	2	3	3	5	16	5	16	10		8	11	5	10	5	2	4	2	9	2
Aircharge Cooler	33	16	18	16	13	16	8	8	7	1	8	3	4	1	1	3	1		2	2	1	1	9	2	2	2	3	4	8	4	9	4	8		6	2	5	2	1	4		6	1
Air Intake	34	55	70	71	64	66	17	14	25	1	9	10	11	3	4	3	5	1	3	7	5	1	12	5	1	3	2	3	14	4	13	10	11	6		6	6	2	2	4	1	6	3
Air Filter	35	19	25	26	22	23	5	4	6	1	3	3	3	1	1	1	1		1	2	1		4	1		1	1	1	4	1	4	3	5	3	6		2	1		2		3	1
Exhaust Manifold	36	98	98	99	97	98	42	49	68	4	37	31	37	13	18	13	27	5	11	35	26	8	49	20	6	14	9	18	50	15	55	36	23	7	14	5		6	8	16	7	28	10
Low Pressure Fuel System	37	53	45	55	46	48	17	13	16	3	13	11	10	2	3	4	4		2	6	5	2	14	4	2	3	3	4	14	5	14	8	5	2	3	2	6		5	4	2	10	2
Fuel Filter	38	38	37	41	36	36	17	14	15	5	13	12	9	3	3	4	3		2	5	8	3	15	5	2	4	4	4	14	5	15	6	2	1	2	2	3	6		5	1	10	2
Starting Aid	39	48	61	61	53	56	15	13	20	5	8	12	14	3	3	2	4		2	6	4	3	11	5	1	4	2	4	13	5	12	9	2	1	1	1	3	3	3		1	5	3
Lifting Eyes	40	15	23	24	20	21	4	3	6		2	3	3	1	1	1	2	2	1	2	1		3	1		1		1	3	1	3	2	1				1	1	1	1		1	1
Wiring Harness	41	71	73	69	62	67	53	53	50	11	48	24	24	13	16	21	5		8	24	7	9	61	18	16	21	24	31	55	31	63	29	10	6	5	14	6	14	4	29	2		3
Radiator	42	25	29	33	27	28	7	6	9		3	4	4	1	1	1	2		1	3	2	1	6	3	1	3	1	3	6	2	6	4	1				1	1	1	1	1	2	

Figure 61: Aggregated combined risk DSM for the diesel engine (FBS Linkage) (in %)

For high level analyses, the behavioural and structural layers of the combined risk MDM were aggregated using the maximum operator to obtain the component-component risk DSM in Figure 61. Such a DSM helps identify risk absorbers and multipliers (Eckert *et al.* 2004) and compare the component risk profiles to each other (Keller *et al.* 2009). This aggregated matrix includes the maximum combined risk values of the three behavioural and four structural attribute DSMs as well as the 24 square DMMs between them as depicted in Figure 60. Thus, this result represents the worst case scenario of change propagation; the DSM does not differentiate between the types of change (e.g. *Geometry, Material,* or *Electrical* behaviours) and assumes that all component attributes are affected simultaneously while taking the highest risk into account.

The colour scale indicates the risk values as follows: Green is used for low risk, yellow for medium risk, and red for high risk. The overall average of the risk values is 24.9%, with a distribution of {min; 0.25-quantile; median; 0.75-quantile; max} = {0; 5%; 14%; 34%, 100%} and a population-density (i.e. actual risk values above zero divided by possible links) of 98.3%. The distribution is right-skewed and the majority of the links have low risk values. The colour scale of Figure 61 indicates that the core components (*C1* to *C12*) are critical towards receiving changes from other components (i.e. rows 1 to 12) as well as imposing changes to other components (i.e. columns 1 to 12) and especially among each other (cells within rows and columns 1 to 12). The links between most of the non-core components are less critical. The high population density of this DSM reflects the view that the whole diesel engine is one fully integrated system and suggests that all components are interlinked to each other. A change to one component may affect almost any other component.

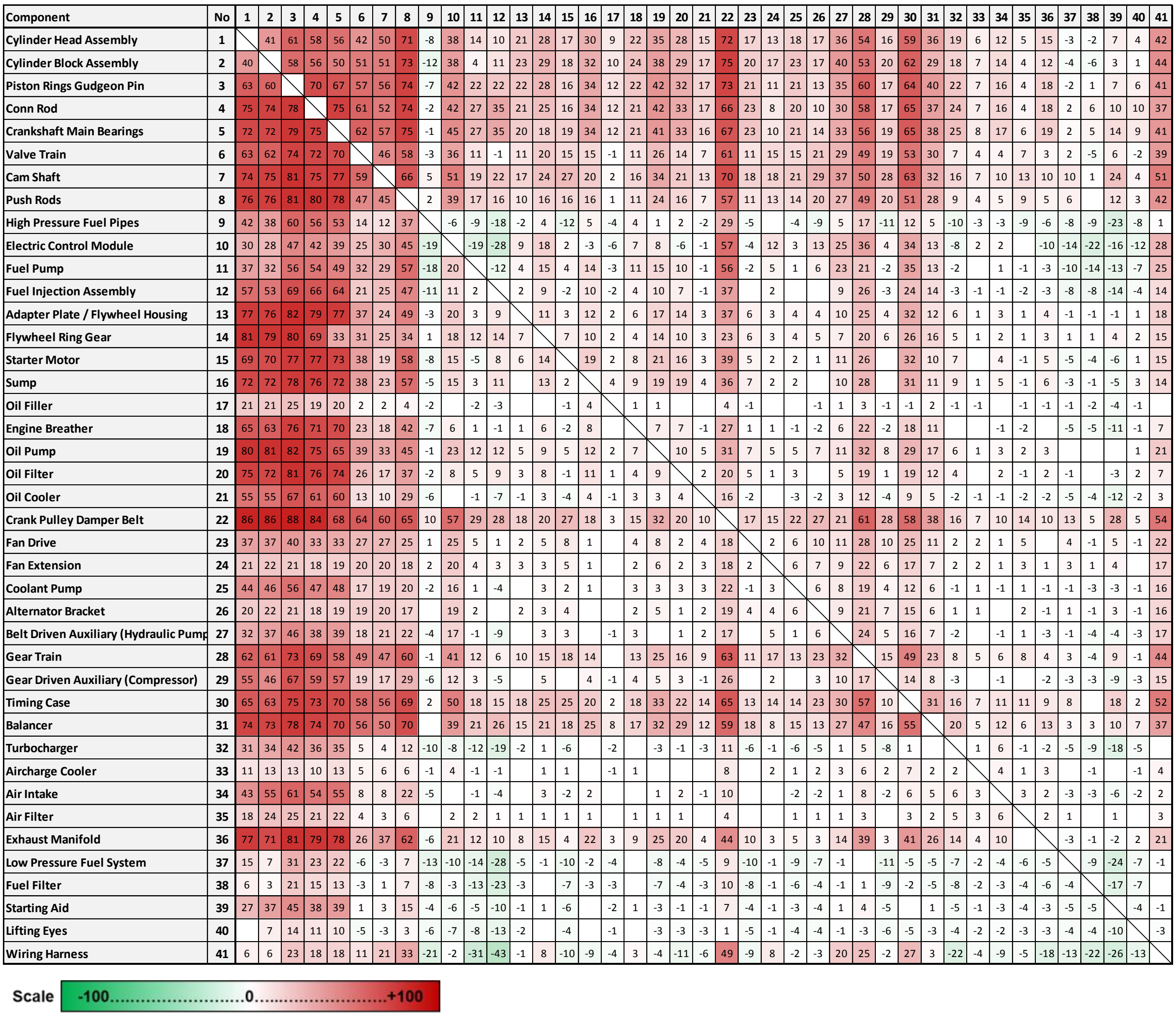
The combined risk matrix generated by applying the Forward CPM algorithm considering six steps of change propagation to the original CPM diesel engine model reported by Jarratt (2004) is represented in Figure 62. It should be noted that Jarratt’s model exists only on the component level and comprises 41 components as the *Radiator* was not considered. This DSM has an overall average of risk values of 10.8%, with a distribution of {min; 0.25-quantile; median; 0.75-quantile; max} = {0; 3%; 7%; 15%; 67%} and a population-density (i.e. actual risk values above zero divided by possible links) of 96.4%. Thus, the distribution of the risk values calculated with the original CPM model is also right-skewed. Compared to the FBS Linkage result, the CPM risk matrix has a significantly lower overall average (by 15.1%-points), a significantly lower maximum risk value (by 33%-points), and a slightly lower population density (by 1.9%-points).



Component	No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Cylinder Head Assembly	1		59	39	41	44	36	27	13	21	32	36	53	10	6	19	12	5	4	25	13	10	10	19	6	19	12	9	25	26	29	23	16	6	9	11	11	19	17	36	9	16
Cylinder Block Assembly	2	60		42	43	49	35	25	13	26	38	41	58	10	7	22	11	6	4	25	12	10	11	19	6	18	17	11	26	24	28	22	20	7	11	14	18	22	22	44	15	20
Piston Rings Gudgeon Pin	3	37	40		29	32	26	19	10	16	25	27	43	8	4	14	8	3	2	17	9	7	7	16	4	13	10	6	17	18	21	15	12	4	6	8	10	14	14	29	9	12
Conn Rod	4	25	26	22		24	17	16	7	8	15	18	27	5	3	7	6	1	1	12	5	3	5	11	3	9	6	4	12	11	14	13	6	2	4	4	6	7	7	17	5	6
Crankshaft Main Bearings	5	28	28	21	24		18	14	8	10	17	19	30	6	3	9	7	2	1	13	6	4	6	12	4	11	7	5	14	13	16	14	7	2	4	5	7	9	9	20	6	8
Valve Train	6	33	35	23	23	26		15	9	14	21	24	39	7	3	12	6	3	2	13	8	6	6	13	3	11	9	5	14	15	17	12	11	3	6	7	9	12	12	26	8	11
Cam Shaft	7	24	23	18	22	21	16		8	8	14	16	25	5	3	7	5	2	1	12	5	3	5	10	3	9	6	4	16	11	14	11	6	2	4	4	6	7	8	16	5	6
Push Rods	8	22	22	17	17	19	16	11		8	14	16	25	5	3	8	5	2	1	10	5	4	5	10	3	8	6	4	10	10	13	9	6	2	4	4	6	7	8	17	5	6
High Pressure Fuel Pipes	9	51	52	35	34	38	32	24	13		34	40	52	10	6	20	10	6	4	21	14	16	9	21	5	17	15	8	22	25	27	19	19	6	9	12	16	19	22	41	13	18
Electric Control Module	10	64	67	46	46	52	42	34	18	28		55	65	14	9	36	15	8	5	26	20	14	13	28	8	24	21	12	31	33	38	27	27	7	10	12	21	23	29	44	18	23
Fuel Pump	11	62	66	43	44	49	40	30	17	29	38		61	14	8	25	14	8	5	28	18	14	12	27	8	23	19	11	33	32	35	26	23	8	12	15	20	25	24	47	17	23
Fuel Injection Assembly	12	36	40	26	26	29	24	17	9	16	23	25		7	4	14	7	4	3	15	10	7	6	15	4	12	10	6	15	18	20	14	13	4	7	8	11	14	14	29	9	12
Adapter Plate / Flywheel Housing	13	17	16	13	13	14	11	8	4	6	10	12	19		5	10	6	1	1	8	4	3	3	7	2	6	4	3	8	8	10	7	4	1	3	3	4	5	6	12	4	5
Flywheel Ring Gear	14	4	4	3	4	5	3	2	1	1	2	3	4	1		2	1			2	1		1	2		2	1	1	2	2	2	2	1		1	1	1	1	1	2	1	1
Starter Motor	15	29	27	21	20	23	18	13	7	11	17	22	30	6	3		6	2	2	12	9	5	5	12	3	10	7	5	13	13	16	11	8	3	5	5	8	9	11	20	7	8
Sump	16	26	25	20	21	24	17	13	7	8	15	18	27	12	4	9		2	1	13	5	4	6	11	3	10	6	5	12	12	16	15	6	2	4	4	6	7	8	17	5	7
Oil Filler	17	7	8	4	5	5	4	3	2	3	3	6	7	1	1	2	1			2	2	1	1	3	1	2	2	1	3	3	4	2	2	1	1	1	2	2	3	5	2	2
Engine Breather	18	26	26	18	18	20	16	12	6	10	16	20	28	5	3	9	5	2		11	6	5	4	10	3	9	7	4	11	12	14	10	8	3	6	5	7	9	10	19	6	8
Oil Pump	19	13	12	10	11	13	9	6	3	4	8	9	14	3	2	4	3	1	1		2	2	3	6	2	5	3	2	8	6	8	8	3	1	2	2	3	4	4	9	3	3
Oil Filter	20	11	11	7	7	8	7	4	2	4	6	8	12	2	1	6	2	1	1	4		2	2	4	1	3	3	2	4	5	5	4	3	1	2	2	3	3	7	8	2	3
Oil Cooler	21	24	23	18	17	19	15	11	6	9	14	17	26	5	3	8	5	2	1	10	5		5	10	3	9	6	4	11	11	13	10	7	2	4	4	6	8	8	17	5	7
Crank Pulley Damper Belt	22	12	12	9	10	14	7	6	3	3	6	8	12	2	2	3	3			6	2	1		6	2	5	3	5	6	6	9	6	2	1	1	2	2	3	3	7	2	2
Fan Drive	23	9	8	6	6	7	5	4	2	3	5	6	9	2	1	2	2			4	2	1	5		5	5	2	3	4	4	6	4	2	1	1	1	2	2	3	6	2	2
Fan Extension	24	2	2	1	1	1	1	1			1	1	2							1			1	2		1			1	1	2	1								1		
Coolant Pump	25	15	15	11	12	13	10	7	4	5	9	11	16	3	2	5	4	1	1	7	3	2	4	9	3		4	3	9	8	12	7	4	1	2	3	4	5	5	11	3	4
Alternator Bracket	26	4	5	4	4	4	3	2	1	2	3	4	5	1		1	1			2	1	1	1	2	1	2		1	2	2	4	2	1		1	1	2	2	2	3	1	1
Belt Driven Auxiliary (Hydraulic Pump	27	18	21	13	13	15	12	9	5	8	11	13	20	4	2	6	4	2	1	8	4	3	6	8	2	7	5		8	9	11	7	6	2	3	4	5	6	7	14	4	6
Gear Train	28	36	37	25	26	31	22	16	9	13	20	22	35	7	4	11	8	3	2	17	8	6	7	15	4	16	9	6		22	24	17	10	3	6	7	9	12	12	24	8	10
Gear Driven Auxiliary (Compressor)	29	27	27	17	17	20	16	11	6	10	15	16	26	5	3	9	5	2	2	10	6	5	4	10	3	9	7	4	12		15	10	8	2	4	5	7	8	9	19	6	8
Timing Case	30	34	35	24	25	28	21	16	9	13	20	22	35	7	4	11	9	3	2	15	8	6	8	16	5	16	10	8	17	19		15	9	3	5	7	9	11	11	24	8	10
Balancer	31	26	27	21	24	28	17	13	7	8	15	18	27	6	4	7	10	1	1	16	5	4	6	11	3	10	6	5	15	12	15		6	2	4	4	6	7	7	17	5	6
Turbocharger	32	29	28	19	18	21	17	12	7	12	19	22	30	5	3	10	5	3	2	11	7	5	4	11	3	9	8	4	11	13	15	10		7	5	6	12	10	11	22	7	9
Aircharge Cooler	33	5	5	3	3	3	3	2	1	2	4	4	5	1		2	1	1	1	2	1	1	1	2		1	1	1	2	2	2	2	6		2	1	2	2	2	4	1	2
Air Intake	34	12	15	10	10	11	9	6	3	6	9	11	15	3	1	5	3	1	3	6	3	2	2	5	1	5	4	2	6	6	7	5	5	3		3	4	5	5	10	3	4
Air Filter	35	1	1	1	1	1	1	1		1	1	1	2							1				1					1	1	1	1								1		
Exhaust Manifold	36	21	27	18	18	20	16	12	6	10	16	19	27	5	3	9	5	2	2	10	6	4	5	10	3	9	6	4	11	12	14	10	9	3	4	5		9	9	18	5	7
Low Pressure Fuel System	37	38	38	24	23	26	23	16	9	16	23	25	38	7	4	14	6	4	2	14	9	7	5	14	3	12	10	5	14	16	19	13	12	4	7	8	11		14	28	9	11
Fuel Filter	38	32	34	20	21	23	20	13	8	13	16	25	32	6	3	11	6	3	2	12	12	6	5	13	3	10	8	5	13	14	17	11	10	3	5	6	9	10		22	8	10
Starting Aid	39	21	24	16	15	17	14	10	5	9	14	17	24	4	2	8	4	2	1	9	5	4	4	9	2	7	6	3	9	10	12	8	7	2	4	5	6	8	8		5	6
Lifting Eyes	40	15	16	10	9	11	9	6	3	6	9	11	16	3	1	5	2	3	1	5	4	3	2	6	1	5	4	2	6	7	8	5	5	2	2	3	4	5	5	11		4
Wiring Harness	41	65	67	46	44	49	42	32	17	32	50	55	67	14	8	31	14	4	5	28	18	15	12	27	8	23	27	11	30	33	36	26	32	10	14	19	24	27	26	55	15	

Figure 62: Combined risk DSM for the diesel engine model reported by Jarratt (2004) (original CPM) (in %)

The higher risk values calculated with the FBS Linkage model can be explained by both the worst case scenario chosen for the FBS Linkage model and the increase of number of indirect links in the multi-layered FBS Linkage model compared to the single-layered CPM model. The individual differences between the values of FBS Linkage model and the original CPM model are represented in Figure 63. The differences have a distribution of {min; 0.25-quantile; median; 0.75-quantile; max} = {-43%-points; 0%-points; 7%-points; 22%-points; 88%-points}. The overall average of the absolute differences is 17.0%-points. The colour scale in Figure 63 indicates that this absolute deviation can be traced back to a few components for the most part. Notably, the risk values (of both imposed and received changes) for the components *C1* to *C8*, *C22*, and *C28* to *C31* are higher in the FBS Linkage model than in the CPM model. These differences can be traced back to the additional insights gained from explicitly considering the behavioural and functional layers; these components are more interconnected to each other and to other components due to behavioural and functional relations which are underestimated in CPM. This influence of additional information layers on the resulting risk matrix will be discussed in Subsection 7.4.3. The risk values of the FBS Linkage model are lower than the values of the CPM model only for a few connections. For many other connections the differences are minor.

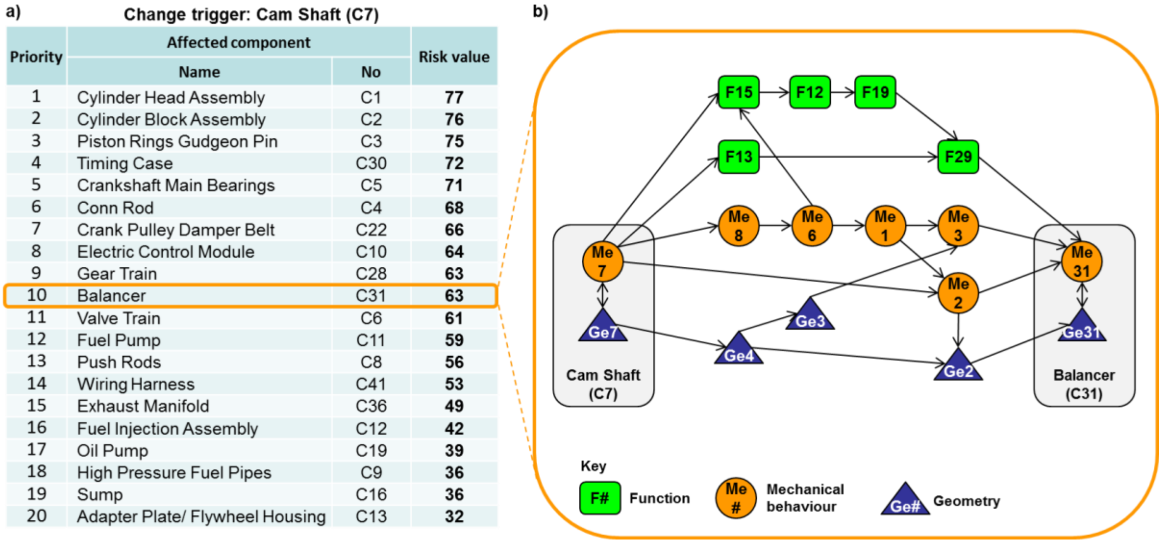


Component	No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Cylinder Head Assembly	1		41	61	58	56	42	50	71	-8	38	14	10	21	28	17	30	9	22	35	28	15	72	17	13	18	17	36	54	16	59	36	19	6	12	5	15	-3	-2	7	4	42
Cylinder Block Assembly	2	40		58	56	50	51	51	73	-12	38	4	11	23	29	18	32	10	24	38	29	17	75	20	17	23	17	40	53	20	62	29	18	7	14	4	12	-4	-6	3	1	44
Piston Rings Gudgeon Pin	3	63	60		70	67	57	56	74	-7	42	22	22	22	28	16	34	12	22	42	32	17	73	21	11	21	13	35	60	17	64	40	22	7	16	4	18	-2	1	7	6	41
Conn Rod	4	75	74	78		75	61	52	74	-2	42	27	35	21	25	16	34	12	21	42	33	17	66	23	8	20	10	30	58	17	65	37	24	7	16	4	18	2	6	10	10	37
Crankshaft Main Bearings	5	72	72	79	75		62	57	75	-1	45	27	35	20	18	19	34	12	21	41	33	16	67	23	10	21	14	33	56	19	65	38	25	8	17	6	19	2	5	14	9	41
Valve Train	6	63	62	74	72	70		46	58	-3	36	11	-1	11	20	15	15	-1	11	26	14	7	61	11	15	15	21	29	49	19	53	30	7	4	4	7	3	2	-5	6	-2	39
Cam Shaft	7	74	75	81	75	77	59		66	5	51	19	22	17	24	27	20	2	16	34	21	13	70	18	18	21	29	37	50	28	63	32	16	7	10	13	10	10	1	24	4	51
Push Rods	8	76	76	81	80	78	47	45		2	39	17	16	10	16	16	16	1	11	24	16	7	57	11	13	14	20	27	49	20	51	28	9	4	5	9	5	6		12	3	42
High Pressure Fuel Pipes	9	42	38	60	56	53	14	12	37		-6	-9	-18	-2	4	-12	5	-4	4	1	2	-2	29	-5		-4	-9	5	17	-11	12	5	-10	-3	-3	-9	-6	-8	-9	-23	-8	1
Electric Control Module	10	30	28	47	42	39	25	30	45	-19		-19	-28	9	18	2	-3	-6	7	8	-6	-1	57	-4	12	3	13	25	36	4	34	13	-8	2	2		-10	-14	-22	-16	-12	28
Fuel Pump	11	37	32	56	54	49	32	29	57	-18	20		-12	4	15	4	14	-3	11	15	10	-1	56	-2	5	1	6	23	21	-2	35	13	-2		1	-1	-3	-10	-14	-13	-7	25
Fuel Injection Assembly	12	57	53	69	66	64	21	25	47	-11	11	2		2	9	-2	10	-2	4	10	7	-1	37		2			9	26	-3	24	14	-3	-1	-1	-2	-3	-8	-8	-14	-4	14
Adapter Plate / Flywheel Housing	13	77	76	82	79	77	37	24	49	-3	20	3	9		11	3	12	2	6	17	14	3	37	6	3	4	4	10	25	4	32	12	6	1	3	1	4	-1	-1	-1	1	18
Flywheel Ring Gear	14	81	79	80	69	33	31	25	34	1	18	12	14	7		7	10	2	4	14	10	3	23	6	3	4	5	7	20	6	26	16	5	1	2	1	3	1	1	4	2	15
Starter Motor	15	69	70	77	77	73	38	19	58	-8	15	-5	8	6	14		19	2	8	21	16	3	39	5	2	2	1	11	26		32	10	7		4	-1	5	-5	-4	-6	1	15
Sump	16	72	72	78	76	72	38	23	57	-5	15	3	11		13	2		4	9	19	19	4	36	7	2	2		10	28		31	11	9	1	5	-1	6	-3	-1	-5	3	14
Oil Filler	17	21	21	25	19	20	2	2	4	-2		-2	-3			-1	4		1	1			4	-1			-1	1	3	-1	-1	2	-1	-1		-1	-1	-1	-2	-4	-1	
Engine Breather	18	65	63	76	71	70	23	18	42	-7	6	1	-1	1	6	-2	8			7	7	-1	27	1	1	-1	-2	6	22	-2	18	11			-1	-2		-5	-5	-11	-1	7
Oil Pump	19	80	81	82	75	65	39	33	45	-1	23	12	12	5	9	5	12	2	7		10	5	31	7	5	5	7	11	32	8	29	17	6	1	3	2	3				1	21
Oil Filter	20	75	72	81	76	74	26	17	37	-2	8	5	9	3	8	-1	11	1	4	9		2	20	5	1	3		5	19	1	19	12	4		2	-1	2	-1		-3	2	7
Oil Cooler	21	55	55	67	61	60	13	10	29	-6		-1	-7	-1	3	-4	4	-1	3	3	4		16	-2		-3	-2	3	12	-4	9	5	-2	-1	-1	-2	-2	-5	-4	-12	-2	3
Crank Pulley Damper Belt	22	86	86	88	84	68	64	60	65	10	57	29	28	18	20	27	18	3	15	32	20	10		17	15	22	27	21	61	28	58	38	16	7	10	14	10	13	5	28	5	54
Fan Drive	23	37	37	40	33	33	27	27	25	1	25	5	1	2	5	8	1		4	8	2	4	18		2	6	10	11	28	10	25	11	2	2	1	5		4	-1	5	-1	22
Fan Extension	24	21	22	21	18	19	20	20	18	2	20	4	3	3	3	5	1		2	6	2	3	18	2		6	7	9	22	6	17	7	2	2	1	3	1	3	1	4		17
Coolant Pump	25	44	46	56	47	48	17	19	20	-2	16	1	-4		3	2	1		3	3	3	3	22	-1	3		6	8	19	4	12	6	-1	1	-1	1	-1	-1	-3	-3	-1	16
Alternator Bracket	26	20	22	21	18	19	19	20	17		19	2		2	3	4			2	5	1	2	19	4	4	6		9	21	7	15	6	1	1		2	-1	1	-1	3	-1	16
Belt Driven Auxiliary (Hydraulic Pump	27	32	37	46	38	39	18	21	22	-4	17	-1	-9		3	3		-1	3		1	2	17		5	1	6		24	5	16	7	-2		-1	1	-3	-1	-4	-4	-3	17
Gear Train	28	62	61	73	69	58	49	47	60	-1	41	12	6	10	15	18	14		13	25	16	9	63	11	17	13	23	32		15	49	23	8	5	6	8	4	3	-4	9	-1	44
Gear Driven Auxiliary (Compressor)	29	55	46	67	59	57	19	17	29	-6	12	3	-5		5		4	-1	4	5	3	-1	26		2		3	10	17		14	8	-3		-1		-2	-3	-3	-9	-3	15
Timing Case	30	65	63	75	73	70	58	56	69	2	50	18	15	18	25	25	20	2	18	33	22	14	65	13	14	14	23	30	57	10		31	16	7	11	11	9	8		18	2	52
Balancer	31	74	73	78	74	70	56	50	70		39	21	26	15	21	18	25	8	17	32	29	12	59	18	8	15	13	27	47	16	55		20	5	12	6	13	3	3	10	7	37
Turbocharger	32	31	34	42	36	35	5	4	12	-10	-8	-12	-19	-2	1	-6		-2		-3	-1	-3	11	-6	-1	-6	-5	1	5	-8	1			1	6	-1	-2	-5	-9	-18	-5	
Aircharge Cooler	33	11	13	13	10	13	5	6	6	-1	4	-1	-1		1	1		-1	1				8		2	1	2	3	6	2	7	2	2		4	1	3		-1		-1	4
Air Intake	34	43	55	61	54	55	8	8	22	-5		-1	-4		3	-2	2			1	2	-1	10			-2	-2	1	8	-2	6	5	6	3		3	2	-3	-3	-6	-2	2
Air Filter	35	18	24	25	21	22	4	3	6		2	2	1	1	1	1	1		1	1	1		4			1	1	1	3		3	2	5	3	6		2	1		1		3
Exhaust Manifold	36	77	71	81	79	78	26	37	62	-6	21	12	10	8	15	4	22	3	9	25	20	4	44	10	3	5	3	14	39	3	41	26	14	4	10			-3	-1	-2	2	21
Low Pressure Fuel System	37	15	7	31	23	22	-6	-3	7	-13	-10	-14	-28	-5	-1	-10	-2	-4		-8	-4	-5	9	-10	-1	-9	-7	-1		-11	-5	-5	-7	-2	-4	-6	-5		-9	-24	-7	-1
Fuel Filter	38	6	3	21	15	13	-3	1	7	-8	-3	-13	-23	-3		-7	-3	-3		-7	-4	-3	10	-8	-1	-6	-4	-1	1	-9	-2	-5	-8	-2	-3	-4	-6	-4		-17	-7	
Starting Aid	39	27	37	45	38	39	1	3	15	-4	-6	-5	-10	-1	1	-6		-2	1	-3	-1	-1	7	-4	-1	-3	-4	1	4	-5		1	-5	-1	-3	-4	-3	-5	-5		-4	-1
Lifting Eyes	40		7	14	11	10	-5	-3	3	-6	-7	-8	-13	-2		-4		-1		-3	-3	-3	1	-5	-1	-4	-4	-1	-3	-6	-5	-3	-4	-2	-2	-3	-3	-4	-4	-10		-3
Wiring Harness	41	6	6	23	18	18	11	21	33	-21	-2	-31	-43	-1	8	-10	-9	-4	3	-4	-11	-6	49	-9	8	-2	-3	20	25	-2	27	3	-22	-4	-9	-5	-18	-13	-22	-26	-13	

Figure 63: Difference DSM for combined risk values of FBS Linkage minus original CPM (in %-points)

The combined risk DSM of the FBS Linkage method can be used as a starting point of the change propagation investigation. For every component, a prioritised list of all affected components can be prepared based on this DSM. Every line in that list can then be further detailed and the risk numbers can be traced back to causal propagation paths on the attribute level using the FBS Linkage MDM and network.

