Designing Resilient Manufacturing Systems In the Presence of Change

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

Hatice Olmez
Hughes Hall College
July 2021

In loving memory of my Mom and Dad

Declaration

Unless otherwise stated, this thesis is the result of my research and does not include the outcome of work done in collaboration. Any reference to the work of others is indicated in the text. Neither this thesis nor similar work has been submitted in whole or in part for consideration for any other degree or qualification at the University of Cambridge or any other institution. This thesis contains 81 figures, 27 tables and fewer than 69,000 words.

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

- Olmez H, Hassannezhad M, Ball NR, Clarkson PJ, (2018) 'Modelling Change with an Integrated Approach to Manufacturing System Design'. In*: Proceedings of the 15th International Design Conference (DESIGN2018),* Dubrovnik, Croatia.

- Olmez, H. and Clarkson, P.J. (2017) 'Change Propagation Analysis with Multilayer Network Models within Manufacturing Systems', Presented at *19th International Dependency and Structure Modelling Conference (DSM2017), The Design Society,* Espoo, Finland.

Hatice Olmez
Hughes Hall College
University of Cambridge
July 2021

Acknowledgements

First and foremost, I would like to express my sincere gratitude to my supervisor, Prof P. John Clarkson for his continual advice and encouragement and for inspiring this research.

I would also like to thank my manager Paul Eveleigh in Universal Oil Products (a Honeywell Company) and the company Laing O’Rourke for their generous funding of this research. I am also grateful to Adam Robinson from Laing O’Rourke and Brian East from Jewson for their support with the modelling of the industrial case studies.

Furthermore, I would like to thank Aylmer Johnson, Dr. Nigel Ball, Dr. Tariq Masood, Dr Mohamed Hani El-Reifi and Dr. Muhammad Hassannezhad for their advice, supervision, and valuable guidance throughout this research project. Many thanks also to my college tutor Dr. Alastair Lockhart from Hughes Hall for his great advice and support.

Finally, I would like to thank the following people for their contribution: Seena Nair for implementing the proposed method as a module into the CAM software; my colleagues at the Engineering Design Centre of the University of Cambridge for their assistance and constructive and useful discussions; Dr. Bahram Hamraz, Dr. Daniel Shapiro, Dr. Hilario Xin-Chen, Dr. Jakob Maier, Dr. Warren P. Kerley, Jonathan Mak, Dr. Gulsum Kubra Kaya and all my current and former colleagues at the Cambridge Engineering Design Centre (EDC) for their moral support and, constructive discussions; Mari Huhtala, Anna Walczyk and Andrew Flintham for their administrative support; and many thanks also to Anthony Haynes from Frontinus Ltd for his mentoring in writing.

Big, genuine thanks to my great friend Cengiz Caglar for his unlimited support and for encouraging me throughout the process of this PhD. Last, and most certainly, I would like to thank my family for their unconditional love and encouragement.

Abstract

Economic and technical changes force manufacturers to redesign and enhance their operational systems. The implications of such changes within a complex system such as manufacturing and the supply chain can be very challenging. In particular, where the number of system elements and their connections result in a high level of complexity, the potential effects of a change can be expensive concerning the delivery time and cost targets, as a change to one part or element of a design requires additional changes throughout the system.

Companies need to understand the characteristics of their manufacturing systems that make them resilient to change. Considered from a system perspective, the structures of the system, and its elements and connections, contribute greatly to the characteristics and behaviour of the system and hence potential resilience. A change prediction method can help to analyse the change properties and improve complex systems by focusing on the underlying structural elements and dependencies.

This thesis proposes a novel system change method that can enable the review of the current manufacturing system and understand how to design a more robust or adaptable system which addresses resilience. This method is a combination of matrix-based approaches and methods to assess the interaction between elements of the product and its manufacturing process in order to understand the risk of changes propagating through the system. Risk assessment across layers of a system can give valuable insight into how an element change interacts within the system. The goal of this thesis is to contribute to gaining fundamental understanding of manufacturing systems resilience by developing a method to evaluate capabilities of changes, performance robustness or adaptability and achieving high resilience.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