For instance, Figure 64a shows such a prioritised change risk list for *Cam Shaft (C7)*. From the list, it can be seen that *Cylinder Head (C1)* and *Block Assembly (C2)* and *Piston-Rings-Gudgeon-Pin (C3)* are at highest risk if the *Cam Shaft* changes. Usually the components at high risk are closely interconnected to the change trigger and the impact on them is preeminent to designers. However, the links to the components in the middle range of the risk values are not always obvious because these components are usually only indirectly connected. Such a prioritised list can help avoid oversight of change impacts on those components. Figure 64b details the links between *Cam Shaft* (C7) and *Balancer (C31)*. This propagation path analysis provides a rationale for the risk value and explains how the change trigger affects the target.



a) Change trigger: Cam Shaft (C7)

Priority	Affected component		Risk value
	Name	No	
1	Cylinder Head Assembly	C1	**77**
2	Cylinder Block Assembly	C2	**76**
3	Piston Rings Gudgeon Pin	C3	**75**
4	Timing Case	C30	**72**
5	Crankshaft Main Bearings	C5	**71**
6	Conn Rod	C4	**68**
7	Crank Pulley Damper Belt	C22	**66**
8	Electric Control Module	C10	**64**
9	Gear Train	C28	**63**
10	Balancer	C31	**63**
11	Valve Train	C6	**61**
12	Fuel Pump	C11	**59**
13	Push Rods	C8	**56**
14	Wiring Harness	C41	**53**
15	Exhaust Manifold	C36	**49**
16	Fuel Injection Assembly	C12	**42**
17	Oil Pump	C19	**39**
18	High Pressure Fuel Pipes	C9	**36**
19	Sump	C16	**36**
20	Adapter Plate/ Flywheel Housing	C13	**32**

Figure 64: a) Prioritised change risk list for Cam Shaft and b) selected change propagation paths from Cam Shaft to Balancer

7.3 Scanning electron microscope case study

Microscopes are used to make objects (i.e. specimens) visible that are otherwise too small for the human eye. Conventional microscopes operate optically using light to image a specimen. Thereby, the light is manipulated by one or more lenses to produce an enlarged image of the specimen. A SEM as depicted in Figure 65 uses electrons instead of light to image a specimen (Goldstein *et al.* 2003). The electron source produces an electron beam, which is focused and manipulated by magnetic lenses in the column and scans the specimen. The electrons interact with the atoms at the surface layers of the specimen and contain information about the specimen's surface topography. This information is collected by different electron and X-ray sensors and used to produce enlarged images. The whole system operates in a vacuum.

Figure 65: Exemplary scanning electron microscope (SEM)
Source: Photo is taken by courtesy of JEOL.

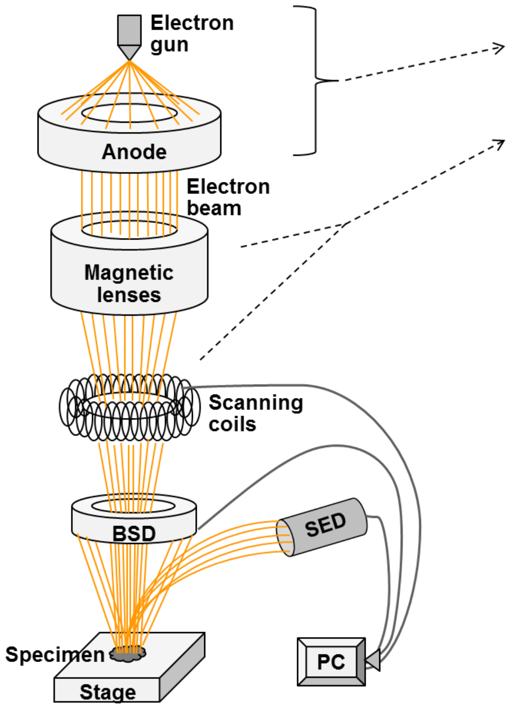
The SEM was modelled following the FBS Linkage technique described in Section 6.6, with focus on the qualitative stream, i.e. including the steps: *1. Decompose the product, 2. Develop FBS Linkage scheme,* and *6. Use the FBS Linkage scheme*. This work was conducted in collaboration with an international SEM manufacturer that wished to remain unnamed to preserve confidentiality and CAPE (Centre for Advanced Photonics and Electronics).

The product decomposition and developing of structural and behavioural layers was assisted by Daniel Aldridge and Dr John Craven, two SEM experts from the collaborating SEM manufacturer. Mr Aldridge has more than ten years of industry experience, including seven years in SEM design, and holds a B.Eng. degree in Mechanical Engineering from Canfield University. He started at the international SEM manufacturer as a Mechanical Design Engineer in 2006 and was promoted to his current role four years ago. His current responsibilities at the SEM manufacturer include project, knowledge, and process management. Dr Craven has several years of academic and industry experience in SEM design and holds a few SEM patents. He has received his M.Eng. degree in Materials Engineering from the University of Oxford in 1998 and his Ph.D. degree in Physics from the University of Cambridge in 2002. He then went to industry and joined the SEM manufacturer as a Project Manager in 2011.

The functional modelling of the SEM was assisted by Bernard C. Breton, an SEM expert from CAPE. Mr Breton has over forty years of experience in SEM design. He was a colleague of the SEM pioneer Prof Sir Charles Oatley and is a pioneer himself holding patents on methods for generating stereo images in the scanning electron microscope and being at the forefront of using web-based technologies to diagnose and control instruments.

7.3.1 Decompose the product

The SEM was decomposed first into its subsystems and then further broken down into its components; the final list included 28 components (Figure 66).



Component breakdown

- Electron source
    - Emitter
    - Anode
    - Wehnelt
- Electron optics
    - Magnetic lenses (C1, C2, C3)
    - Scan coils
    - Stigmator coils
    - Gun alignment coils
    - Apertures
- Vacuum chamber
- Control electronics
    - Scan generator
    - BSD electronics
    - EO electronics
    - VAC electronics
    - Stage electronics
    - LV PSU's
    - X-Ray pulse processor
- Anti vibration system
- Vacuum system
  (high vacuum or low pressure mode)
- X-Ray detector
- EHT power supply
- PC
- Backscattered electron detector (BSD)
- Secondary electron detector (SED)
- Stage/Specimen
- Plinth
- Cladding (plastic housing)

No	Component
1	Emitter
2	Anode
3	Wehnelt
4	Magnetic lens 1
5	Magnetic lens 2
6	Magnetic lens 3
7	Scan coils
8	Stigmator coils
9	Gun alignment coils
10	Apertures
11	Vacuum chamber
12	Scan generator
13	BSD electronics
14	EO electronics
15	VAC electronics
16	Stage electronics
17	LV PSU's
18	X-Ray pulse processor
19	Anti vibration system
20	Vacuum system
21	X-Ray detector
22	EHT power supply
23	PC
24	BSD
25	SED
26	Stage/ Specimen
27	Plinth
28	Cladding

Figure 66: Product decomposition of SEM

7.3.2 Develop FBS Linkage scheme

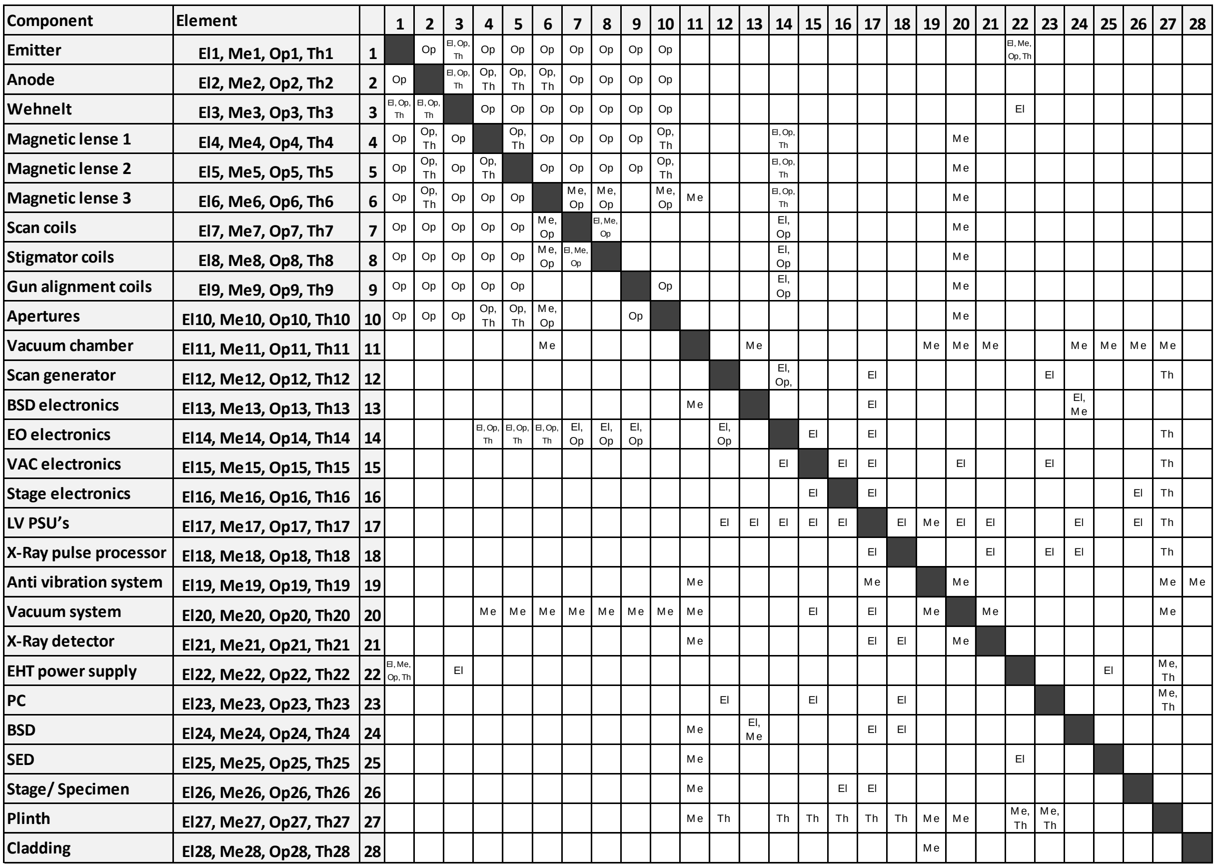
(i) Map the structural layer S: The relevant structural attributes of a SEM were determined to be *Control (Ct)*, *Geometry (Ge)*, and *Material (Ma)*, where *Control* refers to all kinds of microchips, printed circuit boards, codes etc., *Geometry* refers to all diameters, sizes, shapes etc., and *Material* to the composition of all used materials including their states of matter and conditions. For the 28 SEM components, this led to (28*3=) 84 structural elements. The links

between these elements were determined in a single DSM using the symbols *Ct*, *Ge*, and *Me* to distinguish between the linkage types (Figure 67) and transferred into a larger structure DSM afterwards.

Component	Element	No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Emitter	Ct1, Ge1, Ma1	1	■	Ge	Ct, Ge																	Ma		Ct						
Anode	Ct2, Ge2, Ma2	2	Ge	■	Ct, Ge																	Ma		Ge						
Wehnelt	Ct3, Ge3, Ma3	3	Ct, Ge	Ct, Ge	■																	Ge		Ct, Ge						
Magnetic lens 1	Ct4, Ge4, Ma4	4				■	Ge, Ma				Ge	Ge				Ct						Ge, Ma								
Magnetic lens 2	Ct5, Ge5, Ma5	5				Ge, Ma	■				Ge	Ge				Ct						Ge, Ma								
Magnetic lens 3	Ct6, Ge6, Ma6	6						■	Ge	Ge		Ge	Ge, Ma			Ct						Ge, Ma						Ge		
Scan coils	Ct7, Ge7, Ma7	7						Ge	■	Ct, Ge		Ge				Ct						Ge, Ma								
Stigmator coils	Ct8, Ge8, Ma8	8						Ge	Ct, Ge	■		Ge				Ct						Ge, Ma								
Gun alignment coils	Ct9, Ge9, Ma9	9				Ge	Ge				■					Ct						Ge, Ma								
Apertures	Ct10, Ge10, Ma10	10				Ge	Ge	Ge	Ge	Ge		■										Ge, Ma								
Vacuum chamber	Ct11, Ge11, Ma11	11						Ge, Ma					■		Ge						Ge	Ge	Ge, Ma			Ge, Ma	Ge, Ma	Ge	Ge	Ge
Scan generator	Ct12, Ge12, Ma12	12												■		Ct			Ct						Ct				Ge	
BSD electronics	Ct13, Ge13, Ma13	13											Ge		■				Ct							Ct, Ge				
EO electronics	Ct14, Ge14, Ma14	14				Ct	Ct	Ct	Ct	Ct	Ct			Ct		■	Ct		Ct										Ge	
VAC electronics	Ct15, Ge15, Ma15	15														Ct	■	Ct	Ct			Ct			Ct				Ge	
Stage electronics	Ct16, Ge16, Ma16	16															Ct	■	Ct									Ct	Ge	
LV PSU's	Ct17, Ge17, Ma17	17												Ct	Ct	Ct	Ct	Ct	■	Ct		Ct	Ct			Ct		Ct	Ge	
X-Ray pulse processor	Ct18, Ge18, Ma18	18																	Ct	■			Ct		Ct	Ct			Ge	
Anti vibration system	Ct19, Ge19, Ma19	19											Ge								■	Ge							Ge	Ge
Vacuum system	Ct20, Ge20, Ma20	20	Ma	Ma	Ge	Ge, Ma	Ge, Ma	Ge, Ma	Ge, Ma	Ge, Ma	Ge, Ma	Ge, Ma	Ge				Ct		Ct		Ge	■	Ge, Ma						Ge	
X-Ray detector	Ct21, Ge21, Ma21	21											Ge, Ma						Ct	Ct		Ge, Ma	■					Ge		Ge
EHT power supply	Ct22, Ge22, Ma22	22	Ct	Ge	Ct, Ge																			■			Ct		Ge	
PC	Ct23, Ge23, Ma23	23												Ct			Ct			Ct					■				Ge	
BSD	Ct24, Ge24, Ma24	24											Ge, Ma		Ct, Ge				Ct	Ct						■	Ge	Ge		Ge
SED	Ct25, Ge25, Ma25	25											Ge, Ma											Ct		Ge	■	Ge		Ge
Stage/ Specimen	Ct26, Ge26, Ma26	26						Ge					Ge					Ct	Ct				Ge			Ge	Ge	■		Ge
Plinth	Ct27, Ge27, Ma27	27											Ge	Ge		Ge	Ge	Ge	Ge	Ge	Ge	Ge		Ge	Ge				■	Ge
Cladding	Ct28, Ge28, Ma28	28											Ge								Ge		Ge			Ge	Ge	Ge	Ge	■

Figure 67: Structural elements and links of SEM

(ii) Map the behavioural layer B: The relevant behavioural attributes were determined to be *Electrical (El), Mechanical (Me), Electron-optical (Op),* and *Thermal (Th),* where *Electrical* refers to all behaviours to do with current, voltage, etc., *Mechanical* to all behaviours to do with weight, moments of inertia etc., *Electron-optical* to all behaviours to do with the electron beam, and *Thermal* to all temperature and heat related behaviours. This led to (28*4=) 112 behavioural elements. Similarly to the structural links, the links between the behavioural elements were identified in a single DSM using the symbols *El*, *Ma*, *Op,* and *Th* (Figure 68) and transferred into a larger behaviour DSM afterwards.



Component	Element		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Emitter	El1, Me1, Op1, Th1	1	■	Op	El, Op, Th	Op	Op	Op	Op	Op	Op	Op												El, Me, Op, Th						
Anode	El2, Me2, Op2, Th2	2	Op	■	El, Op, Th	Op, Th	Op, Th	Op, Th	Op	Op	Op	Op																		
Wehnelt	El3, Me3, Op3, Th3	3	El, Op, Th	El, Op, Th	■	Op	Op	Op	Op	Op	Op	Op												El						
Magnetic lense 1	El4, Me4, Op4, Th4	4	Op	Op, Th	Op	■	Op, Th	Op	Op	Op	Op	Op, Th				El, Op, Th						Me								
Magnetic lense 2	El5, Me5, Op5, Th5	5	Op	Op, Th	Op	Op, Th	■	Op	Op	Op	Op	Op, Th				El, Op, Th						Me								
Magnetic lense 3	El6, Me6, Op6, Th6	6	Op	Op, Th	Op	Op	Op	■	Me, Op	Me, Op		Me, Op	Me			El, Op, Th						Me								
Scan coils	El7, Me7, Op7, Th7	7	Op	Op	Op	Op	Op	Me, Op	■	El, Me, Op						El, Op						Me								
Stigmator coils	El8, Me8, Op8, Th8	8	Op	Op	Op	Op	Op	Me, Op	El, Me, Op	■						El, Op						Me								
Gun alignment coils	El9, Me9, Op9, Th9	9	Op	Op	Op	Op	Op				■	Op				El, Op						Me								
Apertures	El10, Me10, Op10, Th10	10	Op	Op	Op	Op, Th	Op, Th	Me, Op			Op	■										Me								
Vacuum chamber	El11, Me11, Op11, Th11	11						Me					■		Me						Me	Me	Me			Me	Me	Me	Me	
Scan generator	El12, Me12, Op12, Th12	12												■		El, Op,			El						El				Th	
BSD electronics	El13, Me13, Op13, Th13	13											Me		■				El							El, Me				
EO electronics	El14, Me14, Op14, Th14	14				El, Op, Th	El, Op, Th	El, Op, Th	El, Op	El, Op	El, Op			El, Op		■	El		El										Th	
VAC electronics	El15, Me15, Op15, Th15	15														El	■	El	El			El			El				Th	
Stage electronics	El16, Me16, Op16, Th16	16															El	■	El									El	Th	
LV PSU's	El17, Me17, Op17, Th17	17												El	El	El	El	El	■	El	Me	El	El			El		El	Th	
X-Ray pulse processor	El18, Me18, Op18, Th18	18																	El	■			El		El	El			Th	
Anti vibration system	El19, Me19, Op19, Th19	19											Me						Me		■	Me							Me	Me
Vacuum system	El20, Me20, Op20, Th20	20				Me	Me	Me	Me	Me	Me	Me	Me				El		El		Me	■	Me						Me	
X-Ray detector	El21, Me21, Op21, Th21	21											Me						El	El		Me	■							
EHT power supply	El22, Me22, Op22, Th22	22	El, Me, Op, Th		El																			■			El		Me, Th	
PC	El23, Me23, Op23, Th23	23												El			El			El					■				Me, Th	
BSD	El24, Me24, Op24, Th24	24											Me		El, Me				El	El						■				
SED	El25, Me25, Op25, Th25	25											Me											El			■			
Stage/ Specimen	El26, Me26, Op26, Th26	26											Me					El	El									■		
Plinth	El27, Me27, Op27, Th27	27											Me	Th		Th	Th	Th	Th	Th	Me	Me		Me, Th	Me, Th				■	
Cladding	El28, Me28, Op28, Th28	28																			Me									■

Figure 68: Behavioural elements and links of SEM

(iii) Map the structure-behaviour (S-B) links: The links between structure and behaviour were defined on the attribute level for all associated elements and transferred into the corresponding domain mapping matrices (DMMs) (Figure 69).

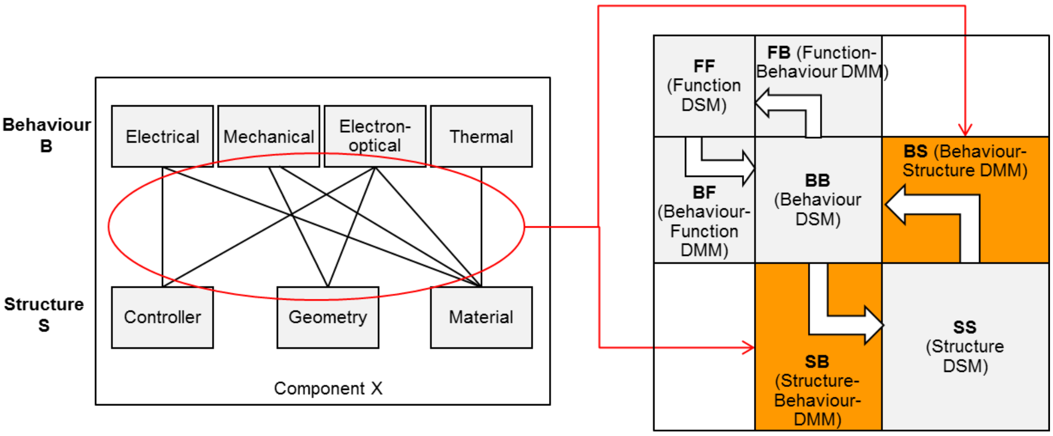


Figure 69: Structure-behaviour links of SEM

(iv) Map the functional layer F: The functional model of the SEM was developed in three successive steps, starting with a black box model first, detailing it into a high level model second, and into the functional block diagram depicted in Figure 70 third. This led to a network of 22 subfunctions (i.e. functional elements) interlinked to each other by flows of energy, material, and signal. These links were finally transferred into an undirected DSM (Figure 71).

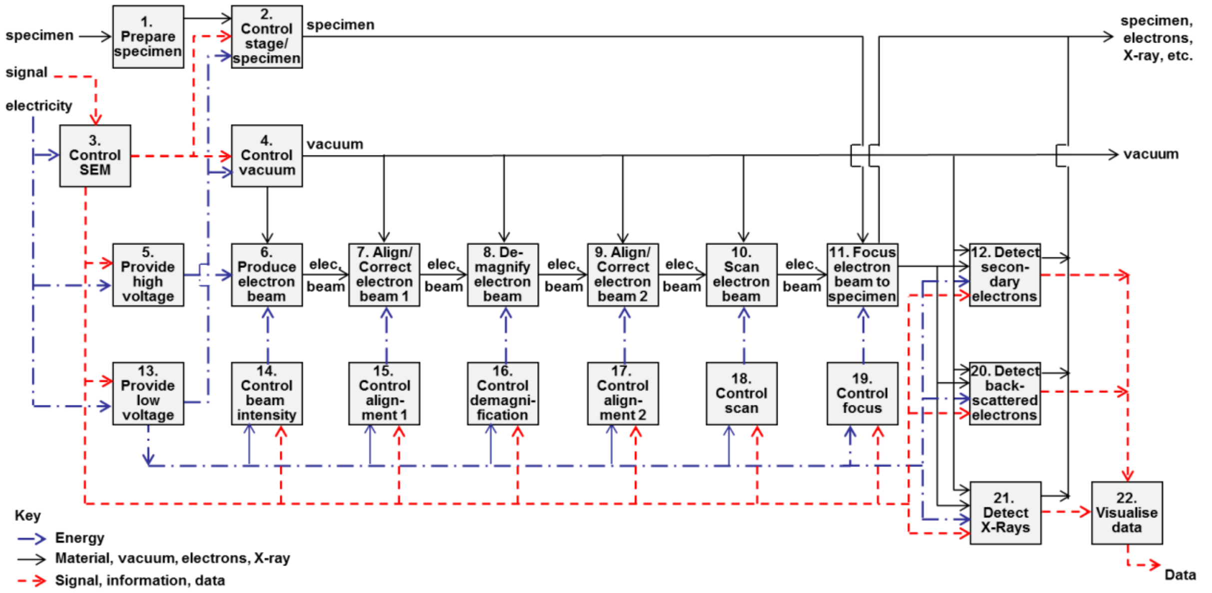


Figure 70: Functional model of SEM

Function	Element		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Prepare specimen	F1	1	■	m																				
Control stage/specimen	F2	2	m	■	s								m		e									
Control SEM	F3	3		s	■	s	s							s	s	s	s	s	s	s	s	s	s	
Control vacuum	F4	4			s	■		m	m	m	m	m	m	m	e							m	m	
Provide high voltage	F5	5			s		■	e																
Produce electron beam	F6	6				m	e	■	m							e								
Align/Correct electron beam 1	F7	7				m		m	■	m							e							
Demagnify electron beam	F8	8				m			m	■	m							e						
Align/Correct electron beam 2	F9	9				m				m	■	m							e					
Scan electron beam	F10	10				m					m	■	m							e				
Focus electron beam to specimen	F11	11		m		m						m	■	m							e	m	m	
Detect secondary electrons	F12	12			s	m							m	■	e									s
Provide low voltage	F13	13		e	s	e								e	■	e	e	e	e	e	e	e	e	
Control beam intensity	F14	14			s			e							e	■								
Control alignment 1	F15	15			s				e						e		■							
Control demagnification	F16	16			s					e					e			■						
Control alignment 2	F17	17			s						e				e				■					
Control scan	F18	18			s							e			e					■				
Control focus	F19	19			s								e		e						■			
Detect backscattered electrons	F20	20			s	m							m		e							■		s
Detect X-rays	F21	21			s	m							m		e								■	s
Visualise data	F22	22												s								s	s	■

Key: e - energy; m -material; s -signal

Figure 71: Functional links DSM of SEM

(v) Map the function-behaviour (F-B) links: First, components were assigned to the subfunctions defined above. Then, these function-component links were specified into function-behaviour links as depicted in Table 15 and transferred into the corresponding DMMs to complete the FBS Linkage scheme, represented as MDM in Figure 72 and as network in Figure 73a.

Table 15: Function-behaviour links for SEM

No	Function	Assigned components	Component 1 and its behaviours					Component 2 and its behaviours					Component 3 and its behaviours				
1	Prepare specimen	26	Stage/ Specimen		Me												
2	Control stage/specimen	16	Stage electronics	El													
3	Control SEM	23	PC	El													
4	Control vacuum	11, 15, 20	Vacuum chamber		Me			VAC electronics	El				Vacuum system		Me		
5	Provide high voltage	22	EHT power supply	El													
6	Produce electron beam	1, 2, 3	Emitter	El		Op	Th	Anode	El				Wehnelt	El		Op	Th
7	Align/Correct electron beam 1	9, 10	Gun alignment coils	El		Op		Apertures	El			Th					
8	Demagnify electron beam	4, 5	Magnetic lens 1	El		Op	Th	Magnetic lens 2	El		Op	Th					
9	Align/Correct electron beam 2	10	Apertures		Me	Op											
10	Scan electron beam	7, 8	Scan coils	El		Op	Th	Stigmator coils	El		Op	Th					
11	Focus electron beam to specimen	6	Magnetic lens 3	El		Op	Th										
12	Detect secondary electrons	25	SED	El		Op											
13	Provide low voltage	17	LV PSU’s	El													
14	Control beam intensity	14	EO electronics	El													
15	Control alignment 1	14	EO electronics	El													
16	Control demagnification	14	EO electronics	El													
17	Control alignment 2	14	EO electronics	El													
18	Control scan	12	Scan generator	El													
19	Control focus	14	EO electronics	El													
20	Detect backscattered electrons	13, 24	BSD electronics	El				BSD	El		Op						
21	Detect X-rays	18, 21	X-Ray pulse processor	El				X-Ray detector	El		Op						
22	Visualise data	23	PC	El													

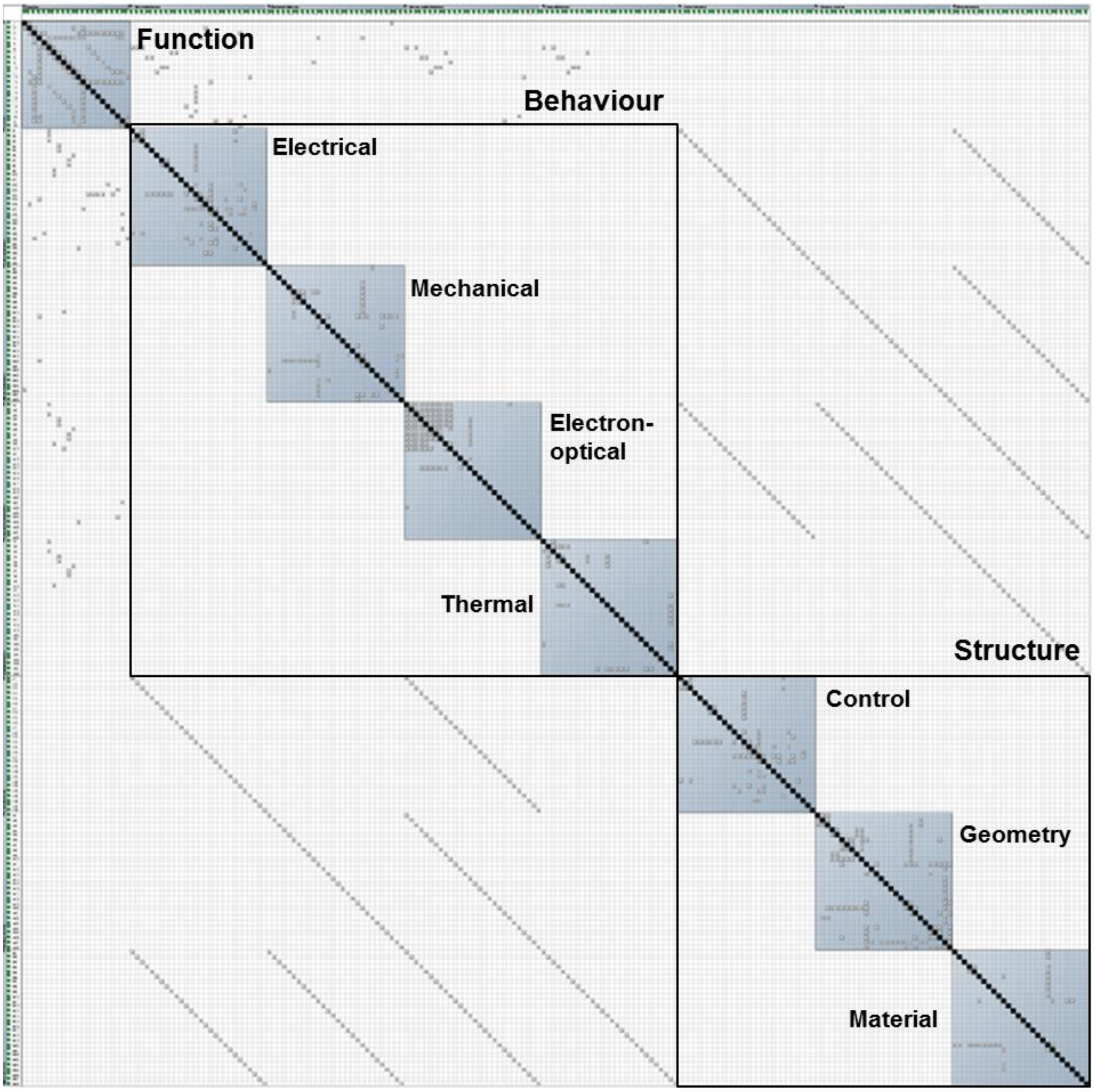


Figure 72: FBS Linkage MDM for SEM

7.3.3 Use the FBS Linkage scheme

For qualitative use of the FBS Linkage scheme, an interactive network was generated from the FBS Linkage MDM using yEd Graphic Editor (Figure 73). This freely available diagrams software was used in addition to the CAM software, because it supports easy generation and manipulation of large networks. Figure 73a shows the complete network for the SEM organised in subnetworks for the different layers and attributes. From the function sub-network it can be seen that the SEM functions are very interdependent and each function may potentially impact all other functions through multiple steps of propagation. The number of links from the *Electrical* and *Electron-optical* elements to the functions and from the *Material* elements to the behaviours underlines the importance of these attributes for the SEM. However, this qualitative network provides rather a solution space by drawing all possible links than a specific design status, where certain elements and links may be frozen and irrelevant for change propagation. This network can be used to obtain a comprehensive view of how the SEM operates.

Figure 73b depicts a partial change propagation tree for the element *Th7*. Such trees can be generated for the change trigger to analyse its direct and indirect impacts on other elements. For a specified change, the designer may have a better understanding which elements are actually impacted and reduce the tree.

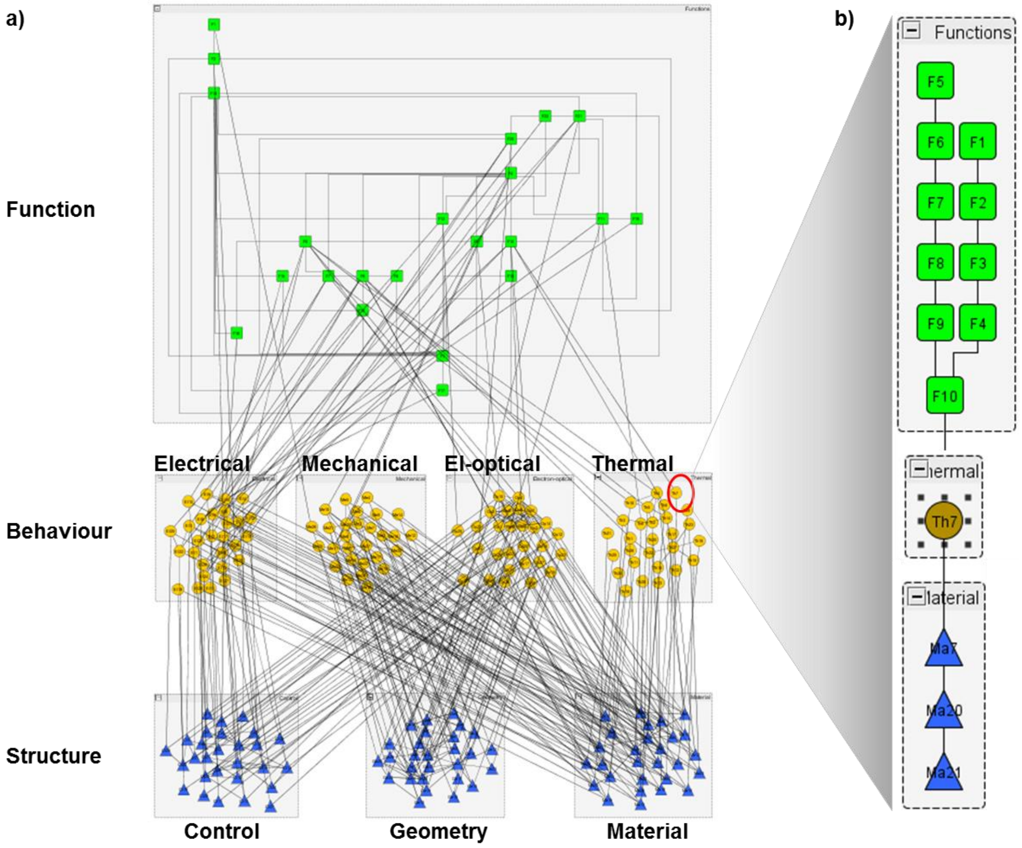


Figure 73: a) FBS Linkage network for SEM, b) partial change propagation tree for Th7

Source: Own depiction using yEd Graphic Editor.

This is the first attempt to model the complete SEM as a network. A CPM model for the SEM does not exist nor has the author found any other similar model of the SEM. This model provides a broad overview of how the SEM operates. The collaborating SEM manufacturer found that apart from change management, this model can be used for knowledge management and training purposes. Through this modelling exercise it was learned that it is possible to develop a FBS Linkage model for a product which primarily operates electron-optically and includes many control elements. However, even though such a linkage model may be useful for a SEM manufacturer, developing it for SEMs poses specific challenges which will be detailed as part of the method evaluation in the next section.

7.4 Method evaluation

In DRM, Blessing and Chakrabarti (2009) differentiate between three kinds of evaluation:

1. *Support evaluation* involves the continuous checking of the method's internal consistency and completeness throughout its development.
2. *Application evaluation* is about the assessment of the usability (or feasibility and practicality) of the proposed method and investigates whether the method can be used in the situation for which it was intended.
3. *Success evaluation* is about the assessment of the usefulness of the proposed method and identifies whether the support contributes to an improvement of the success factor.

Support evaluation is proposed for all four DRM stages and corresponds to *verification*, which is a continuous internal process (IEEE 2012). Application and Success evaluation are suggested for the final stage in the DRM cycle, *Descriptive Study II*, and correspond to *validation*, which involves external acceptance and suitability of the proposed support (IEEE 2012).

In the following three subsections, the results of these evaluations will be presented for the FBS Linkage method. In addition, in Subsection 7.4.4, an evaluation of the method against the requirements for ECM methods developed in Chapter 4 will be presented. Those requirements refer to all three types of evaluations suggested in DRM.

7.4.1 Support evaluation

The internal consistency and completeness of the FBS Linkage method has been continuously checked and improved throughout its development. The Gantt diagram in Figure 74 depicts the review process throughout the project time and DRM phases. The FBS Linkage method was monthly reviewed with the thesis supervisor and co-supervisors as well as occasionally presented to experts from both academia and industry. Their feedback was used to improve and extended the method. Smaller models were first built and tested for a hairdryer (Hamraz *et al.* 2012a) and a simplified diesel engine (Hamraz *et al.* 2012c). An early version of the FBS Linkage ontology was thoroughly discussed with Professor David C. Brown, the Editor in Chief of the AI EDAM journal from 2001 to 2011 and a leading researcher in the field of artificial intelligence (see e.g. Brown and Birmingham 1997, Dym and Brown 2012). Professor Brown found the FBS Linkage ontology plausible and gave valuable feedback. His suggestions helped improve an earlier version of the ontology to obtain the version presented in this thesis. Furthermore, valuable suggestions of a number of anonymous reviewers from different engineering journals as detailed in Figure 74 contributed to the support evaluation.

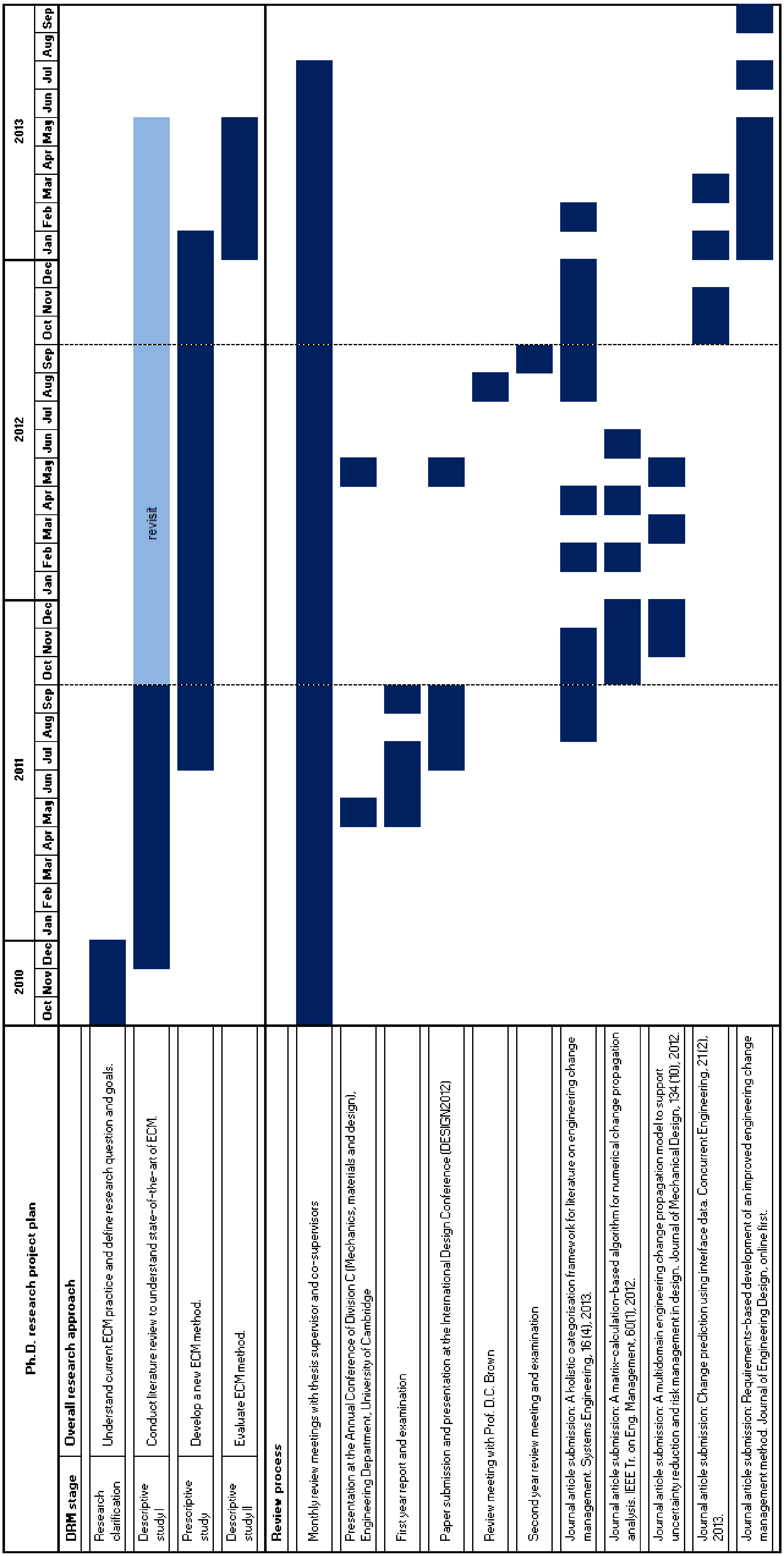


Figure 74: Continuous review process

7.4.2 Application evaluation

The FBS Linkage method is intended to be used on complex products and by any designer working on ECs. The model building should not require FBS modelling experience but merely knowledge about the product design and working mechanisms and the method description provided in the previous chapters. The model use should require only the provided method description.

To evaluate whether the method description is consistent and sufficient for the method to be used by any designer, a fourth year engineering master's student was given the description above and assigned with the implementation of the FBS Linkage method into the CAM software. The student succeeded in implementing the method as a module in CAM. This independent achievement by a separate person indicates that the method can be used by other designers based on the provided description.

For the evaluation of the method's feasibility to complex products, two very different case examples were chosen – a diesel engine design, dominated by mechanical behaviours, and a SEM design, dominated by electron-optical behaviours. As the previous two sections demonstrated, the method was feasible for both designs.

Table 16 lists the effort of model building for the hairdryer, diesel engine, and SEM over the four modelling stages. The total effort was less than one person-day for the hairdryer and between six and seven person-days for the diesel engine and SEM. Considering the re-use and modification potential of the model, this effort is relatively low and justifiable. In summary, the application evaluation can be rated as positive.

Table 16: Effort of FBS Linkage model building for the hairdryer, diesel engine, and SEM

No	Task	No of people involved			Time in hours			Effort in person-hours (= No of people x Time in hours)		
		Hair-dryer	Diesel engine	SEM	Hair-dryer	Diesel engine	SEM	Hair-dryer	Diesel engine	SEM
1	Decompose the product	1	2	3	0.5	2.0	2.0	0.5	4.0	6.0
2i	Map the structural layer S	1	2	3	0.5	5.0	3.0	0.5	10.0	9.0
2ii	Map the behavioural layer B	1	2	3	0.5	3.0	2.0	0.5	6.0	6.0
2iii	Map the structure-behaviour (S-B) links	1	1	1	0.5	3.0	2.0	0.5	3.0	2.0
2iv	Map the functional layer F	1	2	3	2.0	7.0	4.0	2.0	14.0	12.0
2v	Map the function-behaviour (F-B) links	1	2	2	0.5	3.0	3.0	0.5	6.0	6.0
3	Quantify FBS links	1	2	3	1.0	5.0	3.0	1.0	10.0	9.0
4	Compute combined change risk	1	1	1	0.5	2.0	2.0	0.5	2.0	2.0
	Total							**6.0**	**55.0**	**52.0**

7.4.3 Success evaluation

The proposed method can be used to predict changes and support their management. Ideally, the usefulness of such a predictive tool is evaluated in practice based on present data. This could be done, for instance, by applying the FBS Linkage model to present change cases and contrasting the outcome against the situation without the model. However, such a live evaluation would require a pilot-implementation which poses a risk to companies, and therefore, is often not realisable in practice. Researchers get round this problem by using test groups (see e.g. Clarkson and Hamilton 2000, Wyatt *et al.* 2012).

Alternatively, the performance of prediction tools can be evaluated based on historic data. For the model here, this would require historic change cases and a contrasting of predicted change paths to actual change paths. This too is difficult in practice because the reconstruction of historic change paths depends on the available change records. To be able to do so, the change request record has to differentiate between initiated and emergent changes and include information about change initiators and followers (see e.g. Giffin *et al.* 2009). Due to this challenge, developers of EC prediction tools test their tools against hypothetical change scenarios; often using toy examples and case-by-case tests (see e.g. Cohen *et al.* 2000, Ollinger and Stahovich 2004, Keller 2007).

To evaluate the performance of the FBS Linkage method, the following assessments were undertaken: (1) case-by-case tests of exemplar changes, (2) change prediction capability analysis, (3) verbal feedback evaluation, and (4) assessment against the set of requirements. The latter will be presented in Subsection 7.4.4 because it addresses all three types of evaluations in DRM.

(1) Case-by-case tests were performed based on exemplar samples of change cases separately for both the diesel engine and the SEM model by the author as well as the experts who supported model building. The change propagation paths that the models suggested for the exemplar change cases were found to be causally reasonable. For the diesel engine, such a path is for instance: initiated change to the *Geometry* of *Crankshaft (Ge05)* → *Mechanical* behaviour of *Crankshaft (Me05)* → *Translate piston down* (*F9)* function → *Mechanical* behaviour of *Piston (Me03)* → *Material* of *Piston (Ma03)*. This could be a change case of downsizing the *Crankshaft* dimensions to save material cost. Such a downsizing results in a reduction of its mechanical strength and subsequently in a reduction of the parameters of *F9*. This, in turn, could be used to reduce the strength of the *Piston* by changing to a lower quality material to save more material cost. In this case, the last two steps of the propagation path are rather optional; if the *Crankshaft* dimensions were to increase, they would probably be

necessary to support the higher forces. In the numerical change propagation analysis, the preference of such options would be considered when estimating the likelihood of change propagation. Furthermore, to validate the numerical change propagation results of the model, the aggregated combined risk DSM from Figure 61 was investigated in more detail and found to be plausible.

For the SEM, such a change case is for instance the upgrade from operation under high vacuum only (i.e. vacuum mode) to operation under both high and low vacuum (i.e. variable pressure mode). This upgrade was historically brought about after the development of new generation SEMs (Environmental SEMs) in the early 1980s. While conventional (i.e. high vacuum) SEMs restrict the examination to dry and conductive specimens, variable pressure SEMs allow the examination of surfaces of almost any specimen because the environment around the specimen no longer has to be at high vacuum. The effects of this change request can be traced within the FBS Linkage scheme starting with the function *Control vacuum (F4)* as change trigger. The functional DSM in Figure 71 indicates that *F4* is a highly interlinked function with direct connections to *F3, F6-F13, F20* and *F21* and consequently indirect connections to all other functions. It can be seen from Table 15 that on the component level the behaviours of *Vacuum chamber (C11)*, *VAC electronics (C15)*, and *Vacuum system (C20)* are immediately affected by a change to *F4;* and further component behaviours are indirectly affected through other functions and components. Although, the benefit of analysing this change case with the FBS Linkage scheme seems questionable because the model suggests that all components are directly or indirectly affected, the advantage comes from the systematic approach of identifying the effects and avoiding oversight. Furthermore, this avalanche of propagated changes complies in this change case with the reality (Hollis and Shah 1997).

(2) The change prediction capability of the method was investigated by an alternative analysis. As previously discussed, one of the criteria against which ECM methods can be assessed is their change prediction capability. This requires the methods to consider all potential propagation paths between any two product elements, and thus, avoid hidden dependencies. The more propagation paths are captured within the model, the higher are the resulting linkage values. Thus, assuming that the model’s accuracy is predetermined, the resulting average linkage value (or here: the average combined risk value) correlates with the method’s prediction capability. The higher the average linkage value is, the more propagation paths between any two elements are considered in the model, and thus, the better is the prediction capability of the method.

To examine how the product layers contribute to the prediction capability of the FBS Linkage model, the corresponding risk matrices were calculated and compared for three model matrices: (1) single layer change propagation using only the structural layer (Forward CPM(S)), (2) double-layer change propagation using the structural and behavioural layers (Forward CPM(BS)), and (3) triple-layer change propagation using the structural, behavioural, and functional layers (Forward CPM(FBS)). As a baseline, the direct change risk matrix (i.e. no change propagation) was considered.

To obtain the combined risk matrices, the Forward CPM algorithm was applied considering six steps of propagation. The results within the structural layer (i.e. SS MDM) were aggregated to the component level using the maximum operation. Table 17 summarises the metrics calculated for all three examples used in this thesis. Figure 75 depicts the average linkage value (possible) for all three examples. The corresponding matrices can be found in the appendix.

Table 17: Metrics for risk matrices calculated taking different numbers of layers into account

Product	Matrix	Sum of linkage (i.e. risk) values (A)	Number of available linkages (B)	Number of possible linkages (C)	Average linkage value (available) (D=A/B)	Average linkage value (possible) (E=A/C)	Linkage population density (F=B/C*100)
Hair-dryer	Direct risk	700	18	30	38.9	23.3	60
	Forward CPM(S)	1472	30	30	49.1	49.1	100
	Forward CPM(BS)	1778	30	30	59.3	59.3	100
	Forward CPM(FBS)	2014	30	30	67.1	67.1	100
Diesel engine	Direct risk	754	228	1722	3.3	0.4	13.2
	Forward CPM(S)	5084	1336	1722	3.8	3.0	77.6
	Forward CPM(BS)	6911	1436	1722	4.8	4.0	83.4
	Forward CPM(FBS)	14999	1596	1722	9.4	8.7	93.7
SEM	Direct risk	1100	176	756	6.3	1.5	23.3
	Forward CPM(S)	17874	756	756	23.6	23.6	100
	Forward CPM(BS)	35972	756	756	47.6	47.6	100
	Forward CPM(FBS)	36762	756	756	48.6	48.6	100

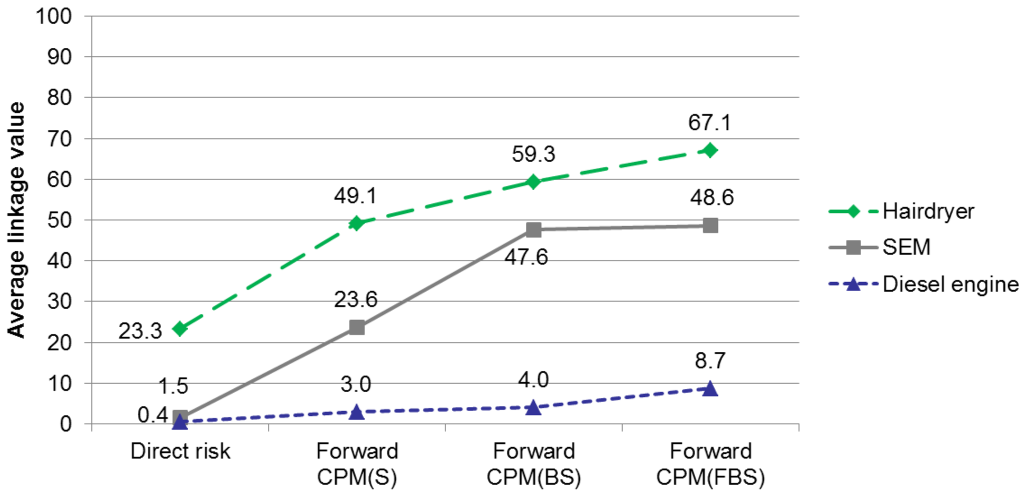


Figure 75: Comparison of single-layer to multi-layer change propagation analysis

For all three designs, the distribution of the average linkage value shows steadily increasing values: the more layers are considered in the change propagation model the higher the average linkage value (Figure 75). This is true for all metrics calculated in Table 17, until some of them reach their upper limit. The absolute levels and the runs of the curves in Figure 75 are different for each design.

The absolute level correlates with the density of the input matrix reflected in the average linkage value for direct risk. The matrix density of the smaller hairdryer model is much higher (23.3) than the matrix density of the SEM (1.5) and diesel engine (0.4). This results into an overall higher absolute level of the hairdryer curve. The direct risk bar could be used as the baseline to normalise the levels.