CAM	Cambridge Advanced Modeler
CPM	Change Prediction Method
CM	Combined Impact
CL	Combined Likelihood
DfM	Design for Manufacturing
DMM	Domain Mapping Matrix
DPR	Design Process Requirement
DRM	Design Research Methodology
DSM	Design Structure Metrics or Dependency Structure Metrics
EC	Engineering Change
ECM	Engineering Change Management
EDC	Engineering Design Centre
FMEA	Failure Mode Effect Analysis
KAS	Kitchen Assembly System
KDS	Kitchen Design System
LOR	Laing O'Rourke
MS	Manufacturing System
MSC	Manufacturing System Changes
MDM	Multi-Domain Matrix
MLN	Multi-Layer Network
PERT	Program (or Project) Evaluation and Review Technique
RMS	Resilient Manufacturing System
RM	Research Methodology
RE	Resilient Engineering
SCM	System Change Method
UOP	Universal Oil Products (A Honeywell Company)

1 Introduction

The competitive manufacturing environment forces companies to respond rapidly and in a cost-efficient manner to their change requirements. It is challenging to cope with the required changes in the manufacturing industry. *Manufacturing systems* and their associated *Supply Chains* are complex systems due to the high connectivity of elements and subsystems such as people, processes, and products. In a complex system where all parts and systems are closely connected, changes to one part of a system are highly likely to result in a change to another part, which in turn can propagate changes further (Eckert *et al.* 2004; Wickel and Lindemann 2015). This makes managing change a challenging problem because the time, cost, and resources that need to be allocated to effect the change are dependent on its potential impact (Wickel and Lindemann 2015).

Change is universal. All systems subject to change whether planned or not. Resilience of system is described is ability to respond to change design resilience in the system. The ability to change is associated with the attributes of resilience. Resilience is strongly related with the whole life-cycle of a system. Resilience is an evolution of the dependability concepts including robust to evolving requirements for the reliable system performances (Heisel *et al.* 2013). Resilience is mostly measured with robustness or adaptability in the context of manufacturing systems (Abech *et al.* 2006, Allen *et al.* 2006, Madni *and* Jackson 2009, Hoffmann *et al.* 2011). A Resilient Manufacturing System (RMS) is a new research area in the system ability to cope with changes and evolve emphasizes the resilience aspect. It was also noted that the area of resilience engineering incompetent in how various proposed methods and tools can enable the design of resilient systems to guide the designers of resilient systems (Heisel *et al.* 2013).

To address designing resilience, novel models and methods are needed that modelling of resilience aspects of a manufacturing system. This thesis aims to define resilience in modelling languages for requirement analysis and system design resilience in implementation and frameworks. In addition, it aims to verify and assessing resilience using a probabilistic model to understand resilience mechanisms at the architectural and implementation level.

This chapter is structured into five sections. Section 1.1 provides the background and motivation of the research. Section 1.2 briefly outlines the research gap. Section 1.3 states the research questions. Section 1.4 discusses the scope of the research. Section 1.5 presents the structure of the thesis. Section 1.6 delivers the chapter summary.

1.1 Background and Motivation

Manufacturing systems are complex and constantly changing business environment. This complexity may cause errors (e.g., human, operational, system) which in turn impact system performance (Hu *et al.* 2013). Given these challenges, a manufacturer reduces the complexity of their manufacturing systems by redesigning manufacturing systems to improve manufacturing performance such as product delivery time, cost, and quality.

Models of complexity can be used to assist in designing systems with robust performances (Hu *et al.* 2013). An adaptable manufacturing system that is responsive to change is essential for a manufacturer to operate in dynamic markets. Manufacturing system resiliency is a term used frequently to describe a company that can adapt robustly to deal with all kinds of changes (Thomas *et al.* 2012; Heinicke 2014). Evaluating change effects and change propagations, with a supporting method and tools, can provide an understanding of manufacturing system resilience (Heisel *et al.* 2013). Modelling and analysis of Resilient Manufacturing Systems (RMS) are thus significant to manufacturers in a competitive business environment (Gu *et al.* 2015).

1.1.1 Designing a Manufacturing System

The objective of any design of a manufacturing system is to achieve a set of *strategic objectives* which includes making a series of decisions over time. Making these decisions requires an understanding of how design issues affect the interactions among various elements of a manufacturing system (Cochran *et al.* 2001). The achievement of business objectives through the assessment of change impacts within manufacturing system design (MSD) needs effective communications of those impacts across the manufacturing system domains that deliver an integrated system (Kim 2002; Cochran *et al.* 2001).

Change is one of the most powerful driving factors of design because changes result in improvements to systems. In some cases, the change is necessary to archive an initially defined standard for the product, which has not previously been met because of a problem. Other changes may be undertaken to adapt the product to new needs and requirements (Eckhert *et al.* 2004). Systems must be designed to meet change requirements and constraints in their systems affect its operational context throughout their entire lifecycle.