The run of the curve describes how many additional connections between the structural attributes become available when considering additional layers. The gradient depends on the characteristics of the three different layers of the network reflected in the linkage population density in Table 17. For the SEM, the inclusion of the functional layer in addition to the behavioural layer does not add significantly new connections between the structural elements whereas for the diesel engine, this extension doubles the average linkage value.

In conclusion, this analysis shows how each layer adds more information to the model and underlines the benefit of a multi-layer approach towards a single-layer approach. However, as most single-layer approaches such as CPM consider influences from other layers implicitly in the linkage values of their single-layer, it is difficult to compare multi-layer methods to single-layer methods directly.

(3) Verbal feedback evaluations were performed separately for both models. In different workshops, the author presented the method and demonstrated the corresponding model to industry experts. With the exception of one expert who supported a part of the modelling, all others were external to reduce bias. Following the demonstration, a discussion and questions & answers session was held to ensure that the experts sufficiently comprehended the method. Then, they were asked to give feedback. Each workshop took between two and three hours and was recorded. The recordings were transcribed and analysed to abstract the key arguments. The evaluation results were sent to the participants by e-mail to allow them to revise any possible transcription errors and to ensure that their arguments were considered completely and correctly.

An evaluation workshop for the diesel engine model was conducted at Dagenham Diesel Centre of Ford Motor Company with two Technical Leaders. Paul N. Turner has been working with Ford for 24 years. He held different positions in the engineering department of

Ford, including component engineer. His responsibilities focus on future engine designs and the acquisition of new technologies to meet future requirements. Mr Turner leads the technical development of mechanical systems for gasoline and diesel engines. Sean G. Harman has been working with Ford for 23 years and spent most of his time in Ford's engine development. His past roles include engineering of both engine components and systems. His current role focuses on performance systems and involves design lead and system integration. Mr Harman leads the technical development of fuel and air path systems, and components in support of the future gasoline and diesel engine developments in Ford vehicles.

Mr Turner and Mr Harman seemed to be overall convinced by the FBS Linkage method. They saw some potential useful applications of the method in their own organisation or similar global organisations and pointed out some directions for further improvement.

Mr Harman praised the method's procedural approach: *"The concept is very good. […] Having a methodology and a structured approach that gets everyone to follow the same steps is a good thing. Anything that is left to too much interpretation will end up with a very complex system with many different types of results."* Mr Turner noted: *"Vehicles and engines are getting more and more complex. System interactions are the things that we generally struggle with. We are quite good at designing a crank shaft - we do it for hundred years. [...] But the systems interactions are very difficult to manage; that's where such a linkage model is very useful."*

Both Technical Leaders emphasised the use of this method to support communication in multinational companies, where component designers may be located all over the world, and so the changes may propagate around the world. Mr Harman explained: "*If you have to change the specifications of one component in your area, the person affected by that change, in a big organisation, might have no way to know that the change is happening. So, if your model can use the existing linkages to flag up the change to all affected designers, each of them would be able to react early. […] There are other methods to flag up changes, […] but you never know how that effect is. Being able to quantify the effect is an advantage. If the structure in this model is set up correctly, you could minimise the number of false alarms and maximise the attention needed. […] For the automotive industry, that would be a useful bonus for the amount of work that you have to put in to develop such a method."* Mr Turner added: *"Today, we have a rigorous change management process trying to make people go through the steps and identify all the effects. […] The component engineer is then responsible for presenting that; but it is incumbent on the people who think they are affected to turn up to the meeting and determine whether they are affected or not. If they don't turn up, or they don't* *think they are affected but they are. […] only later will people realise: 'Oops! A change has happened we didn't know.'"*

Mr Harman noticed that "*Breaking down into function, behaviour, and structure is an excellent idea. At the moment, we look at block diagrams and try to get the linkages between various components and systems. We try to look at the effect from one to another in terms of flows of energy, information, and material. Understanding how functions, behaviours, and structures are interrelated is a level of refinement which I think is very useful."*

Mr Harman regarded the familiarity of the method as an advantage for acceptance in industry: *"We have looked at flows of any form of energy, material, and information between components at the engine level. […] I can see the systems that we do at the moment being quite useful in terms of delivering input for this model, so we are not coming straight from scratch. […] some of these functions could link in into our current models such as our combustion model and use that as input. There are quite well-known function trees, for instance the relations between material properties and surface areas for constant rotations. Today, we look at these functions in isolation and then try to work out what else might have an impact."* He then pointed out the importance of input flexibility for such a model: "*You probably find that a lot of information is already available in the database. It then comes back to getting the information in the right structure. […] I think making sure that the data capture is fit for use for all different types of information would be very useful. Just to ensure that people can take existing information and transfer it into the model rather than having to start from scratch."* Mr Turner supported this argument and saw it as an essential area for further improvement of the method: *"For accurate change prediction to work effectively, I would recommend that the model is linked to real data to continually update and learn as it is being used, based upon actual events. […] Expert estimations are fine to get it started, but then in reality, the actual data can surprise you. Having a methodology to refine that input and evolve the model is mandatory."*

Mr Harman highlighted the Planning Office as a potential good area to use this model for project size estimation: "*If we had a reasonable model to start with, we could perhaps put in a level of change or define a new function. So, we know what the function is and we know what we need to change to get that function; and we can put that in [the model] and that would tell us what the knock-on effect would be to the whole engine. I'm sure with a certain amount of expert input from the cost estimating finance side you could probably start estimating the size of the program based on the change."*

Mr Turner emphasised it potential use to compare and optimise between different engines: *"Potentially, if you take a diesel engine, and apply this to different types of engine. You can compare what's happening on Engine 1 versus Engine 2 versus Engine 3. It might be a useful way of saying: 'well actually, something is going strange on Engine 2 because we are seeing a higher occurrence of these sorts of linkages. Is that a design weakness or a usage condition which is causing more problems on this engine?'"*

Both evaluators appreciated the flexibility of the model. Mr Harman referred to the different types of input: *"For a mechanical system like an engine, quite a few of these links are based on laws of physics and therefore quite easy to be more accurate in that relationship – it is not just an estimate – there is often an equation behind it. [...] I think this model could be fairly accurate for critical attributes and vaguer for secondary attributes of the engine."* Mr Turner referred to the different levels of detail: *"Rather than doing it for every component, you might want to stick at the systems level and then focus on the key systems, and break them down further."*

They briefly checked the functional block diagram of the engine but did not have enough time to check the model and its results in more detail. However, with regard to model accuracy and validation, Mr Turner suggested: *"You have to create the model. You have your expert input as starting point. You need to then use the model to see how the changes actually flow through the system and record the change paths in your change control system. We don't record that today; it would require some system type changes in how we operate the company. You have to do something like that to refine, update, and validate the model."*

Mr Harman noticed an application limitation of the method: *"If the key enabler for the tool to work is having the expert input, I think, if you picture that for a very large system (i.e. the entire vehicle), you won't find anybody who is expert enough to give you that information and you have to get too many experts together; and if you get two engineers in one room, you get four solutions. You might want to think about where to pitch the models size. For a diesel engine, which is quite a complex thing to do, we are probably talking about half a dozen experts to get enough detail. So, that doesn't seem to be beyond the level to make it. The bigger you make it the more expertise you need or the higher level you have to go in terms of linkages; the higher the level the less resolution you get; and there is a trade-off between how much time you spend to develop the model and how much benefit you get from it. In terms of evaluating the model, you might want to think about how you would perhaps look at the input versus the resolution of the model, and then, try to have a metric of how much accuracy you need vs. how much input you need [...]. If you pitch it [the resolution] too high it will be a too* *big task and you won't get enough input; if you pitch it [the resolution] too low you won't have enough resolution in order to be useful. […] So you have an upfront requirement for the model."*

Mr Turner concluded*: "The thing that's making me think is how this would integrate with our current quality tools; and could it enhance our current quality tools? I think the answer is probably yes [to both]. It is just making sure that it is aligned with our operating practices globally. I think there is a merit to do this. You have to start somewhere, start small and then expand and grow. I think this method could do that. Particularly, as we are now trying to think in a system way and look at the interactions between components, this model potentially has an opportunity to help construct some of that. The hard bit in reality is always: 'how do you actually do it to make it an automated tool?' If it's manual, it's never used. If it's a tool that is straightforward and easy to use and interlinking to existing systems, then this potentially could work very well."*

The first evaluation workshop for the SEM model was conducted with Jane Breton, a former Technical Sales Manager with over 20 years of industrial experience for SEM manufacturers, with roles in performance specifications, PD proposals, and review committees.

Mrs Breton praised the qualitative use of the FBS Linkage model but was sceptical about the required effort for quantification. She appreciated the method's concept and flexibility which allows modelling at different levels of decomposition. For the high-level model of the SEM developed in Chapter 6, Mrs Breton explained three useful applications: (1) configuration management, (2) management of changes forwarded by other original equipment manufacturers (OEMs), and (3) solution selection.

1. *"SEMs are built based on a basis model, but almost every delivered instrument [SEM] is different from that [basis model] because the customers ask, for instance, for different detectors or want the SEM adapted for specific samples. Every time you add another detector, it has an impact back into the main system. And I think that can be quite a good application. Such a method can account for these impacts both during new product development to improve compatibility of optional subsystems and to estimate the effect when a customer request is made.*"
2. *"OEM subsystems (i.e. parts bought off the shelf such as pumps or computers) have become more and more an integral part of SEMs. The SEM manufacturers have control over parts they produce in-house but limited or no control over OEM subsystems. SEM producers may not have the volume purchasing power to request the OEMs for a change; or, if the OEMs decide to make a change to their equipment, the*

SEM producers may have to redesign their systems to fit in the new subsystem. It may be a very valid use of this FBS method to account for such changes pushed forward by the OEMs."

3. *"Usually, there are a number of alternatives solutions to address the same change request. This method could support to select the best alternative."*

At the same time, Mrs Breton noticed that a deeper level of detail might be required for most of the changes the designers deal with on a day to day basis and expressed her concerns that such a model might be very complicated and time consuming to develop. She pointed out, that *"Experts tend to put too many details into such a model to make it more accurate. This poses a potential hazard for the method to consume too much effort and become too complex.*" She emphasised that *"The model requires input from experts who in general have severe time constraints, and the quantification in particular could be very time consuming"* and *"Individuals show bias towards likelihood and impact".* This might lead to inaccuracies when different parts of the model are quantified by individual designers. To reduce the effort and improve the quantification accuracy, she suggested linking the method to the change history database of the company and using past change cases to inform the model. Overall, Mrs Breton concluded that the method might be more beneficial for high-volume production where risk factors and part cost are crucial and such a model can be used more intensively; and added: *"I have yet to be convinced that such a model is workable for SEMs where the volumes are around 100 units per year and the actual change implications and the quality of the final product are more important than risk factors."*

The second evaluation workshop for the SEM model was conducted with Dr Richard Stephen Paden, the former Director of the SEM manufacturer Obducat CamScan Ltd. Dr Paden holds a Ph.D. from the University of Cambridge and has in total 45 years of industry experience in SEM design and manufacturing. Throughout his career, Dr Paden was involved in developing different SEM systems and led the development of new microscope product ranges, before becoming a Technical & Managing Director.

Overall, Dr Paden rated the method and the SEM model as positive. However, he raised some concerns about the challenges of applying such a method to SEMs. Dr Paden concluded that *"This tool, if you can implement it honestly and efficiently, does give a very good way of actually trying to manage engineering changes. I think it's a great fun actually, an interesting project. And taking it to scanning microscope is a bold step. […]I like the idea very much; I think there is a lot of opportunity for applying it to improve decision making in engineering design."*

Dr Paden found the SEM model to be plausible and suggested some minor revisions to it. In particular, he checked the SEM decomposition into its components and the functional block diagram. He agreed with the decomposition for the most part but pointed out some details that he would have left out and others that he would have included: *"You have got some peripheral components like the X-ray system which I wouldn't have integrated within the microscope model – an X-ray system is an additional facility and not part of the product. The BSD [back scatter detector] is also an accessory to the basic microscope. On the other hand, I would include some elements to the list. The plinth in the microscope is very fundamental to the quality and performance of SEM because it determines the SEMs sensitivity to its environment. There are three [disturbing] inputs [from the environment]: vibrations, electromagnetic and acoustic interference. They constitute the elements you got to consider within the design of the microscope. The plinth has to contain a very good anti-vibration system which has to be really identified as an element within it; [...] I think that's an element that might be well-added on its own into the component list. Second, the column has to be shielded by a screen to protect the electron beam from electromagnetic interference. This really has to be considered in the context of the mechanical design of the SEM. And the third thing is screening to protect against acoustic noises. I would also list the column structure as a separate component."*

With regard to the functional model, Dr Paden commented: *"I don't really see any major issues. It's a good analysis of the flows and interactions that go on."* He suggested some minor changes to the wording to make it more understandable for microscopy experts. Furthermore, he noted that some functions which are modelled as a sequence actually take place simultaneously. For instance, he noted, *"you can't align or correct the beam [F8] until you actually set values for the magnetic lenses [F9]. You know, the two things are, a two-way process."*

Dr Paden emphasised the benefit of this model to capture and transfer knowledge: *"You're building into a program what otherwise would been known as an expert engineer's analysis: Somebody who has grown with the product and knows it in its entirety, he knows the interactivities that go on within it, but a new engineer coming in to work on a certain system doesn't have that knowledge. This tool would allow him [the new engineer] to make better assessments. [...] I can see that you could apply such a principle to train engineers who would come in to a development and the production groups [...] to lead them to better decision making."*

As one of the limitations of such a probabilistic and experience based model, Dr Paden noted the difficulty to account for unknown relations between some elements: *"It's a very challenging task. It can be criticised because in many ways it is not a precise model. It cannot be by its very nature precise; it can only give you a probability of the issues. What you have to consider […] are the things that haven't been entered in the data of the model because if they end up becoming an issue then the model will not predict those problems."* Dr Paden remembered an example where he and his colleagues added a metal liner tube inside the column to shield the beam and create an improved vacuum system, but they did not take into account that this tube would also become a preferred conductor for ripple currents. Only when they saw that the performance of the microscope was reduced, they investigated the problem and finally identified where it was coming from - it was resolved by inserting a high resistance break point in the tube. He added: *"Very difficult, because nothing would have let us to believe that from any other analysis."*

Dr Paden noted further challenges for the numerical use of the FBS Linkage model in particular for SEMs: *"I think it's a very challenging task to quantify this model. It's going to be a very difficult thing to do because every microscope is going to have a different set of relationships that exist between a change in the EHT [Extra High Tension] set, or a change in the gun, or a change in the design of the lenses etc. Perhaps in simple terms you can do it, but in detail terms, it will become rather more difficult."*

Furthermore, he noted that the method's benefit-to-cost ratio may be low for SEMs because *"Modelling the microscope is a particularly difficult thing to do. […] There will be certain commonalities to it, but each microscope will be very unique. […] What might be relevant to a CamScan microscope may not be relevant to a JEOL microscope, or a Zeiss microscope, or a Tescan microscope. Each one will have his own particular network. You have got a generic picture. There are sufficient elements to make it generic, that's for sure, but there may be elements in there which would be difficult to be generic about. I like the idea very much. […] I think it's a difficult one because also the manufacturing volumes you are dealing with are small and each microscope model may have many different variants. The biggest manufactures are only making perhaps 100 or 200 hundred a year and that model may only prevail for say three or four years. And how you build that conceptually into your design is also very important. You might start off with a basic model which is then presented in perhaps three different packages with different embodiments of hardware and elements that go into it and perhaps different performance levels. […] The question that always comes out in these things is: "Is the work and the effort justified by the result?" The more detail you go into, [the* *more] the data sets mushroom and you get more and more data. […] the challenge is actually getting it over to the people. It is very difficult in high level products to relate all the parameters in an honest and truthful way. If you can't get the data in relatively sensibly, then it prejudices the data that comes out."*

Dr Paden summarised his judgement as following: *"I think your choice of a SEM is a very challenging one. I think you have done a very good job on it. I can't really add a great deal to what you have done. I think with Bernie's [Bernard Breton] help and advice you have modelled the instrument in a pretty comprehensive way – taken into account a few thing that I might not have added in a base level instrument, but it doesn't really impinge very much in the overall picture that emerges. It's a very complex object, there may be other issues; and I think when you try to put in numbers to it, it might become very time consuming and difficult."*

The third SEM evaluation workshop was conducted with Daniel Aldridge, who supported the early phases of SEM model building from the collaborating SEM manufacturer's side and was involved in decomposing the SEM and developing the structural and behavioural layers.

Overall, Mr Aldridge was impressed that such a large SEM model was developed in less than ten person-days and saw some benefits of the FBS Linkage approach. As his main concern, Mr Aldridge mentioned the complexity and effort required to develop and maintain an FBS model at an appropriate level of detail and accuracy for it to be practically useful.

Mr Aldridge was convinced that an FBS Linkage tool could be useful to support PD: "*The benefits that I can see with this type of approach is that, […] assuming that the engineers are working on a new product development or some product sustain […], by having this type of model you capture the knowledge of how a change in one part of a microscope could propagate to have an impact to other parts of the microscope. That's a tool for really improving the quality of product sustain and product development. I think that's a good use of the tool."*

He went on to compliment the capability of the model to capture tacit knowledge and make it available: "*I think the way designer traditionally dealt with the impact of design changes is just from knowledge - the knowledge in their heads basically. I am actually pushing a number of initiatives - not at this level of a tool - to capture knowledge, get knowledge of people's head, and documented it […], partly, because some of the experts we have are coming towards the age of retirement, but also, you know, it's always dangerous to have knowledge locked within people's head and it's difficult to use it. One of the concepts that we use in there is a design check list, which is a way of capturing knowledge in a check list format which a* *designer engineer can use just to make sure they consider a number of manufacturing processes, geometric tolerances and that kind of things. But that's very much at a component level and is not really considering how that component might affect other components within the systems. So I think this tool is something different to what we are trying to do at the moment and I can see that it would be useful, but I still do have concerns how to practically implement it."*

Mr Aldridge referred to the required effort as his main concern: "*The difficulty of it, having implemented it, is just the overhead that it requires to create and maintain the tool. That's a difficulty I have with the process at the moment. For it to be useful, it requires quite an investment in time, and the resources that would be required to create the model are the experts - the experts that are working on other stuff and are the most difficult people to free out to actually work on this."* Furthermore, he added the complexity of developing an FBS Linkage model as a challenge: *"John and myself were working on this. John is a very experienced engineer; he is probably one of the most experienced SEM engineers in the world, in fact. When we were putting together the matrices and dependencies, even he was struggling with some of it. [...] So I think the complexity of the tool is a challenge."* Mr Aldridge explained, *"I suppose, it is a balance about which level we are trying model things. If you can model it at the right level, it becomes almost like a generic model which can be used from one generation to the next generation [and so forth]. If it's too detailed, then you are going to have to keep continuing changing the model. That's where I haven't quite got my head around: Would we be able to do it to enough detail for it to be valuable without having too much of overhead and a burden on the design engineers [...]? They certainly wouldn't be able to update the model for every generation of the product. There is too much of an overhead I think. [On the other hand,] I have doubts on how useful the model would be if it is a generic. I can see certainly some potential but I have some reservations."*

Mr Aldridge concluded: "*So, while I can see it being very important and useful, there are some practical difficulties that I have with actually being able to implement it at the moment."*

As further research to improve the method and tool, Mr Aldridge suggested the integration of the FBS Linkage method with computer aided design (CAD) programs: "*If something like this could be built into a 3D CAD program, I think that would make it much more accessible to the design engineers. Having that sort of functionality bedded into a CAD program, where those dependencies are intelligently built into the overall 3D design, I think that could be a really powerful tool."*

To summarise the evaluation, the author read through the manuscripts and abstracted the arguments to create a separate list of distinct arguments for each expert. Then, the arguments were compared among the experts, and similar ones were clustered. For the clusters, a comprehensive description was generated by combining or rephrasing the arguments. The result is represented in Table 18, where the arguments are categorised into advantages or disadvantages of the method and ordered according to the number of mentions by the industry experts, indicated by *"x"*. As can be seen from this overview, there are many advantages of the FBS Linkage method that the industry experts praised. However, there are also a number of limitations that they pointed out and that need to be considered in the future improvement of the method.

Table 18: Overview of the key arguments of the industry experts about the FBS Linkage method

Key arguments about the FBS Linkage method	Diesel engine Paul Turner	Diesel engine: Sean Harman	SEM: Jane Breton	SEM: Dr Richard Paden	SEM: Daniel Aldridge
Praised advantages					
Can be used to trace and predict change impact.	x	x	x		x
Is based on a good concept and idea.	x	x		x	
Facilitates understanding of how functions, behaviours, and structures are interrelated, and how the product works.		x		x	x
Provides a comprehensive integrated overview of the whole product and shows how all systems interact.	x	x			x
Improves decision making in ECM.			x	x	x
Supports communication.	x	x			
Allows detecting changes earlier.	x	x			
Helps to estimate project size and change effort.		x	x		
Is flexible towards the input accuracy – can be build based on expert estimations, and refined using calculations for critical connections and continuously as the model is used.	x	x			
Can be integrated with current quality tools and use available data.	x	x			
Captures and transfers knowledge.				x	x
Has a structured procedural approach.		x			
Quantifies the effect of changes.		x			
Allows comparing and optimising between different product variants.	x				
Is flexible to model a product at different levels of decomposition.	x				
Criticised disadvantages (or rather suggested improvements)					
The relation between the required level of detail and the usefulness of the model should be investigated and predetermined to optimise the benefit-to-effort ratio.		x	x	x	x
The dependency on expert input should be reduced.		x	x		x
Should be implemented into an automated tool and interlinked to existing systems and data (to reduce manual effort).	x		x		x
Might not be very useful for low-volume and highly customised products such as SEMs due to the high effort of adopting and updating the model.			x	x	x
Should be flexible to use different types and formats of input information.	x	x			
Complexity and effort of model building at a useful level of detail should be reduced.			x		x
Complexity and effort of linkage quantification should be reduced.			x	x	
Should be linked to real data to be continually updated and improved.	x				
Inaccuracies of linkage quantification due to subjectivity should be reduced.			x		
Can only take into account known relations inserted into the model, but sometimes new issues arise and surprise designers.				x	

7.4.4 Requirements-based evaluation

The requirements for ECM methods developed in Chapter 4 refer to all three kinds of evaluations suggested in DRM by Blessing and Chakrabarti (2009) (Figure 76). Thus, an assessment against them indicates the overall performance of a method.

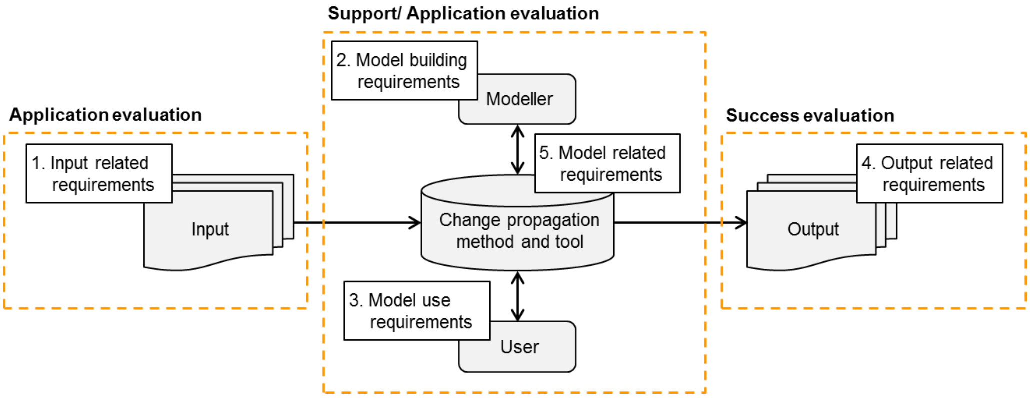


Figure 76: DRM evaluation types addressed by the requirements for ECM methods

The assessment of the FBS Linkage method against the developed set of requirements was first undertaken by the author. Although the author's eligibility for assessment of the method that he developed himself is arguable, this evaluation step is useful due to its comparative nature: the assessment followed the same procedure applied to the eight selected methods in Chapter 4. The assessment results contrasting the FBS Linkage method from CPM are summarised in Table 19.

Table 19: Comparative assessment of FBS Linkage by the author against the developed requirements set

No	Category	Requirement name	CPM score	FBS Linkage score	FBS Linkage rationale
1	1. Input related (scope/ feasibility)	Range of products covered	5	5	very broad; applied on hairdryer, diesel engine, scanning electron microscope; supported hierarchical decomposition allows managing of modelling effort and complexity, i.e. products of higher complexity can be modelled on a higher level of decomposition to reduce effort
2		Range of levels of decomposition supported	2	4	good; models systems, components, and attributes
3		Range of different changes covered	3	4	good; all kind of possible changes to functions, behaviours, attributes, and their relations; magnitude of changes not considered in numerical change prediction analysis but could be taken into account in qualitative case-by-case analysis
4	2. Model building	Ease of model building	5	3	average; model building process well described; developing of the functional block diagram requires expert knowledge
5		Availability of information to build the model	4	3	average; expert interviews; basic information; available documentation about the product's architecture, functions, and working mechanism
6		Accessibility of tools to build the model	5	5	very good, any tools to capture DSMs can be used
7		Accuracy	3	4	high; expert estimations with causality as rationale
8		Consistency	4	4	high; consistency ensured in the context of the product's functions and causality; model elements and links well defined
9		Adaptability	4	4	high; existing models can be used to a certain extent and need to be manually modified to adapt to other products

No	**Category**	**Requirement name**	**CPM score**	**FBS Linkage score**	**FBS Linkage rationale**
10		Benefit-to-cost ratio of model building	4	4	very high benefit (detailed causal product model can be used for change modelling, functional reasoning, communication support etc.) and medium cost (much information but no programming or buying of tools needed)
11	3. Model use	Ease of model use	4	3	average; easy numerical prediction analysis: run calculation, identify changed element, read imposed change risk to other elements; rather complicated use for qualitative case-by-case change propagation analysis as expert knowledge required to determine propagation paths and develop solutions
12		Accessibility of tools to use the model	4	3	average, Java-based CAM tool and CPM module (both available for free) can be used in combination with Microsoft Excel. A prototype FBS Linkage module in CAM has been developed.
13		Practicality	4	4	high; when a component attribute or function changes, the model provides information about imposed risks on other component attributes or functions; moreover, the model can be used for functional reasoning purposes
14		Flexibility	3	3	average; links and linkage values need to be changed or defined for new component attributes and functions and calculations updated
15		Benefit-to-cost ratio of model use	4	4	very high benefit (numerical change prediction, causal change propagation, functional reasoning, communication support etc.) and medium cost (fairly low use effort and free software)
16	4. Output related (results)	Utility of results	4	4	high; risk profiles, critical components, depiction of change paths, etc.; clearly depicted; but no different levels of detail for different users
17		Quantity of results	4	4	high; combined likelihood, impact, risk, for different number of steps and for the whole product; different other analyses; but currently only for one change at a time
18		Quality of results	-	-	not assessed
19	5. Model related (capability / function-ality)	Product modelling capability	3	4	good; causal product model including component breakdown, structural and behavioural attributes, and functions
20		Change modelling capability	4	4	good; change propagation along all possible attribute and function links
21		Change prediction capability	3	4	good; change prediction considering all direct and indirect links between attributes, components, and functions
22		Change containment capability	2	4	good; causal relations in the FBS Linkage network can help to contain changes
23		Solution finding capability	2	4	good; the FBS Linkage scheme could be used to find solutions for changes, thereby considering functions, behaviours, and structures
24		Numerical analysis capability	5	5	very good; numerical linkage values and algorithm for change risk calculation
25		Compatibility	4	4	good; DSM based data with import/export to xml and excel files
Unweighted average score			**3.7**	**3.9**	

Rating scale: 1 (poor) … 3 (average) … 5 (excellent)	**Other methods are better than CPM (i.e. competitive gap)**	Improvement on CPM	Degradation of CPM

As Table 19 shows, FBS Linkage implements the seven suggested improvements to CPM. Overall, the unweighted average score increases from 3.7 to 3.9. The FBS enhancement allows modelling a product in greater detail and in a more systematic way by causally linking structural elements to the behaviours they show, and the behaviours to the functions they realise. This systematic basis reduces the possibility of modelling mistakes while the causal linkage model improves the understanding of the product's architecture and working mechanisms as well as the implications of changes. The detailed network model allows investigation of different change alternatives to reduce change propagation. Furthermore, the model helps identifying solutions to change requests, which is specifically helpful when it is not obvious which components to change and how to implement a change request.

However, on the downside, this enhancement increases the effort and complexity of model building and use (i.e. ease and availability of information and tools to build and use the model) compared to CPM. The times required to build the FBS Linkage models are in Table 15 (i.e. 6, 55, and 52 person-hours for the hairdryer, diesel engine, and SEM correspondingly). For the CPM diesel engine, Jarratt (2004) reported 45 person-hours for model elicitation, spent by a team of seven engineers and two researchers. Considering that the FBS method used the pre-existing CPM model as input, it can be estimated that it requires approximately double as much time-effort as CPM. Although this increase can be justified by the additional insights gained from the modelling, it is a degradation worth addressing in future research.

In addition, stand-alone assessments of the FBS Linkage method against the requirements were conducted by the industry experts who participated in the evaluation workshops. At the end of the workshops, the experts were given a questionnaire including the requirements and their descriptions as shown in Table 4, and they were asked to rate the method against the requirements. These evaluation results must be interpreted on their own because the industry experts did not assess any of the other ECM methods in comparison. To account for that, the rating scale was modified to: 1 (strongly disagree), 2 (disagree), 3 (neither agree nor disagree), 4 (agree), and 5 (strongly agree). A summary of the assessment results is given in Table 20.

The assessment results in Table 20 show that overall the experts agree that the FBS Linkage method meets the requirements (total average: 4.1). However, this questionnaire based assessment is indicative and subject to expert opinions. A few limitations of this assessment should be emphasised here: With the exception of Daniel Aldridge, the other evaluators were not involved in model building and the evaluation was solely based on the method details presented to the experts by the author during a two to three hours sessions. These details covered most of Chapter 6 and were presented in form of slides. In this context, it should be noted that the assessment could also be distorted because of the influence of the presentation itself on the evaluation. Furthermore, the assessment was performed in presence of the author. This allowed the experts to ask questions and clarify any issues they had with the questionnaire or the understanding of the method, but anonymity was not provided. Thus, the experts may have been intimidated by the author and assessed the method more positively.

Table 20: Stand-alone assessment of FBS Linkage by industry experts

No	Category	Requirement name	Diesel engine - Paul Turner	Diesel engine – Sean Harman	SEM – Jane Breton	SEM – Dr Richard Paden	SEM – Daniel Aldridge	Un-weighted average
1	1. Input related (scope)	Range of products covered	5	5	5	5	5	**5.0**
2		Range of levels of decomposition supported	5	4	4	5	4	**4.3**
3		Range of different changes covered	5	4	5	4	5	**4.5**
4	2. Model building	Ease of model building	4	4	4	4	2	**3.5**
5		Availability of information to build the model	3	3	3	4	3	**3.3**
6		Accessibility of tools to build the model	3	3	na	4	5	**4.0**
7		Accuracy	4	4	4	4	5	**4.3**
8		Consistency	4	3	4	5	4	**4.0**
9		Adaptability	5	5	5	5	4	**4.8**
10		Benefit-to-cost ratio of model building	3	4	3	5	3	**3.8**
11	3. Model use	Ease of model use	4	4	4	4	2	**3.5**
12		Accessibility of tools to use the model	3	3	na	4	5	**4.0**
13		Practicality	5	4	5	5	4	**4.5**
14		Flexibility	5	5	5	4	4	**4.5**
15		Benefit-to-cost ratio of model use	4	5	5	5	3	**4.5**
16	4. Output related (results)	Utility of results	5	4	4	4	3	**3.8**
17		Quantity of results	5	4	3	3	4	**3.5**
18		Quality of results	3	5	na	3	3	**3.7**
19	5. Model related (capability / function-ality)	Product modelling capability	5	4	4	5	4	**4.3**
20		Change modelling capability	3	4	4	4	5	**4.3**
21		Change prediction capability	3	5	5	4	5	**4.8**
22		Change containment capability	5	3	5	5	5	**4.5**
23		Solution finding capability	4	5	5	3	4	**4.3**
24		Numerical analysis capability	4	4	4	4	5	**4.3**
25		Compatibility	4	3	na	3	2	**2.7**
Unweighted average			**4.1**	**4.0**	**4.3**	**4.2**	**3.9**	**4.1**
	Rating scale: 1 (strongly disagree) … 3 (neither agree nor disagree) … 5 (strongly agree)							

One expert summarised these limitations very well: *"Change scenarios in product development involve change requests whose impacts we cannot really understand in a broader view. This framework seems to be valuable for identifying and mapping all the possible links between product components and quantifying the likelihood and impact. So it is not really difficult to see what the benefits are in this framework. But without actually using the method in real life and seeing its actual results, particularly when it feeds the enterprise resource planning tools about cost of engineering changes, this evaluation gives limited evidence."* However, in line with the DRM, the evaluation in this thesis was meant to be only an initial evaluation. For the further development of this method, a more comprehensive evaluation is inevitable. To conduct such an evaluation with enough confidence, first, the method has to be fully implemented in a software program, before it can be used by practitioners and applied to real cases. This will be an essential part of the future work.

7.5 Chapter summary

This chapter has presented the application and evaluation of the FBS Linkage method using the example of two complex designs of different engineering domains – a diesel engine (predominantly mechanical) and a SEM (predominantly electron-optical).

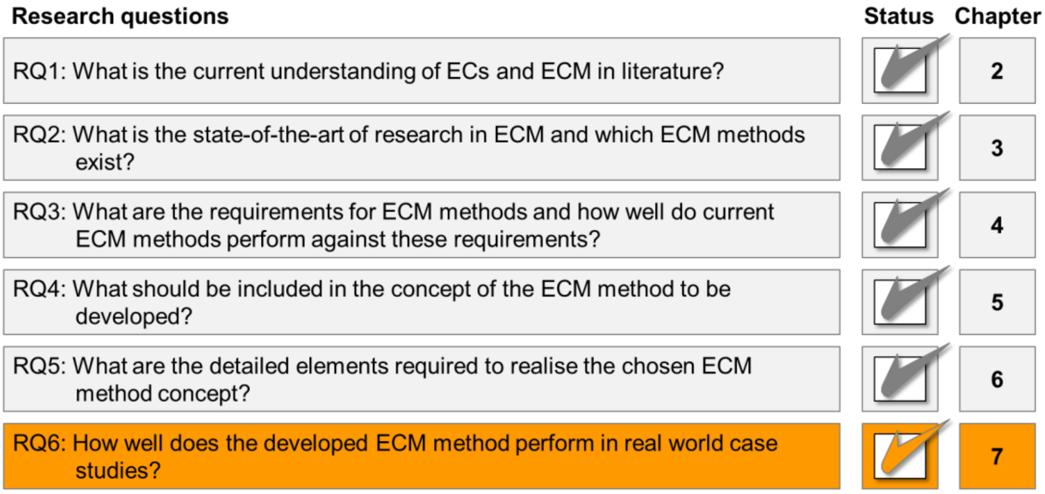
In the first case study, the diesel engine was decomposed into 42 components. For each component, four structural and three behavioural attributes were defined and their elements were linked to each other. A functional block diagram comprising 40 subfunctions was developed and the FBS Linkage scheme was completed by linking each subfunction to the responsible behavioural elements. Subsequently, the FBS links were quantified and a combined change risk matrix was calculated using the Forward CPM algorithm. The numeric change risk model was used to generate component-level risk profiles and prioritised change risk lists. A comparison with the results of the original CPM diesel engine model indicated that the FBS Linkage model reveals more links between the design elements and thus produces higher combined risk values.

In the second case study, an FBS Linkage scheme was developed for a SEM, comprising 28 components, each with three structural and four behavioural elements, and 22 subfunctions. This qualitative FBS Linkage scheme was used to generate an interactive network which provides a broad overview of how the SEM operates and could be used beyond ECM for knowledge management and training purposes.

The evaluation of the FBS Linkage method comprised four parts:

1. The *Support* evaluation ensured continuously internal consistency and completeness of the method.
2. The *Application* evaluation showed that the method can be used in the situation for which it was intended.
3. The *Success* evaluation showed that the method contributes to an improvement of ECM and pinpointed further improvement directions.
4. The *Requirements-based* evaluation showed that the method is an improvement to CPM with regard to the targeted requirements and could be further improved with respect to ease of model building and use.

Thereby, this chapter has answered the sixth research question (Figure 77).



Research questions	Status	Chapter
RQ1: What is the current understanding of ECs and ECM in literature?	☑	2
RQ2: What is the state-of-the-art of research in ECM and which ECM methods exist?	☑	3
RQ3: What are the requirements for ECM methods and how well do current ECM methods perform against these requirements?	☑	4
RQ4: What should be included in the concept of the ECM method to be developed?	☑	5
RQ5: What are the detailed elements required to realise the chosen ECM method concept?	☑	6
RQ6: How well does the developed ECM method perform in real world case studies?	☑	7

Figure 77: Research questions and status after Chapter 7

8 Conclusions

"Be the change that you wish to see in the world."

(Mahatma Gandhi, Indian nationalist leader, 1869-1948)

8.1 Chapter introduction

This chapter summarises and concludes the thesis. First, the answers to the six research questions developed throughout the thesis are briefly summarised and their contributions are presented in Section 8.2. Next, in Section 8.3, the FBS Linkage method is reflected back to the introduction to discuss the outcome in light of the objective of this research. Then, the limitations of this research are discussed in Section 8.4; and finally, opportunities for further work are highlighted in Section 8.5, and the thesis is concluded in Section 8.6.

8.2 Key findings and research contributions

The key findings and research contributions of this thesis can be summarised under the answers to the six research questions stated in Chapter 1:

RQ1: What is the current understanding of ECs and ECM in literature?

The answer to *RQ1* comprises a review of key ECM publications and the elaboration of important topics in ECM (Chapter 2). The main contribution of this answer can be summarised as follows.

1. *Comprehensive understanding of ECs and ECM:* Based on a profound review of key ECM themes, this thesis developed a comprehensive and manifold understanding of ECs and ECM (Sections 2.2 and 2.3). Drawing on different EC definitions, an accurate and concise new definition for EC was developed. Multiple facets were used to describe and characterise ECs. Findings from the latest surveys were used to elaborate and quantify the frequency of the sources, targets, and consequences of ECs. Furthermore, the EC process, the role of ECM, and current ECM methods were discussed.

RQ2: What is the state-of-the-art of research in ECM and which ECM methods exist?

The answer to *RQ2* comprises the development of a categorisation framework for ECM research, the application of this framework to categorise all relevant ECM publications from the early 1980s up to the end of August 2011, and the identification of 54 unique ECM methods which address one or more of the guidelines *Earlier*, *More effective*, and *More efficient* (Chapter 3). Consequently, the main contributions of this answer can be summarised under three headings.

2. *Categorisation framework for ECM:* A new, holistic and process-oriented categorisation framework for ECM was proposed (Figure 21). This framework depicts the big picture of the ECM research field and allows a comprehensive coverage and precise categorisation of publications in ECM and related areas. It helps understand the research area of ECM in its broad context and organise relevant topics.
3. *Exhaustive systematic literature review and categorisation:* Over 420 relevant publications for ECM were identified and categorised using the developed categorisation framework (Figure 23). The result depicts the current picture of research in ECM in the broader sense and highlights both major ECM research areas

addressed by many publications as well as areas where little research has been done yet, thereby, indicating the categorised publications. The result of this positioning and analysis can be used by both researchers and practitioners to (1) look for relevant publications for their research or work, (2) position their research or work in the overall picture of ECM, (3) focus on the identified research gaps, and (4) search for further research and improvement opportunities.

4. *List of unique ECM methods:* Drawing on the literature review and categorisation, 54 unique ECM methods were identified and classified according to (1) the change management guidelines (*i.e. Earlier*, *More effective,* and/or *More efficient* implementation of changes) that they address and (2) their availability in computer tools. Table 3 in Chapter 3 thus provides an overview and brief description of current ECM methods with their references. It could be used by researchers as well as practitioners to obtain a quick overview of all ECM methods. For instance, when searching for a method with specified characteristics, the table can be scanned to shortlist potential methods, which then can be studied in more detail by reviewing the indicated publications.

RQ3: What are the requirements for ECM methods and how well do current ECM methods perform against these requirements?

The answer to *RQ3* comprises the development of a set of 25 requirements for ECM methods and the competitive assessment of eight promising ECM methods against them (Chapter 4). Consequently, the main contributions of this answer can be summarised under two headings:

5. *Requirements for ECM methods:* A comprehensive set of 25 requirements for ECM methods was developed (Table 4). These requirements were obtained from the publications on the 54 unique ECM methods identified within the categorisation framework, combined with industrial experience from several case studies. The requirements set can provide guidance for improvement of current ECM methods and development of future methods.

6. *Competitive assessment of eight promising ECM methods:* A competitive assessment of the eight most promising ECM methods was conducted using the set of requirements as benchmark criteria. These eight methods were selected from the list of 54 unique ECM methods. For each method, a detailed assessment table including the scores and rationales were prepared, and eventually, all scores were summarised in a combined table (Table 7). This table highlights the comparative strengths and

weaknesses of each method as well as benchmarks for each requirement. It can be used to select the method that best meets a particular set of needs. Furthermore, the table can be used as a starting point for a benchmarking approach to improve any of the eight compared methods or any other yet to be rated method, similarly as conducted for CPM in this thesis.

RQ4: What should be included in the concept of the ECM method to be developed?

The answer to *RQ4* comprises the identification of CPM's improvement potentials and the conceptual design of an improved ECM method, as outcomes of the undertaken benchmarking approach (Chapter 5). Consequently, the contributions of this answer can be summarised under two headings.

7. *Competitive gaps and improvement suggestions for CPM:* As the comparatively best ECM method, CPM was selected as the basis method to build upon and develop the concept of an improved ECM method. The comparative assessment of CPM and seven other ECM methods revealed seven competitive gaps for CPM. For these criteria, the best-in-class methods were investigated and improvement suggestions for CPM were drawn (Table 8). This qualitative evaluation of the competitive shortcomings and potential improvement opportunities of CPM could provide insight to further improve CPM. Furthermore, using the same approach, a detailed profile could be developed for any other ECM method, and used to identify competitive gaps as starting points for improvement.
8. *Conceptual design of an improved ECM method:* Based on the improvement suggestions drawn for CPM, a concept for an improved ECM method was developed (Table 10). This concept prescribes the integration of the CPM approach with a three-layered functional reasoning scheme. It is a novel concept for change propagation modelling and termed FBS Linkage method.

RQ5: What are the detailed elements required to realise the chosen ECM method concept?

The answer to *RQ5* comprises the detail design of the FBS Linkage method including the presentation of its adapted ontology developed based on a detailed comparison of three seminal three-layered FR ontologies (Chapter 6). Consequently, the contributions of this answer can be summarised under three headings.

9. *Comparison of three FR schemes:* A comprehensive review and comparison of the three seminal three-layered FR schemes: FBSta, FBStr, and SBF, was presented (Table 11). The comparison highlights the key characteristics of each ontology with regard to the three layers structure, behaviour, and function and the two intersections between structure and behaviour, and behaviour and function. This systematic and structured comparison provides a good basis for understanding and applying FR schemes to model products, and more especially, to model change propagation.

10. *A modified FR scheme:* Using the comparison of the three seminal three-layered FR schemes, a new modified function-behaviour-structure scheme was developed: the FBS Linkage scheme (Table 12). This scheme is specifically aimed at developing models for complex products to describe and predict change propagation.

11. *Detail design of an improved ECM method:* The FBS Linkage method was presented and demonstrated using a hairdryer as an illustrative example. The method is a novel approach which models the product as a network of its structural, behavioural, and functional elements and uses their relations to describe and predict change propagation. It proceeds in six stages (Figure 32) and can be used to pursue all five ECM guidelines: *Less, Earlier, More effective, More efficient, and Better* (Figure 78). FBS Linkage implements all seven identified improvement suggestions of the benchmarking analysis to CPM (Table 13) and has a manageable modelling effort for complex products (Section 8.3.2).

RQ6: How well does the developed ECM method perform in real world case studies?

The answer to *RQ6* comprises the application and evaluation of the developed method to two industrial cases studies (Chapter 7). Consequently, the main contributions of this answer can be summarised under three headings.

12. *Application of the FBS Linkage method to a diesel engine*: An FBS Linkage scheme including a novel functional model was developed for a diesel engine (Section 7.2). The scheme was quantified and a combined risk MDM was calculated (Figure 60). Consequently, the risk model was used for numerical change propagation analysis.

13. *Application of the FBS Linkage method to a SEM*: For the first time in literature, a SEM was investigated with regards to change propagation (Section 7.3). The developed FBS Linkage scheme including a novel functional model was used for qualitative change propagation analysis (Figure 73). This model provides a

comprehensive view of how the SEM operates and improves understanding and prediction of change impacts on SEM components.

14. *Evaluation of the FBS Linkage method*: The FBS Linkage method was evaluated based on the evaluation types of DRM (Section 7.4). It was shown that the method is feasible with reasonable modelling effort for complex designs and useful to improve ECM. An assessment of the method against the requirements highlighted both its advantages and disadvantages compared to CPM. On the upside, FBS Linkage improves on CPM in the following ways: (1) it allows representation of the design at more detailed and different levels of decomposition, (2) it enables modelling of changes initiated in different aspects of the product, (3) it models the product in the context of its functions and working mechanisms, thus, improving change prediction accuracy and product modelling capability, and (4) it allows case-by-case reasoning about change propagation, thereby, supporting change containment and solution development. On the downside, the FBS Linkage model requires more information than CPM, and thus, it is more complicated to prepare and use.

8.3 Reflection of the FBS Linkage method

Chapter 1 and 2 found that ECs are crucial for PD because they can be raised by multiple sources along the complete product lifecycle, tend to propagate from one part to another and affect development cost, time-to-market, and product quality. ECM thus is an important discipline which deserves attention from both industrialists and researchers. The overall objective of this thesis was to contribute to an improvement of ECM as depicted in Figure 4. Ways of doing so were summarised under the five strategies proposed by Fricke et al. (2000): *Less, Earlier, More efficient, More effective, and Better;* and to support ECM, many methods were proposed. The thesis then hypothesised that *"The predictive capability of ECM methods can be improved by more detailed modelling of the interactions between components"* and set out to test this hypothesis by developing and evaluating such a method – the FBS Linkage method.

The method was developed through a systematic approach including the identification of current ECM methods in Chapter 3, the development of requirements and the comparative assessment of existing methods against them in Chapter 4, the selection of a concept in Chapter 5 and the detailing of this into an enhanced ECM method in Chapter 6. The method was then applied to two industrial case studies and evaluated based on that in Chapter 7. Overall, the evaluation was positive and revealed some directions for further improvement. Thus, the hypothesis cannot be declined. To support the acceptance of the hypothesis and show that the thesis has achieved his objective of improving ECM, the following subsections will discuss: the method's benefits with regard to the five strategies above, its modelling effort, and a weighing up of both.

8.3.1 Benefits of the FBS Linkage method

The FBS Linkage method collects, generates, organises, stores, and represents thorough knowledge about the product. This information can benefit different stakeholders throughout the product lifecycle for both original and evolutionary design. As the method combines two established approaches, namely: FR and CPM, it can be applied for purposes targeted by both.

FR schemes provide an overall system description which can be applied as a means to support communication and understanding between engineers of various disciplines and facilitate the use of automated reasoning systems (Erden *et al.* 2008).

CPM models provide an overall change description of the system and can be applied during different design stages, amongst others for (Jarratt *et al.* 2004b, Keller *et al.* 2009): knowledge capture and familiarisation with existing designs, identifying and predicting change risks, identifying propagation absorbers/ multipliers, testing alternative solutions, team support, and process management.

In particular for ECM, the FBS Linkage method can be used to pursue the five generic strategies from Fricke et al. (2000) as illustrated along with selected application examples in Figure 78:

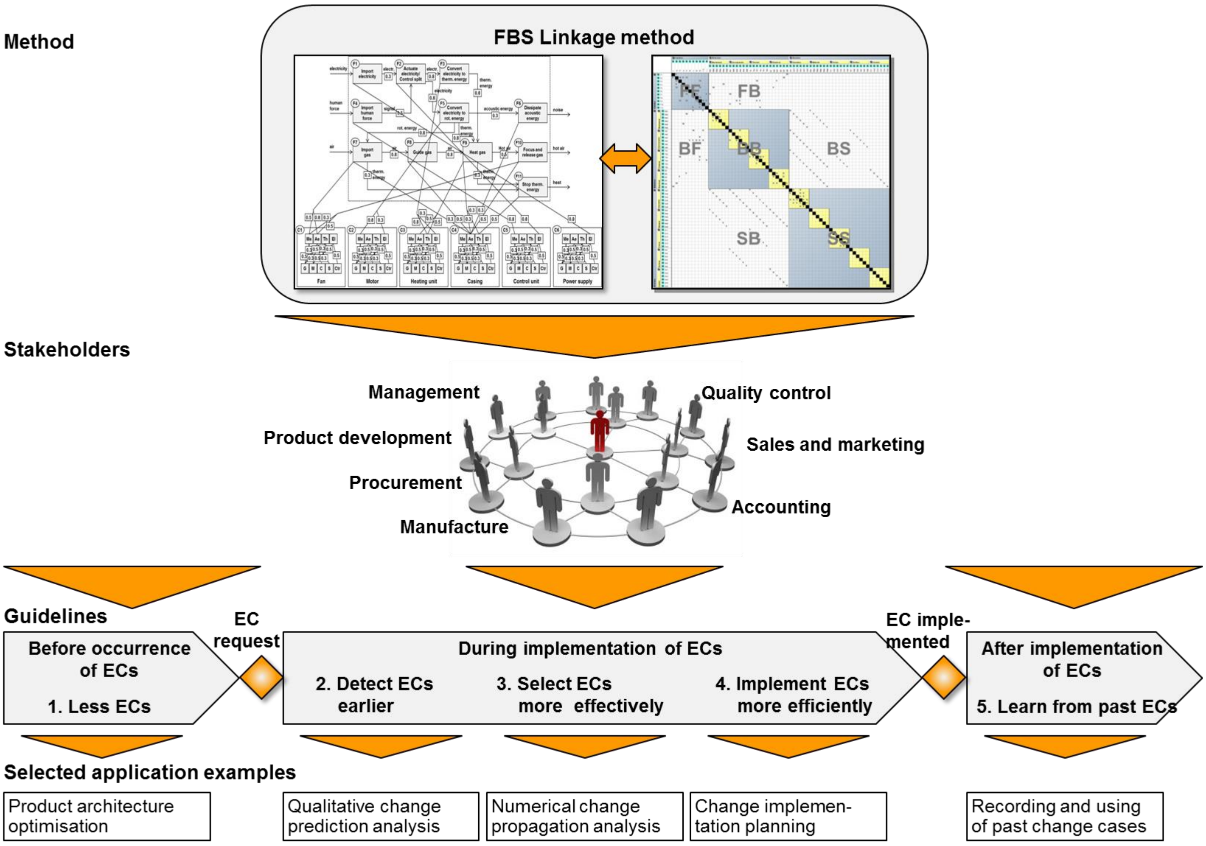


Figure 78: Application of the FBS Linkage method to support ECM

1. To reduce the number of propagated changes, the FBS Linkage model could be used to support optimising the architecture of a design, in such a way that functions are decoupled and critical linkages between structural, behavioural, and functional elements are reduced. Furthermore, Mr Turner recognised a use of FBS Linkage models for diagnosis or optimisation based on comparisons between different product variants (p. 143).

2. To detect ECs earlier and improve communication of propagated changes, the FBS Linkage network could be used to trace possible change propagation paths and predict changes before they actually occur. Mrs Breton and Mr Aldridge suggested that the detection of EC impacts during both new product development and product customisation is a good application of this method (p. 144 and p. 147). Both Ford Technical Leaders emphasised the use of the model to improve early and transparent communication of change impacts (p. 141).

3. To select ECs more effectively, the numerical change propagation analysis could be used to prioritise changes which impose low risk to other parts over changes with high risk. Mr Harman suggested using the model for project size estimations and resource planning (p. 142).
4. To implement EC more efficiently, both the qualitative and quantitative change propagation analysis could be used to select between alternative solutions and develop implementation plans. Mrs Breton accentuated this application of the method (p. 145). Dr Paden and Mr Aldridge saw its potential for improving decision making in engineering design because the model captures tacit knowledge and makes it available for others (p.145 and p. 148).
5. To learn from the EC history for the future, the FBS Linkage model could be used to record EC cases including their propagation paths and apply the historic data to continuously update and improve the numeric network model. Mr Turner added that recording of ECs in such a systematic and detailed way is not the current practice today and thus would facilitate continuous improvement (p. 143).

In contrast to other existing network models of change propagation, particularly the single-layered models, the FBS Linkage network includes all relations between structural, behavioural, and functional elements and therefore avoids hidden dependencies. With the consideration of each additional information layer, more available links are revealed and more possible change propagation paths are taken into account (Subsection 7.4.3). Consequently, two elements cannot influence each other if there is no (direct and/ or indirect) link between them in the FBS Linkage model.

Furthermore, the FBS Linkage model allows analysis of the impact of different attributes, components, or functions on the overall change propagation network. For example, it can be calculated how the linkage values change when two functions are decoupled or a specific attribute of a component is frozen. The risk values can be aggregated at different levels of detail to assess change propagation between e.g. components or attributes. When the size of the MDM becomes too huge to be printed on a single page, such aggregated views can help to localise potential risks which can be further analysed by zooming-in gradually. For instance, if the designer wants to change a given attribute, the risk MDM could provide him with a prioritised list of affected components. In a second step, he could then zoom into more detailed views to understand the interdependencies. This would be especially useful for the components of medium significance as the designers are usually aware of impacts on core-components, at one end, and impacts on low significance components can be neglected, at the other end.

Moreover, the FBS Linkage model allows analysis of all different types of incoming change requests concerning functions, behaviours, structures or any relations between them. Finally, as the model allows a precise definition of structural elements, it provides an interface which can be linked to design tasks of the process domain for an integrated product-process ECM.

8.3.2 Effort of model building

Ideally, available product decompositions and FR models could be used as modelling aids for the FBS Linkage method and reduce the total modelling effort significantly. However, if the FBS Linkage model has to be developed from scratch, the modelling effort depends mainly on the selected level of decomposition and the complexity and architecture of the product. The first determines the number of elements (i.e. the size of the network or MDM) and the last two the actual number of links between those elements (i.e. the density of the network or MDM). The maximum modelling effort can be estimated based on the number of possible links. A general matrix suggests a quadratic relation between the number of its elements and the latter. However, as the FBS Linkage MDM is a block tridiagonal matrix, the number of possible links is less than suggested by its size because many cells are by definition empty, such as:

- The DMM blocks between the structural and functional layers are empty (see e.g. Figure 35), because there are no direct links between these layers.
- In the attribute-clustered MDM (see e.g. Figure 37b), the cells within the SS or BB DSMs but outside the attribute DSMs are empty due to the assumption that the attributes are independent from each other.
- In the component-clustered MDM (see e.g. Figure 37a), the cells within the SB and BS DMMs but outside the diagonals of the sub-DMMs are empty due to assumptions that structural attributes and behavioural attributes are only linked within components.