A resilient architecture leads to lower costs of change, compared to a very constrained, in-resilient architecture. A higher upfront effort at the design stage to incorporate changeability will lead to a lower cost of changes going forward thus, minimising the total cost of the system architecture is dependent on its degree of changeability (Fiksel 2003). This thesis attempts to formalise the idea of changeability into the system architecture. Robustness or adaptability is the key characteristics of the manufacturing system changeability; these will be defined and described in detail in the literature review chapter.

The design of a system must provide for the continuous evolution of its architecture, either by upgrading a system already in service or releasing a new version (Fricke and Schulz 2005). The integration of (a) design and development activities and (b) products and production systems into one system enables existing skills and knowledge to be used more efficiently (Naylund *et al.* 2009). It can offer a wide knowledge and information base to be used in decision-making processes. Thus, a model of integrated manufacturing systems involves manufacturing elements of products, process and organisations which have different parts in the manufacturing system. To this end, this research intends to integrate manufacturing system domains into one system through the efficient use of existing skills and knowledge to examine change propagation and reduce the complexity of the system design.

The relationship and dependencies between change requirements and system elements are fundamental and modelling information needs to be captured to fully describe the propagation of changes. Such information can support the development of change prediction methods (Koh *et al.* 2012). A conceptual method needs to understand and analyse changes within a complex manufacturing system and underpins the design of a resilient manufacturing system (RMS). The following sub-sections, therefore, provide theoretical perspectives on an RMS and change management within such a system.

1.1.2 Resilient Manufacturing Systems

Resilience is a key driver in system design in an uncertain operational environment. Resilience is a new concept in manufacturing systems and has rarely been considered in design and implementation (Madni and Jackson 2009; Jin and Gu 2016). Resilient engineering systems should enable the system's capabilities to cope with changes in a predictable way, and ensure that robust behaviours are maintained despite faults (Heisel *et al.* 2013). Rydzak *et al*. (2006) describe the concept of resilience in production systems is the maintenance of functionality when disturbances are experienced. Rydzak *et al.* (2006) address Resilience as the dynamics of dealing with disturbance - how a system absorbs the impacts of stress or shock and how it re-organizes afterward with these temporary changes. Ahern (2011) considers change and disturbance**,** deeming adaptability as fundamental to the emerging science of resilience, the capacity of systems to reorganize and recover from change and disturbance without changing to other states in other words, systems that are "safe to fail." In addition, Heinicke (2014) explains resilience as the capability of a system to recover from failure autonomously.

According to Hollnagel *et al.* (2007), failure is a result of the interactions and adaptations that characterize complex systems behaviour in the real world. Resilience addresses the need to deal with failure - how a system absorbs the impacts of pressure and how it subsequently re-organises. In other words, it is defined as the capacity of the system to experience disturbance and still maintain its functions and structures.

Most manufacturing systems fail to sustain productivity when changes or uncertainties occur because the manufacturers lack a robust and adaptable system to cope with the changes. Therefore, it is necessary to develop resilient manufacturing systems with the ability to roll back to the previous stage or move on to the desired stage. Resilience can be broadly assessed by three system characteristics: (1) the amount of change the system can undergo and remain in the same configuration (retain the same controls on structure and function), (2) the degree to which the system is capable of self-organization, and (3) the degree to which the system can build the capacity to learn and adapt (Carpenter *et al.* 2001; Walker et *al.* 2004; Rydzak *et al.* 2006).

The difficulties of designing resilient systems are discussed from both theoretical and practical perspectives in the literature. In theory, the aim is to design a system that can respond to unexpected failures in a '*predictable*' way. In practice, partial failures can occur in several system elements. The failure rate can be extremely small, and the distribution time to failure is unknown and that can lead to uncertainty (Liu *et al.* 2009). A systematic presentation of MSD can help manufacturing engineers and designers capture and examine resilience and changes through the interrelationships of the different system domains and elements. Understanding the attributes and characteristics that emerge from the interactions of elements and subsystems in the design stage is very important (Mehrpouyan *et al*. 2015). Hence, the objective of this research is to develop techniques and supporting tools to enhance the resilience of complex manufacturing systems during the design stages. This thesis particularly focuses on the resilience as an ability of a system to cope with change effectively in manufacturing systems.