For the FBS Linkage MDM, the number of possible links n for a product with f functions, b behavioural attributes, s structural attributes, and c components is:

$$\begin{aligned} n &= f^2 + 2 \cdot f \cdot c \cdot b + c^2 \cdot b + 2 \cdot c \cdot b \cdot s + c^2 \cdot s - f - c \cdot b - c \cdot s \\ &= f^2 + 2 \cdot c \cdot b \cdot (f + s) + c^2 \cdot (b + s) - (f + c\,(b + s)). \end{aligned} \tag{1}$$

For the hairdryer above with $f=11$, $c=6$, $b=4$, $s=5$, this means: $n= 1{,}148$. Compared to the CPM model which has only $n=c^2-c=30$ possible links (*ca. 3%* of *1,148*), this seems to be much more work. However, it must be noted that the actual effort is much less than this comparison suggests due to five reasons:

1. In addition to the empty cells listed above, the FBS Linkage MDM includes many empty elements (corresponding lines and columns) that could be deleted but are kept to keep the MDM structure consistent and represent the possible solution space.
2. The FBS Linkage MDMs are less dense than CPM DSMs due to the attribute-level modelling, despite considering the reduced number of possible links from Equation 1. For instance, the hairdryer FBS Linkage model has an actual density of only *20%* (*224* actual links */ 1,148* possible links) compared to *73%* (*22* actual links / *30* possible links) of the CPM model.
3. Although the FBS Linkage model appears complex, the network can be constructed through a straightforward logical process once the functional block diagram and components have been identified. As the DSMs for the attributes as well as the DMMs for the links between them consider all dependencies explicitly, they can be filled in much faster than the DSM for CPM models where each link subsumes implicit dependencies. For the hairdryer, the stepwise model building technique was demonstrated in Section 6.6 and showed that the mappings can be built up fairly unambiguously by considering functions and their physical embodiment one-at-a-time.
4. The DSMs could be worked out relatively independently by different groups and thus increase efficiency and decrease lead time of model development.
5. Furthermore as discussed in Subsection 6.6.3, the symmetry assumption, the collective definition of the links between the structural and behavioural elements, and the use of standard values can lower the modelling effort significantly.

For the three examples presented in this thesis, the total effort of model building summed up to 6.0 person-hours for the hairdryer, 55 person-hours for the diesel engine, and 52 person-hours for the SEM. It is difficult to make any general estimations of the effort required to model other products, because the effort depends on the complexity and architecture of the specific product. However, using the number of determined components, a rule of thumb could be deduced based on the three examples presented here: 6 person-hours for 6 components (hairdryer), 55 person-hours for 41 components (diesel engine), and 52 person-hours for 28 components (SEM). This rule of thumb suggests:

The total FBS Linkage modelling effort in person-hours is between 1 and 2 times the number of components; for products of lower complexity such as a hairdryer, the effort is in the order of one person-day; and for products of medium to high complexity such as a diesel engine or a SEM, the effort is in the order of 10 person-days.

8.3.3 Weighing of benefits and effort

The FBS Linkage method combines the benefits of two established methods and can be used to support all five strategies of improving ECM. The modelling effort for products of medium to high complexity is in the order of 10 person-days and thus fairly reasonable. Furthermore, once an FBS Linkage scheme has been built, the effort to modify it to model other product variants is probably significantly less than the initial modelling effort. The vast majority of the components with their structural and behavioural attributes as well as the functions and accordingly the links between structural, behavioural, and functional elements presumably remain similar across product variants. Thus, only a few elements or links need to be changed, added, or dismissed. This is especially useful for platform based product families.

In conclusion, the benefits of the FBS linkage method outweigh the extra effort required to use it. This shows that ECM capability can be improved by the incorporation of structural, behavioural, and functional layers which essentially result in a more comprehensive product model and advance change propagation analysis and prediction. Thus, the research hypothesis can be accepted and the thesis achieved his objective to improve the quality of ECM.

8.4 Research limitations

A few methodological issues related to this research should be acknowledged as research limitations:

1. *Theoretical approach with initial industrial validation:* This research was undertaken as an academic research project within the EDC research group of University of Cambridge, independently from any industrial collaboration. As such, it was predominantly informed by literature and expertise from other researchers from the EDC and elsewhere. Direct industrial expertise from practitioners who actually deal with ECs was incorporated in a mostly complementary fashion. While the industrial collaborators of the EDC played a significant role in testing and evaluating the developed method, they did not determine the objectives and course of research. Therefore, the thesis might have underestimated or even missed out some practical issues and needs related to ECs. This limitation can be considered as a challenge of most theory-based research projects. It can be gradually overcome by applying the method to more case studies and improving it continuously to better meet industrial needs.
2. *Unavoidable subjectivity and inaccuracy during method development:* First, the proposed set of requirements was developed mainly based on literature and complemented through discussions with design researchers and the industry experts who supported the model building. The requirements were not evaluated in an industry context. Second, the comparative assessment of the ECM methods against the requirements was undertaken by the author based on the associated publications. The results were discussed with the co-supervisors of this thesis and revisions were made. Thus, the assessment involves both some unavoidable subjectivity and inaccuracy.
3. *Industrial implementation and evaluation of the developed method:* The industrial evaluation presented in this thesis was based on demonstrations of the method to industry experts. The method was not implemented in industry and the experts did not have a chance to apply the method themselves. In addition, only five industry experts evaluated the method. Therefore, this evaluation can only serve as an initial one. This is in line with the chosen DRM research type for this thesis. A complete evaluation of the FBS Linkage method in an industry context, ideally against the set of requirements, remains to be done.

4. *Applicability of the developed method to other products:* As stated in Chapter 1, the objects of investigation of this thesis were technical artefacts of medium to high complexity. Despite this focus, the FBS Linkage method might be applicable to a certain degree to non-technical artefacts but this was not tested in this thesis. Furthermore, the concept of the FBS Linkage method was developed based on the input of a limited number of products for which either FBS schemes or change models existed in the literature and in the EDC. For evaluation, the method was applied then to a diesel engine and a SEM, two fairly complex products of different industries: the diesel engine representing a mechanical artefact which operates in cycles to transform chemical energy into rotational and the SEM representing an electro-optical artefact which scans specimen with an electron beam to produce higher resolution images of its surface. However, there may still be products from other engineering fields or with higher degrees of complexity, to which the FBS Linkage model might not be applicable.

5. *FBS related limitations:* FBS modelling requires a profound understanding of the product, its working mechanisms, and physical dependencies between its attributes, and thus, might be very difficult and time consuming for some products. Despite the reasoning-based links between the FBS attributes, the accuracy of the model and its results depends on the availability of expertise to build such an FBS scheme. As discussed in Chapter 6, the three seminal three-layered FR schemes focus predominantly on products of low complexity and are not practicable for products of higher complexity where change propagation analysis is more relevant. Furthermore, the problematic concept of function in design might lead to different models for the same product. To reduce the complexity and potential ambiguity, a new, simplified ontology was proposed for the FBS Linkage model. This ontology provides a systematic basis which allows developing FBS Linkage models step by step and increases consistency. It focuses on technical functions and adapts the reconciled functional basis from Hirtz *et al.* (2002). However, it should be acknowledged that despite this, developing FBS schemes is not a straightforward task.

6. *CPM related limitations:* For numerical change prediction calculation, the FBS Linkage method applies the CPM procedure to the FBS scheme. CPM proceeds by quantifying the links in terms of direct likelihood and impact of change propagation and applying the Forward CPM algorithm to calculate combined risk of change propagation. Both steps are based on some assumptions which are important to

consider when eliciting the change likelihood and impact values. As these assumptions can be changed and do not limit the application of the FBS Linkage method but rather define prerequisites for change risk calculation, they can be regarded as soft limitations of the FBS Linkage method.

In the first step, the links are quantified based on expert estimations for generic change cases. Although, the subjectivity compared to CPM is reduced because the FBS links are more specific and based on reasoning, there is still a human-induced uncertainty factor involved in the quantities. Generic change cases are used instead of specific ones to avoid the high complexity of deterministic change propagation and prediction. Hence, the calculated change risks are probabilistic and might differ from actuals when the initiated and propagated changes differ significantly from the assumed generic changes.

In the second step, the Forward CPM algorithm presumes that the imposed risk to a target component is the product of combined change likelihood to the penultimate component and the direct change risk from the latter to the target component. Thus, whereas the change likelihood values are combined along the propagation path, only the direct change impact value from the penultimate to the target component is considered. This means in other words that change likelihood has a memory but change impact not. This is a very reasonable assumption that goes along with the presumption of generic change cases when eliciting the direct impact values but might need reconsideration if the way the links are quantified is refined. Furthermore, the combined likelihood is calculated by applying intersection and union operators along possible propagation trees under the exclusion of cyclic paths. Since cyclic change paths actually might exist – for instance, an initiated change to a source component might take a cyclic path and propagate back to its source – this makes only sense if the change impact values take the total impact including such cyclic paths into account. This assumption proved beneficial in CPM case studies. However, if cyclic paths need to be included in the calculations, modified matrix multiplications can be applied instead of the Forward CPM algorithm.

8.5 Opportunities for further research

Future work may include:

1. *Implementation into a software tool:* This research concentrated on the conceptual and detail design of the FBS Linkage method. For testing and application of the method to the case studies, different software programs were used for model building (i.e. Microsoft Excel and CAM), representation (i.e. Microsoft PowerPoint, yEd Graph Editor, and CAM), and calculation (i.e. CAM). As part of the method evaluation, an initial implementation of the method into CAM was successfully accomplished by an engineering master student. This CAM module can be further detailed and improved.
2. *Method applications to more industrial case studies:* For testing and evaluation purposes, the FBS Linkage method was applied to two case studies. For further evaluation and improvement, it must be applied to more industrial case studies. The method's implementation into a software program would facilitate such case studies and help continuous improvement and industrial acceptance of the method.
3. *Full industrial evaluation of FBS Linkage:* Ideally, the evaluation of predictive methods such as FBS Linkage is performed in practice based on real data. This could be accomplished by implementing the method within a company, applying it to day-to-day change cases, and contrasting the outcome against the situation without the tool. That way not only the feasibility and performance of the tool can be evaluated but also its usability in real-life conditions. This thesis presented detailed results of an initial evaluation, which overall indicated that the method improves upon CPM and laid the foundation for further improvement. However, a full industrial evaluation of the FBS Linkage method remains essential for future work.
4. *Considerations of frozen parts and tolerance margins:* The models developed in this thesis represent general designs of the products and not a certain design status. Therefore, they do not include any frozen parts and tolerance margins but show all possible change propagation paths. Frozen parts and tolerance margins decrease the number of possible propagation paths. Frozen design parts (i.e. attributes, components, or functions) cannot be changed and represent fixed nodes in the FBS network where possible change propagation paths come to a halt. Tolerance margins may have similar effects dependent on the change magnitude. The FBS Linkage model with its attribute network provides a good basis for exploring the influence of frozen parts and tolerance margins on change propagation.

5. *Automated sending of change notifications:* During the evaluation, the Technical Leaders at Ford Engine Centre emphasised the use of the FBS Linkage method as a communication support in a multinational company by flagging up changes to globally organised designers. This requires the assigning of designers to the FBS elements or components and the automated sending of change notifications to them, when they might be affected by propagated changes. The rules, when a change notification should be sent, and the technical details need to be investigated before it can be implemented in the software tool as an automated feature.

6. *Automation of model building:* The models in this thesis were manually built and mostly created from scratch. The required information was gathered from technical product documentations and expert interviews. Techniques which facilitate or even partly automate information gathering and model building can significantly reduce the model building effort. These may include knowledge-based techniques which use information from existing models to support building of new models as well as automated reading and analysing of technical documents. In this context, building a repository of FBS Linkage models may be very helpful. It could be investigated whether the *Design Repository* of the Design Engineering Lab at Oregon State University could be used for this purpose.

7. *Automated learning and improving of models:* For change prediction to work effectively, one of the evaluators at Ford recommended *"that the model is linked to real data to continually update and learn as it is being used, based upon actual events."* Once the initial model is in place, it could be used to record actual change propagation paths and apply that data to update the linkages and correlate the model to reality. Such an automated learning and continuous improvement of the models needs to be studied first.

8. *Sensitivity analysis:* As discussed under the limitations of this research, two challenges of the FBS Linkage method are: the subjectivities attached to the two steps of functional modelling and links quantification. The former might lead to different FBS schemes for the same product and the latter to different weighting of the links. Therefore, it would be interesting to explore the sensitivity of the results of the method to both uncertainty factors.

9. *Consideration of other design domains:* The focus of this work has been on the product domain, where ECs propagate between structural, behavioural, and functional attributes and affect different parts of a product. The product domain is considered as

crucial for understanding, modelling, and predicting change propagation, and thus, the subject of most of the ECM publications. However, when it comes to the implementation of ECs, the design process domain is affected as well. ECs are implemented by coordinated tasks and assigned resources. This might require other tasks to be rescheduled and impact other projects. An integrated product-process change propagation model would support holistic decision making in a multi-project environment. The FBS Linkage model provides a potential basis to help with integrated modelling by including additional process layers to the model. For instance, a design task layer could be added below the structural layer to the FBS network. As only structural attributes are explicit, and thus, directly manipulated to achieve the required behaviours and functions, the task layer needs to be connected only to the structural layer. Structural attributes can then be defined as deliverables of the tasks. Consequently, this can be extended to consider resources and other projects.

10. *Alternative uses of FBS Linkage:* The FBS Linkage models developed in this research were used for change propagation analysis. It has been argued that such models can be used beyond that for a variety of other purposes for which FR models are typically used, such as knowledge representation of systems to support design automation and process management. Moreover, the FBS models developed here provide a rich representation of the product architecture, and thus, could be applied to optimise it. The application of FBS schemes for robust product architecture development is a neglected but very promising research area that could be further explored.

11. *Integration of the FBS Linkage method with computer aided design (CAD) programs*: The integration of the FBS Linkage method into a 3D CAD program would help to increase the accessibility and acceptance of the approach as well as the usage of its results. This possibility was not investigated in this Ph.D. thesis and would require additional research.

12. *Industrial evaluation of requirements for ECM methods:* The developed set of requirements was not evaluated. An industrial evaluation of the requirements would add significant value to research on ECM and facilitate the development of enhanced methods.

13. *More rigorous ranking of ECM methods:* Possibilities to extend and improve the comparative scoring of different ECM methods could be explored, and a more rigorous ranking developed to support method selection in industry.

8.6 Concluding remarks

ECs are essential for complex designs and their management is important to the commercial success of products. This thesis aimed to improve ECM by developing a method which supports early detection of ECs and effective and efficient decision making to handle them.

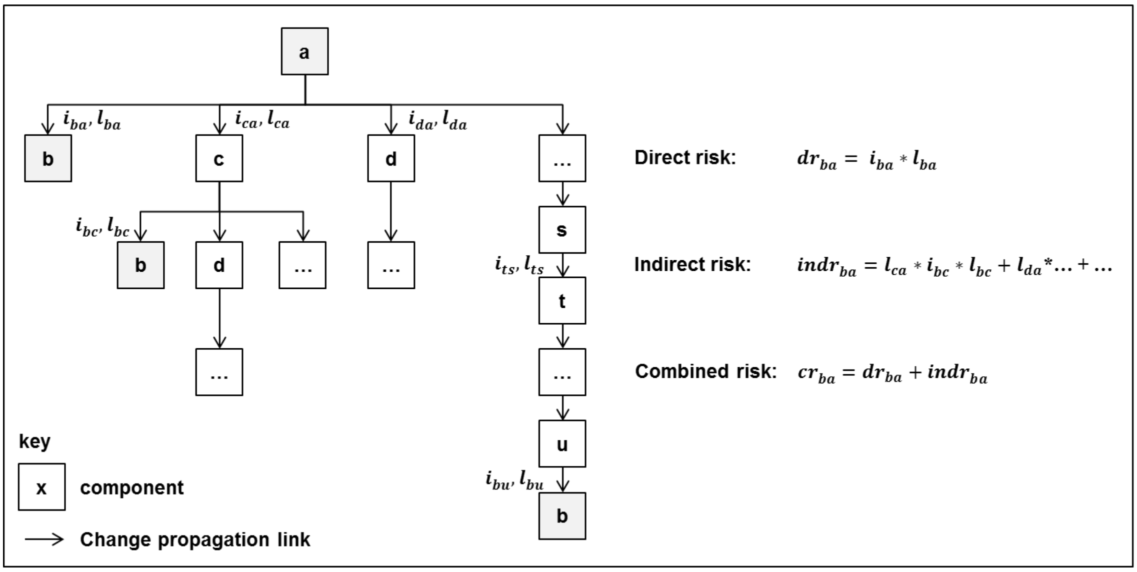
Based on a comprehensive analysis of the state-of-the-art of research in ECM, the thesis contributed a set of requirements for ECM methods and followed a benchmarking approach to develop a concept for an enhanced ECM method. This concept was then detailed into the FBS Linkage method. The application of this novel method to two industrial case studies and its evaluation based on that was successful and insightful. A number of advantages of the method were highlighted and further improvements were suggested.

The author is convinced that this thesis advances the current understanding of ECs and trusts that the FBS Linkage method has the potential to improve current practice of ECM and provides promising opportunities for further research and development.

Appendix

Appendix 1: Forward CPM algorithm (Clarkson et al. 2004)

The Forward CPM algorithm calculates the combined risk of change propagation from component **a** to component **b** as follows:



$$cr_{ba} = 1 - \prod_{u} (1 - cr_{bu}),$$

where
$$cr_{bu} = cl_{ua}\, l_{bu}\, i_{bu}$$

and
$$cl_{ua} = 1 - \prod_{p(a \to u)} \left(1 - \prod_{ts} (l_{ts})\right).$$

Indices: ***a*** – change initiating component (sender)

b – change propagation affected component (target)

p – propagation path from sender to target

s,t – components in the propagation path; component **s** is a predecessor to **t**

u – penultimate component in the propagation path from component ***a*** to ***b*** (intermediate)

Variables: ***cl*** *– combined likelihood*

cr *– combined risk*

i *– direct impact*

l *– direct likelihood*

Appendix 2: Rating and rationales of the method from *Chen & Li* (see e.g. Li and Chen 2010)

No	Category	Requirement name	*Chen & Li* score	Rationale for *Chen & Li* score
1	1. Input related (scope/ feasibility)	Range of products covered	4	broad; applied on air-cooled condenser; potentially applicable to more complex products; requires a design dependency matrix (DDM) which captures the relations between functions and parameters
2		Range of levels of decomposition supported	3	captures functions and parameters; hierarchical decomposition not explicitly supported
3		Range of different changes covered	4	changes to functions/requirements and parameters, where the latter describes the physical constituents and/or behavioural properties of concern for a design; magnitude of changes not considered
4	2. Model building	Ease of model building	3	average; DDM can only be built by an expert and could be very complicated
5		Availability of information to build the model	3	average; DDM requires a huge amount of information
6		Accessibility of tools to build the model	4	any tools to capture matrices for relations; storing of proactive patterns require matrix manipulation algorithms which need software support; Matlab-based software available
7		Accuracy	4	high; expert estimations with rationales based on parameter relations
8		Consistency	3	average; not clear how to model functions and which parameters to use, this could cause inconsistencies
9		Adaptability	4	high; existing models can be used to a certain extent and need to be manually modified to adapt to other products
10		Benefit-to-cost ratio of model building	3	medium benefit (i.e. DMM provides function-parameter relations) at low to medium cost (much information but no programming or buying of tools needed)
11	3. Model use	Ease of model use	3	average; determine function or parameter to be changed, apply decomposition, select pattern, select redesign strategy
12		Accessibility of tools to use the model	4	Matlab-based software available for free
13		Practicality	4	high; when a function or parameter change is requested, the method suggests redesign strategies based on decomposition patterns in DDM
14		Flexibility	3	average; DDM needs to be changed or defined for new components and calculations and proactive patterns updated
15		Benefit-to-cost ratio of model use	4	high benefit (change strategies, solution support etc.) and medium (moderate effort to generate change strategies and evaluate results if software available for free)
16	4. Output related (results)	Utility of results	4	high; redesign strategies could be useful for decision making and efficient change management
17		Quantity of results	3	average; only redesign patterns and strategies; no further change propagation analyses
18		Quality of results	-	not assessable
19	5. Model related (capability/ function-ality)	Product modelling capability	3	average; DDM with function-parameter relations and decomposition patterns
20		Change modelling capability	2	rather poor; change propagation only between parameters and functions but not within each of these domains
21		Change prediction capability	2	rather poor; limited to changes between parameters and functions; manual analysis using design dependency matrix
22		Change containment capability	5	very good; decomposition patterns help to limit change propagation within blocks (i.e. sub-problems)
23		Solution finding capability	5	very good; redesign strategies; sub-problems with low interaction; identifies parameters that need to be changed to meet new requests
24		Numerical analysis capability	2	rather poor; limited to binary matrices
25		Compatibility	3	average; matrix-based results could be used in other tools

Appendix 3: Rating and rationales of *RedesignIT* (Ollinger and Stahovic 2004)

No	Category	Requirement name	*Rede-signIT* score	Rationale for *RedesignIT* score
1	1. Input related (scope/ feasibility)	Range of products covered	4	broad; applied on diesel engine; potentially applicable to more complex products
2		Range of levels of decomposition supported	2	only one level; 'quantities' may refer to components, attributes, behaviours, or flows; hierarchical decomposition not explicitly supported
3		Range of different changes covered	3	all changes affecting 'quantities'; changes to functions must be translated to 'quantity' changes; magnitude of changes not considered
4	2. Model building	Ease of model building	3	average; quantities, their constraints, and relations need to be mapped; not clear how to select quantities
5		Availability of information to build the model	3	average; expert interviews; detailed information needed; limited use of available documentation
6		Accessibility of tools to build the model	3	graphs require graphic editor software
7		Accuracy	4	high; expert estimations with causality as rationale
8		Consistency	3	average; causality assures consistency; not clear which quantities, constraints, and relations to include
9		Adaptability	4	high; existing models can be used to a certain extent and need to be manually modified to adapt to other products
10		Benefit-to-cost ratio of model building	3	high benefit (causal product model etc.) and medium cost (much information is needed and potentially buying of a graphic editor software)
11	3. Model use	Ease of model use	4	easy; identify the quantity to be changed, run program, choose proposed change options
12		Accessibility of tools to use the model	1	RedesignIT computer program not available (no link in paper, Google search shows no results)
13		Practicality	3	average; the model generates abstract change plans to further analyse change impacts
14		Flexibility	3	average; quantities, their constraints, and relations can be modified, added ,or deleted
15		Benefit-to-cost ratio of model use	4	high benefit (change prediction, solution support etc.) and medium to low cost (relatively low effort to evaluate change plans if software available for free)
16	4. Output related (results)	Utility of results	3	average; change plans can support decision making, but very abstract plans
17		Quantity of results	3	average; abstract change plans, possibly cost and benefit calculation
18		Quality of results	-	not assessable
19	5. Model related (capability/ function-ality)	Product modelling capability	4	good; causal product model; high level only
20		Change modelling capability	3	average; causal change propagation along links between quantities; quantities only
21		Change prediction capability	3	average; causal change propagation along links between quantities; but no consideration of indirect change impacts over several steps
22		Change containment capability	5	very good; causality and proposed change plans support containment
23		Solution finding capability	4	good; abstract change plans as solutions
24		Numerical analysis capability	2	rather poor; change plans generated (implicitly) by cost and benefit comparison, but no numeric analysis provided
25		Compatibility	2	rather poor; presumably limited; not specified in the paper

Appendix 4: Rating and rationales of the method from *Rouibah & Caskey* (2003)

No	Category	Requirement name	*Rouibah & Caskey* score	Rationale for *Rouibah & Caskey* score
1	1. Input related (scope/ feasibility)	Range of products covered	3	average; applied on railcar bogie; but limited to medium complexity due to high number of parameters
2		Range of levels of decomposition supported	3	components and parameters
3		Range of different changes covered	4	all changes affecting parameters; changes to functions and behaviours must be translated to parameter changes; magnitude of changes considered
4	2. Model building	Ease of model building	2	rather complicated; complicated mapping of parameters, their relations, corresponding product parts, and responsible people; difficult to determine relevant parameters and develop parameter network
5		Availability of information to build the model	3	average; expert interviews; detailed information required; limited use of available documentation
6		Accessibility of tools to build the model	3	any tools to capture DSMs for parameter network, but necessary graphs require graphic editor software
7		Accuracy	4	high; expert estimations with rationales based on parameter relations
8		Consistency	3	average; not clear which parameters to include; parameter relations might be inconsistence
9		Adaptability	3	average; potentially many parameters and parameter relations need to be re-defined to adapt to other products
10		Benefit-to-cost ratio of model building	3	high benefit (parameter network, transparency among collaborators etc.) and medium cost (much information is needed and potentially buying of a graphic editor software)
11	3. Model use	Ease of model use	3	average; identify initial parameter to be changed, inform responsible designers of neighbouring parameters which are possibly affected by the initial change, approve and release changes jointly
12		Accessibility of tools to use the model	1	the software is not available (unpublished company property); for implementation a product data management (PDM) system is required
13		Practicality	4	high; when a parameter changes, the model supports its implementation and sends notices to responsible designers of neighbouring parameters to analyse potential impacts
14		Flexibility	3	average; parameter network can be up-dated to a certain extent
15		Benefit-to-cost ratio of model use	3	medium benefit (parameter network, change notice to responsible designers of potentially affected neighbouring components etc.) and medium cost (moderate amount of manual analysis required if software available for free)
16	4. Output related (results)	Utility of results	3	average; automatically generated notices to responsible designers of neighbouring parameters to check for potential impacts
17		Quantity of results	2	rather low; only change notices
18		Quality of results	-	not assessable
19	5. Model related (capability / function-ality)	Product modelling capability	4	good; component-parameter-people model
20		Change modelling capability	4	good; change propagation along all possible parameter links; change propagation along components considered only indirectly
21		Change prediction capability	3	average; potential impact of changes on neighbouring parameters; only directly neighbouring parameters considered at each step; impact needs to be manually evaluated
22		Change containment capability	3	average; parameter relations could be used as change rationale for control and containment of changes
23		Solution finding capability	3	average; the parameter network could be used to find solutions for changes
24		Numerical analysis capability	1	no numerical analysis supported
25		Compatibility	3	average; possibly compatible with product data management system

Appendix 5: Rating and rationales of the *Reddi & Moon 1* method (Reddi and Moon 2009)

No	**Category**	**Requirement name**	***Reddi & Moon 1* score**	**Rationale for *Reddi & Moon 1* score**
1	1. Input related (scope/ feasibility)	Range of products covered	2	rather narrow; applied on electric toothbrush only; probably limited to low to medium complexity due to the high number of paths to be considered
2		Range of levels of decomposition supported	3	components and attributes; hierarchical decomposition not explicitly supported
3		Range of different changes covered	3	all changes affecting structural attributes; changes to functions and behaviours must be translated to attribute changes; magnitude of changes not considered; even though the authors limit its application to after release phase, the model could be applied also during design phase
4	2. Model building	Ease of model building	3	average; a list needs to be elicited with initiator, initiator type, target, target type, likeliness for all possible combinations
5		Availability of information to build the model	3	average; required information filled in by designers during design phase; dependent on the number of types of changes (TOCs), the amount of information can be expensive; limited use of available documentation
6		Accessibility of tools to build the model	4	any spreadsheet program can be used to build the list
7		Accuracy	4	high; expert estimations with rationales based on attribute relations
8		Consistency	3	average; pairwise linkage building; definition of types of changes (TOCs) can produce inconsistencies
9		Adaptability	2	rather low; representation in lists impede adaptability; potentially modelling from scratch is better than re-use of models
10		Benefit-to-cost ratio of model building	3	medium benefit (a list with all possible links between types of changes etc.) and medium cost (much information but no programming or buying of tools needed)
11	3. Model use	Ease of model use	4	easy; identify the component and type of change, run program, notifications send by the system to responsible people to check affected attributes
12		Accessibility of tools to use the model	2	the presented software program is not available (no link in paper, Google search shows no results); a tool could be programmed in a spreadsheet program
13		Practicality	3	average; when an attribute is changed, the program produces a list of all potential affected attributes in multiple levels; for complex products this list might be too long; no calculation of combined likeliness values
14		Flexibility	3	average; can be updated by changing the lines in the list
15		Benefit-to-cost ratio of model use	3	medium benefit (identifies a long list of potentially affected attributes) and medium cost (moderate amount of manual analysis required if software available for free)
16	4. Output related (results)	Utility of results	3	average; multi-level change propagation tree on component level; notice to responsible designers of all affected attributes to check for potential impacts
17		Quantity of results	2	rather low; no numerical results and analyses
18		Quality of results	-	not assessable
19	5. Model related (capability / function-ality)	Product modelling capability	3	average; attribute-component-component model; difficult for complex products
20		Change modelling capability	4	good; change propagation along all possible attribute links
21		Change prediction capability	4	good; change prediction considering all direct and indirect links between attributes and components
22		Change containment capability	3	average; attribute relations could be used as change rationale for control and containment of changes
23		Solution finding capability	2	rather poor; the attribute-component-component graphs could be used to find solutions for changes, but difficult
24		Numerical analysis capability	1	no numerical analysis supported
25		Compatibility	3	average; possibly compatible with spreadsheet programs

Appendix 6: Rating and rationales of *C-FAR* (Cohen et al. 2000)

No	Category	Requirement name	*C-FAR* score	Rationale for *C-FAR* score
1	1. Input related (scope/ feasibility)	Range of products covered	3	average; applied on bottle, car bumper, injection moulding etc.; but limited to medium complexity due to the intense amount of data and calculations
2		Range of levels of decomposition supported	4	systems, components, and attributes
3		Range of different changes covered	3	all changes affecting attributes; changes to functions and behaviours must be translated to attribute changes; magnitude of changes not considered
4	2. Model building	Ease of model building	2	rather complicated; complicated entity relations and matrices (C-FAR matrix, Semi-C-FAR matrix)
5		Availability of information to build the model	3	average; expert interviews; detailed information; limited use of available documentation (EXPRESS schema)
6		Accessibility of tools to build the model	4	any tools to capture matrices, but (optional) graphs require graphic editor software
7		Accuracy	4	high; expert estimations with rationales based on attribute relations
8		Consistency	3	average; pairwise linkage building; not clear which attributes to include; change receiver vector could be inconsistence
9		Adaptability	4	high; existing models can be used to a certain extent and need to be manually modified to adapt to other products
10		Benefit-to-cost ratio of model building	2	high benefit (change model, product model, communication support etc.) and very high cost (extensive information and potentially a graphic editor software is needed)
11	3. Model use	Ease of model use	1	very complicated; identify source and target, identify path, multiply matrices along the path
12		Accessibility of tools to use the model	2	no tool available (no link in paper, Google search shows no results); matrix multiplication software needed for semi-manual use instead
13		Practicality	2	rather low; shows possible propagation paths and helps to calculate impact along selected paths
14		Flexibility	3	average; linkage values need to be changed or defined for new components and calculation renewed
15		Benefit-to-cost ratio of model use	2	moderate benefit (calculates impacts on pre-selected targets) and high effort (much effort required to select targets and use method if software available for free)
16	4. Output related (results)	Utility of results	2	rather low; change path depiction and impact estimation for source-target selection; no critical paths etc.
17		Quantity of results	2	rather low; only impact estimations for selected paths; only one change at a time
18		Quality of results	-	not assessable
19	5. Model related (capability/ function-ality)	Product modelling capability	3	average; attribute-component product model; difficult for complex products
20		Change modelling capability	3	average; change propagation along links between attributes, but only for pre-selected path
21		Change prediction capability	3	average; change prediction considering multiple indirect links, but only for selected paths
22		Change containment capability	3	average; attribute relations could be used as change rationale for control and containment of changes
23		Solution finding capability	3	average; the attribute relation graphs could be used to find solutions for changes
24		Numerical analysis capability	5	very good; numerical linkage values and algorithm for change impact calculation
25		Compatibility	3	average; possibly compatible with EXPRESS based tools

Appendix 7: Rating and rationales of the method from *Ma et al.* (2008)

No	Category	Requirement name	***Ma et al.* score**	**Rationale for *Ma et al.* score**
1	1. Input related (scope/ feasibility)	Range of products covered	2	rather narrow; applied on the cooling system design and ejection system design in an injection mould assembly; probably not applicable on complex products
2		Range of levels of decomposition supported	2	hierarchical decomposition not explicitly supported, but implicitly in the context of conceptual design and detail design
3		Range of different changes covered	5	all kind of possible changes to any entity, i.e. functions, behaviours, features, components, attributes, constraints; magnitude of changes considered
4	2. Model building	Ease of model building	2	rather complicated; building of a dependency network is very complicated and not sufficiently described
5		Availability of information to build the model	2	rather low; Justification-based Truth Maintenance System (JMTS) dependency network includes a huge number of different elements and requires extensive information, which is partly not available for a product; limited use of available documentation
6		Accessibility of tools to build the model	2	the dependency network can be developed using a graphic editor, but the complete model requires UML programming; the tool used is not accessible
7		Accuracy	2	rather low; the dependency network can be very subjective and inaccurate
8		Consistency	2	rather low; consistency of parameter network not sufficiently assured, only partly due to causality of links
9		Adaptability	2	rather low; dependency network is very product specific and probably not adaptable; adaptability is not shown
10		Benefit-to-cost ratio of model building	2	medium benefit (graphical representation of entities and relations but possibly not very accurate etc.) and high cost (much information and programming of tools are needed)
11	3. Model use	Ease of model use	4	easy; identify initial element to be changed, run program, select solution
12		Accessibility of tools to use the model	2	no tool available (no link in paper, Google search shows no results); change propagation algorithm described for implementation in a program; solution selection procedure not described
13		Practicality	3	average; when an element is changed, the program identifies affected elements based on the dependency network; it is not clear if the program can suggest solutions
14		Flexibility	3	average; probably changeable to keep up-to-date, but with a certain amount of effort
15		Benefit-to-cost ratio of model use	4	high benefit (change prediction, solution support etc.) and low cost (low effort if software available for free)
16	4. Output related (results)	Utility of results	3	average; changed elements in the parameter network
17		Quantity of results	2	rather low; only affected elements; no other analyses
18		Quality of results	-	not assessable
19	5. Model related (capability/ function-ality)	Product modelling capability	3	average; Justification-based Truth Maintenance System-based dependency model including elements from different design stages; difficult for complex products
20		Change modelling capability	4	good; changes along different interrelated elements in the dependency network
21		Change prediction capability	4	good; JTMS-based dependency network and change propagation algorithm conduct complete search in the whole dependency network for all affected elements
22		Change containment capability	4	good; causal relations in the dependency network can help to contain changes
23		Solution finding capability	4	good; dependency network with constraints can be used to support solution finding; it is not clear whether the prototype program supports solution finding already
24		Numerical analysis capability	1	not supported
25		Compatibility	3	average; possibly compatible with UML-based tools

Appendix 8: Rating and rationales of *ADVICE* (Kocar and Akgunduz 2010)

No	Category	Requirement name	*ADVICE* score	Rationale for *ADVICE* score
1	1. Input related (scope/ feasibility)	Range of products covered	2	rather low; only applied on a table; probably not applicable on more complex products
2		Range of levels of decomposition supported	4	product, component, and attribute using the BOM structure
3		Range of different changes covered	3	changes to explicit and implicit attributes of components; changes to functions need to be translated into these; magnitude of changes not considered
4	2. Model building	Ease of model building	2	rather complicated; complicated set up of all parts, e.g. prioritisation agent, propagation agent
5		Availability of information to build the model	3	average; extensive information needed for prioritisation and propagation agent; use of available information possible from BOM, CAD, user entry, change database; the latter might not be available
6		Accessibility of tools to build the model	2	expensive tools required and not accessible, i.e. virtual reality platform, 3D CAD, data mining software
7		Accuracy	3	average; accuracy probably average as it depends on many factors, such as expert estimations, BOM, CAD, and data mining quality
8		Consistency	4	high; consistency based on BOM and CAD information used
9		Adaptability	3	average; potentially much content of the model has to be re-done
10		Benefit-to-cost ratio of model building	2	medium benefit (graphical representation, data mining etc.) and high cost (much information and programming tools are needed)
11	3. Model use	Ease of model use	3	average; requires much input from the co-ordinator (e.g. priority index if missing, change propagation evaluation)
12		Accessibility of tools to use the model	1	ADVICE computer program is not available (no link in paper, Google search shows no results)
13		Practicality	3	average; change prioritisation and graphical representation useful; interactive; supports the whole EC lifecycle; but much manual input/evaluation required
14		Flexibility	3	average; probably changeable to keep up-to-date, but with a certain amount of effort
15		Benefit-to-cost ratio of model use	3	medium benefit (supports communication, graphical representation, data mining etc.) and medium cost (moderate amount of manual analysis required if software available for free)
16	4. Output related (results)	Utility of results	3	average; change prioritisation and sending of notifications; could be depicted more clearly
17		Quantity of results	3	average; only priority lists, patterns, and notices; no further graphics and analyses
18		Quality of results	-	not assessable
19	5. Model related (capability/ function-ality)	Product modelling capability	2	rather poor; BOM and CAD based model; no new insights
20		Change modelling capability	3	average; can capture change details and patterns, but does not show how changes propagate through the product
21		Change prediction capability	2	rather poor; prediction capability depends on historic change data and quality of data mining
22		Change containment capability	2	rather poor; no rationale of change propagation within the model; requires expert knowledge for control of propagation
23		Solution finding capability	1	very poor; no solutions provided
24		Numerical analysis capability	3	average; priority indices; uses probabilities and impacts from CPM, but not further elaborated
25		Compatibility	3	average; possibly compatible with BOM and CAD; but no PLM yet

Appendix 9: Hairdryer risk matrices calculated considering different numbers of layers

Direct risk		Maximum values within the structural layer					
Component	**No**	**1**	**2**	**3**	**4**	**5**	**6**
Fan	**1**		30		50		
Motor	**2**	30			50	30	
Heating unit	**3**				50	30	
Casing	**4**	50	50	50		30	50
Control unit	**5**		30	30	30		30
Power supply	**6**				50	30	

Forward CPM(S)		Maximum values within the structural layer					
Component	**No**	**1**	**2**	**3**	**4**	**5**	**6**
Fan	**1**		52	37	60	41	37
Motor	**2**	50		41	65	52	41
Heating unit	**3**	37	43		59	50	38
Casing	**4**	59	64	58		58	58
Control unit	**5**	39	51	48	59		48
Power supply	**6**	37	43	38	59	50	

Forward CPM(BS)		Maximum values within the structural layer					
Component	**No**	**1**	**2**	**3**	**4**	**5**	**6**
Fan	**1**		61	59	70	50	43
Motor	**2**	59		62	75	59	46
Heating unit	**3**	56	62		76	60	47
Casing	**4**	67	72	74		64	59
Control unit	**5**	50	60	62	68		51
Power supply	**6**	46	51	53	62	54	

Forward CPM(FBS)		Maximum values within the structural layer					
Component	**No**	**1**	**2**	**3**	**4**	**5**	**6**
Fan	**1**		73	75	85	56	47
Motor	**2**	75		74	86	63	48
Heating unit	**3**	78	73		86	64	50
Casing	**4**	83	81	82		66	59
Control unit	**5**	62	66	68	74		52
Power supply	**6**	57	55	59	62	55	

Appendix 10: Diesel engine risk matrices calculated considering different numbers of layers

Direct risk		Maximum values within the structural layer																																								
Component	**No**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**
Cylinder Head Assembly	1		18	1			9		2		1	5	2	3										1		4	1	1			3				2		4		1	2	2		1
Cylinder Block Assembly	2	18		1	24	5	6	1	2			2		3			1			1	1	3		1		1			1	6	2	1											0
Piston Rings Gudgeon Pin	3	2	2		1	5	6						25																														
Conn Rod	4		6	5		2		8																								4											
Crankshaft Main Bearings	5		3	6	2										0					1			0						1		1	4											
Valve Train	6	2	4	6					1				25																														
Cam Shaft	7		2		8																								1														
Push Rods	8	5	14				0																																				
High Pressure Fuel Pipes	9	1	10								9	1	1									12																1	4	8		4	
Electric Control Module	10	4								5		6																		4					1			6				4	
Fuel Pump	11	5	3								10																		3		1								6				
Fuel Injection Assembly	12	4		4			3																																	10			
Adapter Plate / Flywheel Housing	13	2	2												3	4	3																										
Flywheel Ring Gear	14					1										1																											
Starter Motor	15		9												1						3																						
Sump	16		2		1	4								8																	3	6											
Oil Filler	17										2																				1										1		
Engine Breather	18	4	9								1																								2								
Oil Pump	19		2			1																							1			3											
Oil Filter	20		1													3																							6				
Oil Cooler	21	3	5							1	1																																
Crank Pulley Damper Belt	22					2																		0				1			4												
Fan Drive	23		1																				1		1	2					2												2
Fan Extension	24																							1							1												
Coolant Pump	25	2	2																					3					1		2												
Alternator Bracket	26	1																													1						1						
Belt Driven Auxiliary (Hydraulic Pump	27	3										4											1								1												
Gear Train	28		0			2		0				2								1						1				1	8	1											
Gear Driven Auxiliary (Compressor)	29		6									7																	1		1							2					
Timing Case	30	2	2			1						1					4						3	3	2	3	1	1	4	2													
Balancer	31		1		3	8											6			6									1														
Turbocharger	32		3																															2			2					6	
Aircharge Cooler	33																																4		0								
Air Intake	34	5																	3															1									
Air Filter	35	1																																									
Exhaust Manifold	36	3																															1										
Low Pressure Fuel System	37		2							1		5									2									2									2				
Fuel Filter	38	1								1	9										6																						
Starting Aid	39	3								4			6																													1	
Lifting Eyes	40	1																2																									
Wiring Harness	41	1	1								8	6				3											2						3		2					2			
Radiator	42	1	0																					2																			

Forward CPM(S)		Maximum values within the structural layer																																								
Component	**No**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**
Cylinder Head Assembly	1		18	7	10	11	9	5	4	3	6	10	8	5	2	2	4		1	5	3	2	3	6	2	8	2	3	7	7	10	6	1		2		4	4	4	4	2	2	3
Cylinder Block Assembly	2	18		12	28	14	12	7	4	3	6	8	14	5	2	2	4			6	2	3	3	6	2	5	2	3	7	9	8	7	1		2		4	4	4	6	4	2	3
Piston Rings Gudgeon Pin	3	15	15		11	13	15	5	4	3	6	8	30	4	2	1	3		1	5	2	2	3	7	2	6	2	3	6	6	9	6	1		2		3	3	4	9	1	2	4
Conn Rod	4	10	11	6		10	7	10	3	2	4	6	8	3	1	1	3			5	2	1	3	5	2	5	2	2	6	5	7	8			1		2	2	3	3	1	1	3
Crankshaft Main Bearings	5	9	10	8	8		7	4	2	2	4	5	8	3	1	1	3			4	2	1	2	5	1	4	1	2	4	4	6	7			1		2	2	2	3		1	3
Valve Train	6	17	16	13	12	12		5	4	4	6	9	30	4	1	1	4		1	5	3	2	3	8	2	6	3	3	7	6	9	7	1		2		3	3	4	9		2	4
Cam Shaft	7	6	6	4	10	6	4		1	1	2	3	5	2	1		2			3	1	1	1	3	1	2	1	1	4	3	4	3			1		1	1	1	2		1	2
Push Rods	8	18	19	11	14	15	12	7		4	7	10	14	5	2	2	5		1	7	3	3	4	9	3	8	3	4	8	8	11	8	1		2		4	4	5	6		2	5
High Pressure Fuel Pipes	9	24	25	14	18	18	15	8	6		18	17	18	7	2	3	6		1	9	6	14	5	12	3	10	4	5	11	12	14	10	2	1	4		5	9	11	15		8	6
Electric Control Module	10	14	14	8	10	11	9	5	3	6		13	10	4	1	2	3		1	5	4	3	3	7	2	6	2	3	7	10	9	6	1		2		3	8	6	5		4	4
Fuel Pump	11	15	15	9	11	11	10	5	4	6	13		11	4	1	2	3		1	5	4	3	3	7	2	6	2	3	7	7	8	6	1	1	3		3	7	9	6		4	4
Fuel Injection Assembly	12	9	9	8	7	7	8	3	2	3	4	5		2	1	1	2			3	2	2	2	4	1	3	1	2	4	4	5	4	1		1		2	2	2	11	1	2	2
Adapter Plate / Flywheel Housing	13	6	6	4	5	5	4	2	1	1	2	3	5		4	4	4			3	1	1	1	3	1	3	1	1	3	3	4	3			1		1	1	2	2		1	2
Flywheel Ring Gear	14	1	1		1	1							1			1																											
Starter Motor	15	10	10	6	8	8	6	4	2	2	4	5	7	3	2		2			4	5	1	2	5	1	4	1	2	5	4	6	4			1		2	2	3	3		1	3
Sump	16	12	13	8	12	13	8	5	3	2	5	7	9	10	2	2				6	2	2	3	6	2	6	2	3	7	6	9	11			1		2	2	3	4		1	3
Oil Filler	17	2	3	1	2	2	1	1	1	1	2	2	2	1			1			1	1		1	1		1			1	1	2	1						1	1	1	1	1	1
Engine Breather	18	14	14	8	11	11	9	5	3	3	6	8	11	4	1	1	3			5	3	2	3	7	2	6	2	3	6	6	8	6	1	1	4		3	3	4	5		2	4
Oil Pump	19	4	4	3	4	4	3	2	1	1	2	2	3	1	1		2				1	1	1	2	1	2	1	1	3	2	3	4					1	1	1	1			1
Oil Filter	20	4	4	2	2	2	2	1	1	2	3	3	2	1	1	3	1			1		1	1	2		1	1	1	2	2	2	1			1		1	1	6	1		1	1
Oil Cooler	21	9	9	6	7	7	6	3	2	3	5	6	7	3	1	1	2			4	2		2	5	1	4	1	2	4	4	6	4			1		2	3	3	4	1	1	3
Crank Pulley Damper Belt	22	4	5	3	4	4	3	2	1	1	2	2	3	1	1		1			2	1	1		3	1	2	1	1	2	3	5	2					1	1	1	1			1
Fan Drive	23	4	5	3	3	4	3	2	1	1	2	3	3	1			1			2	1	1	1		2	4	1	1	2	2	4	2			1		1	1	1	1			3
Fan Extension	24	1	1	1	1	1	1					1	1											1		1			1	1	1												
Coolant Pump	25	6	7	4	5	5	4	2	2	1	3	4	5	2	1	1	2			3	1	1	2	6	2		1	2	4	3	5	3			1		1	1	2	2		1	2
Alternator Bracket	26	2	2	1	1	1	1	1			1	1	1							1				1		1			1	1	1	1					1			1			
Belt Driven Auxiliary (Hydraulic Pump	27	6	7	4	5	5	4	2	1	2	4	6	5	2	1	1	1			2	1	1	2	3	1	3	1		3	3	4	3			1		1	2	2	2	1	1	2
Gear Train	28	9	10	5	7	8	6	3	2	2	4	6	6	2	1	1	3			4	2	1	3	5	2	6	2	2		6	10	4			1		2	2	2	3		1	2
Gear Driven Auxiliary (Compressor)	29	12	13	7	9	10	8	4	3	3	8	11	9	3	1	1	3			5	3	2	3	6	2	5	2	2	6		8	6	1		2		2	5	5	4		2	3
Timing Case	30	10	11	7	9	9	7	4	3	2	4	6	8	3	1	1	6			5	2	1	5	8	3	6	2	3	8	5		6			1		2	2	3	3		1	3
Balancer	31	10	11	7	11	13	7	5	2	2	4	6	8	4	2	1	7			10	2	1	3	5	1	4	2	2	6	5	7				1		2	2	2	3		1	3
Turbocharger	32	5	5	3	4	4	3	2	1	1	3	3	4	1	1	2	1			2	1	1	1	2	1	2	1	1	2	2	3	2		2	1		3	1	2	3		6	1
Aircharge Cooler	33	1	1			1																											4				1						
Air Intake	34	5	3	2	2	2	2	1	1	1	1	2	2	1			1		3	1			1	2		1	1	1	1	1	2	1		1			1	1	1	1	1		1
Air Filter	35	1	1	1	1	1	1					1	1											1							1												
Exhaust Manifold	36	3	4	2	3	3	2	1	1	1	1	2	3	1			1			1	1	1	1	2	1	1	1	1	2	2	2	2	1					1	1	1	1	1	1
Low Pressure Fuel System	37	5	6	3	4	4	3	2	1	2	4	5	4	1	1	1	1			2	3	1	1	3	1	2	1	1	3	4	3	2			1		1		4	2		1	1
Fuel Filter	38	8	9	5	6	6	5	3	2	4	10	8	6	2	1	2	2			3	8	2	2	4	1	3	1	1	4	5	5	3	1		2		2	5		3		3	2
Starting Aid	39	8	8	5	6	6	6	3	2	5	4	5	11	2	1	1	2			3	2	2	2	4	1	3	1	1	3	3	5	3	1		1		2	2	3		1	2	2
Lifting Eyes	40	2	2	1	1	1	1	1			1	1	1					2		1				1		1			1	1	1	1								1			
Wiring Harness	41	6	7	3	4	5	4	2	1	3	8	6	5	2	1	3	1			2	2	1	1	3	1	2	3	1	3	3	4	2	3		2		2	3	2	4			2
Radiator	42	2	2	1	2	2	1	1	1		1	1	2	1			1			1			1	3	1	1		1	1	1	1	1							1	1			

Appendix 10 continued.

Forward CPM(BS)		Maximum values within the structural layer																																									
Component	No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Cylinder Head Assembly	1		29	18	20	23	17	11	7	3	8	16	18	6	3	2	6		1	9	4	3	6	12	3	10	4	5	12	10	14	13	1	1	3		5	4	5	6	2	2	5
Cylinder Block Assembly	2	27		19	31	21	19	10	6	3	8	13	20	6	3	2	5		2	8	3	3	6	11	3	8	4	5	12	11	13	10	1	1	3		6	4	6	7	4	2	6
Piston Rings Gudgeon Pin	3	26	26		17	20	21	9	6	4	8	15	32	6	2	2	5		1	7	3	3	5	10	2	8	3	4	10	8	12	10	1	1	3		5	4	5	10	3	2	5
Conn Rod	4	17	18	10		14	10	12	4	2	5	9	11	4	2	1	4		1	7	2	2	4	7	2	6	2	3	9	6	9	10			2		3	2	3	4	2	1	4
Crankshaft Main Bearings	5	17	17	12	12		11	6	4	2	5	9	12	4	1	1	4		1	5	2	2	3	7	2	5	2	3	7	6	8	10			2		3	2	3	4	2	1	3
Valve Train	6	25	24	15	16	18		8	5	4	8	14	31	5	2	2	4		1	7	3	3	4	10	2	8	3	4	10	8	12	10	1	1	3		4	4	5	10	3	2	5
Cam Shaft	7	10	10	7	12	9	6		2	1	3	5	7	2	1	1	2		1	4	1	1	2	4	1	3	1	2	5	4	5	5			1		1	1	2	2	1	1	2
Push Rods	8	25	25	17	18	21	16	10		4	8	14	19	6	3	2	5		1	9	4	3	6	11	3	9	4	5	12	9	13	11	1	1	3		4	5	5	7	3	2	5
High Pressure Fuel Pipes	9	31	29	19	21	24	19	11	7		20	22	23	7	3	4	6		1	10	7	14	7	13	3	11	5	6	15	13	16	13	2	1	4		6	10	12	16	3	9	7
Electric Control Module	10	17	20	11	13	14	12	6	4	6		16	14	4	2	2	4		1	6	4	3	4	8	2	6	3	3	10	11	10	8	1	1	2	1	4	8	7	6	2	4	4
Fuel Pump	11	21	22	13	15	17	14	8	5	6	13		16	5	2	2	4		1	7	5	4	4	9	2	7	3	4	10	9	11	10	1	1	3	1	4	7	9	7	2	4	5
Fuel Injection Assembly	12	13	15	9	9	10	11	4	3	3	5	8		3	1	1	2			4	2	2	2	6	1	4	2	2	5	5	7	5	1		2		3	3	3	12	2	2	3
Adapter Plate / Flywheel Housing	13	10	11	7	8	9	6	4	2	1	3	6	7		4	5	5			4	2	1	2	4	1	3	1	2	5	4	5	5			1		2	1	2	2	1	1	2
Flywheel Ring Gear	14	1	2	1	2	2	1	1				1	1			1				1				1					1		1	1											
Starter Motor	15	16	15	10	11	13	9	6	3	2	5	9	11	3	3		3		1	5	5	2	3	6	2	5	2	3	7	5	8	7			2		2	2	3	4	2	1	3
Sump	16	18	19	12	16	18	11	8	4	2	6	10	12	11	3	3		3	1	8	3	2	4	8	2	7	2	3	10	7	11	13			2		3	3	3	4	2	1	4
Oil Filler	17	3	4	2	2	3	2	1	1	1	2	3	2	1			3			1	1	1	1	1		1	1	1	2	2	2	2					1	1	1	1	1	1	1
Engine Breather	18	18	19	12	13	16	12	7	4	3	7	11	14	4	2	1	4			7	3	2	4	8	2	6	3	3	9	7	10	8	1	1	4		3	4	4	5	2	2	4
Oil Pump	19	7	7	5	6	7	4	3	1	1	2	4	4	2	1		2		3		1	1	2	3	1	2	1	1	4	2	4	5			1		1	1	1	2	1		1
Oil Filter	20	5	5	3	3	4	3	2	1	2	3	4	3	1	1	3	1			1		1	1	2		2	1	1	2	2	3	2			1		1	1	6	2		1	1
Oil Cooler	21	13	13	8	9	11	8	5	3	3	5	8	10	3	1	1	3		1	4	2		4	6	1	4	2	2	6	5	7	6			1		2	3	3	4	1	1	3
Crank Pulley Damper Belt	22	7	8	4	6	7	4	3	1	1	2	4	4	2	1		2			3	1	3		3	1	3	1	3	4	4	6	3			1		1	1	1	1	1		1
Fan Drive	23	6	6	4	5	6	4	2	1	1	2	4	4	1	1		1			2	1	1	2		2	4	1	2	3	3	5	3			1		1	1	1	1	1		3
Fan Extension	24	1	1	1	1	1	1					1	1										1	1		1			1	1	1	1											
Coolant Pump	25	8	9	6	7	8	6	3	2	1	3	5	6	2	1	1	2			3	1	1	3	6	2		3	2	5	4	6	4			1		2	2	2	2	1	1	2
Alternator Bracket	26	3	3	1	2	2	2	1	1		1	2	2	1			1			1			1	1		3		1	1	1	2	1					1			1			1
Belt Driven Auxiliary (Hydraulic Pump	27	8	10	5	6	7	6	3	2	2	4	6	6	2	1	1	2			3	1	1	2	4	1	3	1		4	4	5	4			1		2	2	2	3	1	1	2
Gear Train	28	13	16	8	11	13	8	5	3	2	5	9	9	3	2	1	3		1	6	2	2	4	6	2	7	3	3		8	12	7			1		2	3	3	3	1	1	3
Gear Driven Auxiliary (Compressor)	29	17	17	11	12	14	10	6	4	4	8	13	12	4	2	1	4		1	6	3	2	4	7	2	6	3	3	9		10	8	1		2		3	5	5	5	2	2	4
Timing Case	30	16	18	10	13	15	10	7	3	2	6	10	11	4	2	1	6		1	7	2	3	6	9	4	7	3	4	11	7		9			2		3	3	3	4	2	1	4
Balancer	31	16	18	11	16	17	10	7	3	2	5	9	11	5	3	1	8		2	11	2	2	4	7	2	6	2	3	9	6	9				2		3	2	3	4	1	1	3
Turbocharger	32	8	7	4	5	6	4	3	2	2	3	5	5	2	1	2	1			2	1	1	1	3	1	2	1	1	3	3	4	3		3	1		3	2	2	3	1	6	1
Aircharge Cooler	33	2	2	1	1	1	1				1	1	1						1					1		1			1		1	1	4		3		1						
Air Intake	34	7	9	4	4	5	6	2	2	1	2	3	5	2			1		3	2	1	1	1	3	1	2	1	1	2	2	3	2	1	3		3	2	1	1	2	1		1
Air Filter	35	2	2	1	1	1	1				1	1	1											1					1	1	1	1		1	3								
Exhaust Manifold	36	8	10	4	5	5	6	2	2	1	3	4	6	2	1		1			2	1	1	1	3	1	2	1	1	3	2	4	3	1		1			3	2	2	1	1	2
Low Pressure Fuel System	37	9	9	5	5	6	5	3	2	2	5	7	6	2	1	1	2			3	3	1	2	3	1	3	1	1	4	5	5	3			1		3		4	3	1	1	2
Fuel Filter	38	10	12	6	7	8	7	3	2	5	10	10	8	2	1	2	2			3	8	2	2	4	1	4	2	2	5	5	6	4	1		2		2	5		4	1	3	2
Starting Aid	39	10	11	6	7	8	7	3	2	5	5	7	12	2	1	1	2			3	2	2	2	4	1	3	1	2	5	4	5	4	1		1		2	3	3		1	2	2
Lifting Eyes	40	2	2	1	1	2	1	1			1	1	2				1	2		1				1		1			1	1	1	1						1	1	1			
Wiring Harness	41	7	8	4	5	6	5	2	2	3	9	7	6	2	1	3	1			2	2	1	1	3	1	3	3	1	4	3	4	3	3	1	2	1	2	3	3	5	1		2
Radiator	42	2	3	2	2	2	2	1	1		1	2	2	1			1			1			1	3	1	1		1	1	1	2	1							1	1			

Forward CPM(FBS)		Maximum values within the structural layer																																									
Component	No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Cylinder Head Assembly	1		84	78	66	64	48	29	44	4	13	29	46	15	8	4	15	6	4	24	12	8	20	24	4	18	8	12	28	19	34	28	9	4	8	2	13	6	9	14	8	7	12
Cylinder Block Assembly	2	82		78	65	63	50	28	45	5	14	27	49	15	9	4	16	6	5	23	12	8	20	25	5	17	9	12	26	18	34	26	8	4	8	2	15	7	10	15	10	7	12
Piston Rings Gudgeon Pin	3	79	81		61	62	45	27	41	5	14	29	45	15	7	3	14	5	3	22	11	7	17	23	4	17	7	10	26	18	32	26	6	3	7	1	13	6	9	17	10	5	12
Conn Rod	4	70	70	63		47	33	19	26	3	8	18	30	10	6	2	10	4	2	15	7	5	12	16	3	11	5	7	18	12	22	19	4	2	5	1	9	4	6	9	7	3	8
Crankshaft Main Bearings	5	71	71	62	47		33	17	26	3	8	18	30	11	3	2	10	4	2	12	8	5	8	16	3	11	5	7	14	11	20	19	4	2	5	1	9	3	6	10	7	2	8
Valve Train	6	61	63	51	42	43		19	26	5	11	20	38	9	4	2	7	2	2	13	6	4	15	16	4	12	7	8	20	13	24	16	3	2	4	1	8	5	6	12	6	7	8
Cam Shaft	7	41	40	37	22	27	20		16	2	9	10	15	5	3	2	4	1	1	8	3	2	12	8	2	7	5	6	14	8	17	10	3	1	2	1	4	2	3	5	3	7	3
Push Rods	8	71	72	68	52	51	40	24		4	15	22	37	11	6	2	10	3	4	17	8	5	20	19	5	14	8	10	25	16	30	19	5	2	6	1	11	6	8	12	8	10	9
High Pressure Fuel Pipes	9	58	58	57	40	41	29	15	21		21	25	32	8	4	4	8	2	2	13	8	14	13	16	4	13	6	8	18	14	21	15	3	2	5		9	11	13	18	5	9	8
Electric Control Module	10	33	37	34	25	26	16	10	12	7		18	17	5	2	3	5	1	1	8	5	4	10	9	3	7	5	4	13	12	14	10	3	2	3	2	6	9	7	6	2	10	5
Fuel Pump	11	47	49	47	34	35	22	13	17	7	14		24	7	3	2	6	1	2	10	7	4	9	12	3	9	4	5	14	11	16	13	3	2	4	1	7	8	10	8	4	5	6
Fuel Injection Assembly	12	39	44	31	26	27	17	9	13	4	6	11		5	2	1	4	1	1	7	4	3	5	9	1	6	3	4	9	7	11	9	1	1	2		4	3	4	13	3	2	4
Adapter Plate / Flywheel Housing	13	31	31	32	22	22	12	7	9	1	4	7	12		6	5	6	1	1	6	3	2	5	6	1	4	2	2	8	5	9	7	1		1		3	2	2	3	2	1	3
Flywheel Ring Gear	14	8	8	7	6	4	3	2	2		1	2	2	2		1	1			1	1		1	1		1			2	1	3	2										1	1
Starter Motor	15	49	44	47	31	29	20	9	15	2	6	10	21	5	4		5	2	2	8	6	2	7	9	2	6	3	4	10	6	12	8	1	1	3		5	3	5	7	4	2	4
Sump	16	47	44	43	32	30	19	11	13	2	6	12	18	12	5	3		4	2	11	4	3	9	11	3	9	4	6	13	9	15	15	1	1	3		5	3	4	6	3	2	5
Oil Filler	17	9	11	8	6	7	3	2	2	1	3	3	3	1			3			2	1	1	2	2	1	2	1	1	2	2	3	3	1		1		1	1	1	1	1	1	1
Engine Breather	18	54	53	53	36	36	24	12	19	3	8	14	25	6	3	1	6	2		11	5	3	9	11	3	8	4	5	13	9	15	12	3	2	5	1	7	4	5	8	5	2	6
Oil Pump	19	28	26	25	18	17	11	6	7	1	3	6	9	3	2	1	3	1	3		2	2	6	5	2	5	3	4	7	5	9	7	1		2		2	1	2	3	2	2	2
Oil Filter	20	16	14	14	10	10	6	3	3	2	3	5	6	2	1	3	2	1		3		1	2	3		3	1	2	3	3	4	3			1		2	2	7	2	1	1	1
Oil Cooler	21	40	40	40	26	26	16	8	12	3	6	10	17	4	2	1	4	1	1	7	4		7	8	2	6	3	4	9	6	11	8	1	1	2		4	3	4	5	3	1	4
Crank Pulley Damper Belt	22	26	28	21	16	15	15	13	14	2	10	9	8	4	2	2	3	1	2	8	3	5		8	4	9	6	7	15	10	18	9	2	1	2	1	2	2	2	4	1	8	3
Fan Drive	23	16	16	15	10	11	8	5	6	1	3	5	6	2	1	1	2		1	4	1	1	6		3	6	3	4	7	5	9	5	1	1	1		2	1	1	2	1	2	3
Fan Extension	24	3	3	2	2	3	2	2	2		2	1	1				1		1	1			3	2		2	1	2	3	2	4	1										1	1
Coolant Pump	25	25	27	26	17	19	11	7	9	2	4	7	10	3	2	1	3	1	1	6	3	2	8	8	3		5	5	9	7	11	7	1		1		2	2	2	3	2	2	3
Alternator Bracket	26	7	9	7	5	6	4	3	4		3	2	2	1			1			2	1	1	4	2	1	5		2	4	3	5	2					1	1	1	1		2	1
Belt Driven Auxiliary (Hydraulic Pump	27	21	25	21	15	16	10	7	8	2	4	8	9	3	1	1	3	1	1	5	3	2	6	5	2	5	3		8	6	10	6	1		1		2	3	3	3	1	2	2
Gear Train	28	34	33	29	22	22	19	14	17	3	11	12	13	5	3	3	5		2	10	3	3	17	11	5	11	7	9		12	22	11	3	1	2	2	3	4	4	5	2	8	4
Gear Driven Auxiliary (Compressor)	29	42	39	39	26	27	19	11	14	4	9	15	19	5	3	1	5	1	2	9	4	2	10	10	3	8	4	6	13		15	10	2	1	3		5	5	6	6	3	3	5
Timing Case	30	44	46	43	32	31	25	18	22	4	13	14	19	7	4	3	8	2	3	13	5	5	19	14	6	11	8	11	22	11		14	3	2	3	2	5	4	4	6	3	10	6
Balancer	31	52	49	46	34	31	20	12	13	2	6	12	18	7	4	1	10	2	3	14	5	3	9	11	3	9	4	6	13	9	16		2	1	3		5	3	4	5	3	2	5
Turbocharger	32	25	24	22	14	14	10	4	7	2	4	6	9	2	1	2	2	1	1	3	2	1	3	4	1	3	2	2	4	3	6	4		7	6	3	8	4	2	4	2	6	2
Aircharge Cooler	33	5	5	3	2	3	2	1	1		1	1	1						1	1	1		1	1		1		1	1	1	2	1	6		4	2	4	2		1		1	
Air Intake	34	27	33	28	19	19	11	6	9	1	2	6	10	3	1		3	1	3	4	2	1	3	5	1	3	1	1	5	4	7	5	6	4		4	4	2	2	3	1	1	3
Air Filter	35	7	9	7	5	5	3	1	2		1	1	2	1			1		1	1	1		1	1		1			1	1	2	1	4	3	5		2	1		1		1	1
Exhaust Manifold	36	27	34	28	19	20	12	6	9	1	3	7	11	3	1		3	1	1	4	3	2	3	6	1	3	2	2	6	4	7	6	6	4	3	1		4	3	3	2	1	3
Low Pressure Fuel System	37	22	20	19	12	12	9	4	6	3	5	8	9	2	1	1	2		1	4	4	1	4	4	1	3	2	2	6	5	7	4	3	2	2	1	5		5	3	2	2	2
Fuel Filter	38	13	18	14	10	11	7	4	4	5	11	11	9	3	1	2	2			4	8	3	3	5	1	4	2	2	6	5	7	5	1	1	2		3	6		4	1	3	2
Starting Aid	39	22	27	23	16	17	10	6	7	5	5	9	14	3	1	1	3			4	3	3	4	5	1	4	2	2	6	5	7	6	1	1	1		3	3	3		1	2	3
Lifting Eyes	40	6	8	7	5	5	2	1	2		1	2	2	1			1	2		1	1		1	1		1			1	1	2	1					1	1	1	1			1
Wiring Harness	41	10	11	9	7	8	9	11	10	3	15	8	6	2	1	4	1			4	2	1	10	3	1	3	5	4	10	4	11	3	3	2	2	3	3	3	3	7	1		2
Radiator	42	9	10	10	6	7	3	2	3		1	2	3	1			1			2	1	1	2	3	1	2	1	1	2	2	3	2					1	1	1	1	1		

Appendix 11: SEM risk matrices calculated considering different numbers of layers

Direct risk		Maximum values within the structural layer																										
Component	**No**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Emitter	**1**		3	13																	3		13						
Anode	**2**	3		13																	3		3						
Wehnelt	**3**	13	13																		3		13						
Magnetic lens 1	**4**					3				3	3				13						3								
Magnetic lens 2	**5**				3					3	3				13						3								
Magnetic lens 3	**6**							3	3		3	3			13						3						3		
Scan coils	**7**						3		13		3				13						3								
Stigmator coils	**8**						3	13			3				13						3								
Gun alignment coils	**9**				3	3									13						3								
Apertures	**10**				3	3	3	3	3												3								
Vacuum chamber	**11**						3							3						3	3	3			3	3	3	3	3
Scan generator	**12**														13			13						13				3	
BSD electronics	**13**											3						13							13				
EO electronics	**14**				13	13	13	13	13	13			13			13		13										3	
VAC electronics	**15**														13		13	13			13			13				3	
Stage electronics	**16**															13		13									13	3	
LV PSU's	**17**												13	13	13	13	13		13		13	13			13		13	3	
X-Ray pulse processor	**18**																	13				13		13	13			3	
Anti vibration system	**19**											3									3							3	3
Vacuum system	**20**	3	3	3	3	3	3	3	3	3	3	3				13		13		3		3						3	
X-Ray detector	**21**											3						13	13		3						3		3
EHT power supply	**22**	13	3	13																						13		3	
PC	**23**												13			13			13									3	
BSD	**24**											3		13				13	13							3	3		3
SED	**25**											3											13		3		3		3
Stage/ Specimen	**26**						3					3					13	13				3			3	3			3
Plinth	**27**											3	3		3	3	3	3	3	3	3		3	3					3
Cladding	**28**											3								3		3			3	3	3	3	

Forward CPM(S)		Maximum values within the structural layer																										
Component	**No**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Emitter	**1**		9	18	6	6	10	7	7	5	9	11	2	4	2	2	2	2	2	8	5	8	18	2	9	9	12	7	12
Anode	**2**	9		13	9	9	15	11	11	7	13	15	3	7	3	3	3	3	3	10	8	12	9	3	14	13	17	8	15
Wehnelt	**3**	18	13		11	11	21	15	15	9	16	23	5	14	5	5	5	5	5	17	8	20	18	5	26	25	28	15	26
Magnetic lens 1	**4**	6	9	11		16	36	27	27	13	22	43	17	22	13	19	18	20	21	33	19	35	14	19	41	39	45	34	47
Magnetic lens 2	**5**	6	9	11	16		36	27	27	13	22	43	17	22	13	19	18	20	21	33	19	35	14	19	41	39	45	34	47
Magnetic lens 3	**6**	10	14	20	35	35		27	27	32	32	42	17	27	16	19	18	20	21	43	37	41	22	19	45	43	42	44	51
Scan coils	**7**	7	10	14	27	27	28		21	25	24	45	22	25	18	26	23	27	27	39	29	40	17	24	45	43	46	40	52
Stigmator coils	**8**	7	10	14	27	27	28	21		25	24	45	22	25	18	26	23	27	27	39	29	40	17	24	45	43	46	40	52
Gun alignment coils	**9**	5	7	9	14	14	33	26	26		22	37	17	18	13	19	18	20	21	27	16	29	11	19	34	33	39	27	39
Apertures	**10**	8	12	15	21	21	32	23	23	21		50	14	29	14	14	14	14	14	43	28	44	20	14	51	49	52	44	58
Vacuum chamber	**11**	11	14	21	41	41	41	43	43	34	48		13	14	13	13	13	13	13	32	40	32	19	13	30	30	36	33	34
Scan generator	**12**	2	3	5	15	15	18	21	21	15	16	14		28	32	38	35	35	37	10	30	29	3	32	34	16	28	3	14
BSD electronics	**13**	4	7	13	23	23	29	27	27	19	31	16	29		30	35	28	24	28	26	34	26	12	30	24	21	26	27	26
EO electronics	**14**	2	3	5	13	13	18	18	18	13	16	14	32	29		36	34	37	39	10	30	31	3	35	36	16	29	3	14
VAC electronics	**15**	2	3	5	17	17	18	24	24	17	16	14	37	32	35		33	41	42	10	28	34	3	36	39	16	30	3	14
Stage electronics	**16**	2	3	5	16	16	18	22	22	16	16	14	34	27	34	34		33	38	10	28	29	3	35	34	16	25	3	14
LV PSU's	**17**	2	3	5	17	17	18	24	24	17	16	14	33	23	35	40	32		35	10	28	26	3	35	29	16	24	3	14
X-Ray pulse processor	**18**	2	3	5	18	18	18	24	24	18	16	14	36	27	39	43	38	36		10	33	26	3	34	31	16	30	3	14
Anti vibration system	**19**	8	10	16	33	33	44	39	39	26	44	33	10	25	10	10	10	10	10		36	37	14	10	41	40	45	27	35
Vacuum system	**20**	5	7	7	19	19	36	27	27	15	27	41	31	31	31	30	29	30	34	34		38	14	31	50	48	49	34	48
X-Ray detector	**21**	8	11	19	35	35	42	40	40	28	44	34	30	25	32	36	30	27	27	37	40		18	30	38	37	36	38	36
EHT power supply	**22**	18	9	18	15	15	24	19	19	11	22	21	3	12	3	3	3	3	3	15	15	19		3	22	21	26	8	21
PC	**23**	2	3	5	17	17	18	23	23	17	16	14	33	29	36	38	36	37	36	10	31	29	3		34	16	29	3	14
BSD	**24**	9	13	23	40	40	45	44	44	33	51	31	34	24	36	41	34	31	31	40	51	38	21	34		26	33	41	33
SED	**25**	9	12	23	38	38	44	43	43	31	49	32	14	21	14	14	14	14	14	40	50	37	20	14	26		31	40	32
Stage/ Specimen	**26**	11	15	25	43	43	42	44	44	36	51	37	29	24	30	32	25	26	31	44	49	35	24	30	32	31		44	38
Plinth	**27**	7	8	14	33	33	45	40	40	27	44	34	3	25	3	3	3	3	3	27	36	37	7	3	41	40	45		36
Cladding	**28**	11	14	23	44	44	50	50	50	36	57	35	13	24	13	13	13	13	13	34	49	34	20	13	32	31	38	34	

Appendix 11 continued.

Forward CPM(BS)		Maximum values within the structural layer																											
Component	**No**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Emitter	**1**		60	63	70	70	71	70	70	63	77	42	24	9	71	19	6	22	6	28	77	27	41	7	16	18	29	38	23
Anode	**2**	56		60	69	69	70	69	69	62	76	43	24	10	70	19	6	22	6	29	76	29	41	6	19	18	32	35	25
Wehnelt	**3**	60	62		73	73	74	73	73	67	80	50	28	19	75	20	8	22	8	35	81	36	46	9	32	31	43	40	36
Magnetic lens 1	**4**	58	61	66		69	82	78	78	63	78	69	45	30	68	46	33	47	37	53	79	53	47	33	50	48	60	59	58
Magnetic lens 2	**5**	58	61	66	69		82	78	78	63	78	69	45	30	68	46	33	47	37	53	79	53	47	33	50	48	60	59	58
Magnetic lens 3	**6**	59	63	70	81	81		74	74	76	81	67	44	38	68	45	33	47	36	65	85	62	53	33	57	54	55	70	66
Scan coils	**7**	60	61	67	77	77	75		72	72	81	72	52	35	71	53	40	55	42	60	82	59	48	40	55	53	62	65	65
Stigmator coils	**8**	60	61	67	77	77	75	72		72	81	72	52	35	71	53	40	55	42	60	82	59	48	40	55	53	62	65	65
Gun alignment coils	**9**	54	55	61	65	65	79	74	74		76	61	42	25	62	44	32	45	36	45	73	46	40	32	43	41	53	51	50
Apertures	**10**	59	62	67	70	70	77	73	73	69		74	26	37	70	22	19	26	19	62	80	61	50	21	59	57	66	67	68
Vacuum chamber	**11**	31	33	42	63	63	64	67	67	55	72		19	27	30	18	18	23	18	51	69	49	32	22	44	42	52	52	56
Scan generator	**12**	43	43	45	55	55	54	57	57	46	57	35		45	55	63	55	61	58	23	66	46	21	49	53	18	46	34	22
BSD electronics	**13**	11	11	18	31	31	41	37	37	25	41	32	47		50	57	46	40	48	39	49	39	16	49	36	32	38	40	40
EO electronics	**14**	68	70	77	82	82	85	83	83	77	90	65	58	47		60	58	65	62	45	93	50	55	59	57	24	48	60	40
VAC electronics	**15**	42	42	43	57	57	57	58	58	48	58	43	62	53	59		53	68	66	29	66	55	22	55	61	20	51	41	31
Stage electronics	**16**	17	17	14	34	34	33	41	41	31	23	34	56	44	59	55		56	59	22	46	47	8	56	54	18	38	30	27
LV PSU’s	**17**	45	45	47	60	60	65	61	61	50	64	63	60	42	64	67	55		59	42	73	48	25	61	52	36	46	53	49
X-Ray pulse processor	**18**	14	14	11	35	35	34	41	41	33	20	41	58	46	62	68	58	61		24	53	41	8	51	47	23	49	34	31
Anti vibration system	**19**	21	23	31	51	51	66	59	59	42	63	55	15	37	20	14	14	17	14		57	54	24	17	55	52	60	45	51
Vacuum system	**20**	50	50	55	68	68	78	72	72	60	77	69	51	44	63	48	47	52	55	52		55	38	51	64	62	68	57	67
X-Ray detector	**21**	20	23	31	51	51	62	57	57	42	62	52	48	38	53	59	48	47	42	53	58		26	49	51	48	49	54	49
EHT power supply	**22**	47	54	54	59	59	60	58	58	51	65	36	14	16	58	10	4	10	4	25	63	29		6	29	27	36	25	30
PC	**23**	17	17	15	35	35	34	42	42	31	24	26	50	47	61	57	56	65	52	19	49	47	8		54	21	47	25	23
BSD	**24**	13	16	29	47	47	57	54	54	39	59	45	53	36	59	64	54	52	48	53	65	50	26	54		36	43	54	45
SED	**25**	22	21	28	46	46	55	52	52	38	57	43	17	29	18	16	17	19	17	51	63	48	24	19	36		40	52	42
Stage/ Specimen	**26**	22	26	37	56	56	53	58	58	48	64	51	49	36	51	54	39	43	51	56	67	46	31	49	44	38		57	48
Plinth	**27**	27	25	33	55	55	69	62	62	46	66	56	10	37	24	13	8	17	10	43	59	54	15	8	55	52	60		51
Cladding	**28**	17	20	31	53	53	62	60	60	44	66	49	16	33	19	16	16	19	16	45	64	45	26	19	41	38	47	47	

Forward CPM(FBS)		Maximum values within the structural layer																											
Component	**No**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Emitter	**1**		62	65	71	71	72	71	71	65	78	44	25	9	73	22	7	24	6	30	79	28	43	9	16	21	29	39	23
Anode	**2**	62		61	70	70	71	70	70	63	77	44	25	10	72	21	7	23	6	29	77	29	46	7	19	19	32	36	25
Wehnelt	**3**	68	64		74	74	75	74	74	68	82	51	28	19	77	23	8	24	8	35	83	36	48	9	33	32	43	41	36
Magnetic lens 1	**4**	60	61	67		72	83	78	78	65	81	69	46	30	73	48	33	50	37	53	82	54	47	35	50	48	60	60	59
Magnetic lens 2	**5**	60	61	67	72		83	78	78	65	81	69	46	30	73	48	33	50	37	53	82	54	47	35	50	48	60	60	59
Magnetic lens 3	**6**	60	63	70	81	81		75	75	77	82	68	45	38	70	47	33	51	38	66	86	63	53	36	57	55	55	71	66
Scan coils	**7**	62	62	68	78	78	76		73	73	83	73	53	35	74	54	40	58	43	60	84	60	48	42	56	54	63	65	65
Stigmator coils	**8**	62	62	68	78	78	76	73		73	83	73	53	35	74	54	40	58	43	60	84	60	48	42	56	54	63	65	65
Gun alignment coils	**9**	57	56	61	69	69	79	75	75		77	62	42	25	64	45	32	47	36	46	74	46	40	34	43	41	54	51	50
Apertures	**10**	59	62	68	70	70	78	73	73	70		75	26	38	73	26	19	27	19	62	81	62	50	21	60	57	66	68	68
Vacuum chamber	**11**	33	34	43	65	65	66	68	68	56	73		19	28	35	19	18	27	18	51	70	50	33	22	45	43	52	53	57
Scan generator	**12**	44	44	45	59	59	54	58	58	47	57	37		47	58	64	56	62	59	23	68	50	21	51	55	18	46	34	22
BSD electronics	**13**	11	11	19	31	31	42	37	37	26	41	35	48		52	59	47	43	50	39	49	42	16	51	39	32	38	40	40
EO electronics	**14**	70	71	77	83	83	86	84	84	77	91	69	60	50		63	59	66	64	46	94	55	55	60	61	27	49	61	40
VAC electronics	**15**	44	43	44	62	62	60	60	60	50	61	47	63	54	62		53	69	67	31	69	58	23	56	64	24	51	43	34
Stage electronics	**16**	19	18	15	35	35	34	42	42	32	24	37	56	46	61	55		57	60	23	48	50	8	57	56	20	38	32	27
LV PSU’s	**17**	47	46	47	64	64	67	63	63	52	65	66	61	44	65	68	55		61	44	75	53	25	65	55	38	48	54	50
X-Ray pulse processor	**18**	15	15	11	35	35	37	42	42	34	20	45	58	48	64	69	59	63		25	53	45	8	54	51	25	49	35	32
Anti vibration system	**19**	22	23	31	51	51	67	59	59	42	63	56	15	37	20	14	14	17	14		57	54	24	17	55	53	60	45	51
Vacuum system	**20**	53	52	57	69	69	79	73	73	61	79	70	52	44	68	49	48	52	56	53		56	38	51	65	62	69	57	67
X-Ray detector	**21**	22	23	32	51	51	63	58	58	43	62	53	50	41	57	61	50	49	45	53	59		26	51	52	49	49	55	49
EHT power supply	**22**	54	55	56	59	59	61	58	58	52	65	37	15	16	59	13	4	11	4	25	65	29		6	29	27	36	25	30
PC	**23**	20	18	16	37	37	37	44	44	33	24	28	51	49	62	58	57	68	54	19	50	50	8		56	21	48	27	23
BSD	**24**	15	17	30	48	48	57	54	54	40	60	45	55	39	61	66	55	55	51	53	66	51	26	56		36	44	54	45
SED	**25**	26	24	29	46	46	55	52	52	38	58	44	17	29	18	16	17	19	17	51	63	49	24	19	37		40	52	42
Stage/ Specimen	**26**	22	26	37	56	56	53	58	58	49	64	51	49	37	52	55	39	43	52	56	67	46	31	50	46	38		57	48
Plinth	**27**	28	25	33	55	55	69	62	62	46	67	56	10	37	25	15	9	18	10	44	60	54	15	9	55	53	61		51
Cladding	**28**	17	20	31	53	53	63	60	60	44	66	50	16	33	19	16	16	19	16	45	64	45	26	19	41	38	47	47	

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