Changes in manufacturing systems always interrupt normal production conditions and are a cause of production loss. To meet manufacturing requirements, *an adequate architecture of manufacturing and supply chain systems* in terms of an increased resilience of system elements is vital (Heinicke 2014). The integration of manufacturing systems and supply chain aims to improve operational resilience in terms of manufacturing performance. A resilient system should be designed with the capability to suffer minimum manufacturing loss during changes and settle itself to the steady-state quickly after each disruption (Gu *et al.* 2015). Analysis and understanding changes systematically, manage changes effectively are crucial to design a robust or adaptable manufacturing system.

1.1.3 Change Management for Resilient Manufacturing Systems

Manufacturing systems operate in an uncertain environment with constant changes in customer demands, product innovations, and processing technologies. Changes in manufacturing systems usually increase the complexity of the system (Whindehal 2005; ElMaragyh *et al.* 2012). "*Complex*" term is defined in Oxford dictionaries is "*consisting of many different and connected parts*". A system is considered more complex if more system domains and elements exist with more connections between them (ElMaragyh *et al.* 2012). Elements within a manufacturing system are connected by a complex network of relations such as material flow, information flow, technological dependencies so on. The manufacturing domains such as engineering, procurement, logistics, or business strategy may affect by the changes. Due to complex network relations within systems, the change impact is difficult to predict. Decision support tools are needed for change analysis within manufacturing systems (Plehn *et al.* 2016).

In a complex manufacturing system, a single initiating change can uncontrollably propagate throughout the system, resulting in severely degraded performance or complete failure (Mehrpouyan 2015). The desire to capture and manage changes within complex manufacturing systems requires *modelling of changes* such as through using an integrated model (Ahmad *et al.* 2013). Modelling of changes supports the understanding of the relationship and dependencies between change requirements and system elements. Therefore, the principle of change needs to be considered in the modelling process to support the development of *change prediction methods*, for instance, the types, properties, and interrelationships of the entities which are fundamental to a particular domain or elements (Koh *et al.* 2012).

The proposed novel method in this thesis for designing a Resilient Manufacturing System (RMS) is a case study approach constructed around the ideas of the Multi-Domain Matrix (MDM) (Maurer 2007) and Change Prediction Method (CPM) (Clarkson et al. 2001a; Clarkson et al. 2004). The multi-domain dependency model helps to analyse network-based connections within system domains and system elements while the change prediction method provides a quantitative change propagation analysis. a system is broken down to capture the system dependencies with the change being propagated along with the linkages of a system's network model. Change risk is calculated using the CPM algorithm that computes all direct and indirect paths leading from all initiating elements to all possibly affected elements. As a prerequisite to this process required information (i.e., direct change likelihood and impact results) must be produced by experienced engineers. The concept of the model reduces input information preferences when creating hierarchical risk models. The model building practice is relying on prediction information from experts; thus, it is challenging to avoid subjectivity during the model building. The design concept is capable to prevent the unnecessary inputs data of elements and systems. It's ability reducing the risk of changes by the consistent estimation of risk across all hierarchy levels of a system.

1.1.4 The Motivation of the Research

This research is supported by two companies from two different industries. The UOP Honeywell (Oil & Gas) and Laing O’Rourke (Construction) companies are based in the United Kingdom and both need to effectively model and manage changes within their manufacturing systems. As part of this PhD research, follow-up interviews and meetings were subsequently conducted at the two companies to further understand the need for change modelling.

UOP Honeywell is interested in the development of methods that can adapt to changes within the organisation (while implementing the Honeywell Operational System) or changes external to the company (due to customer requirements). However, there was concern about the deployment and acceptance of such methods. In UOP Honeywell, as described by the Brimsdown plant manager, the expectation is that change management should help to reduce costs, increase resilience and boost plant performance. In particular, manufacturing employees need (1) to know who is interacting with the system and (2) smart change analysis to understand the change propagation process when changes have been made. This helps to minimise errors stemming from changes and improve operator productivity while providing an integrated view of complex interactions. The company expects effective management of change for better decision-making and, in the end, to improve operational effectiveness.

Laing O’Rourke is looking for a way to improve the resilience of novel construction elements and their associated design and manufacturing processes. Fundamental to this requirement is the importance of project management decision making, and the cross-team and cross-company information flow, design, manufacturing and assembly approaches and tools necessary to support effective decisions, which was stated at their quarterly AMSCI (Advanced Manufacturing Supply Chain Integration) consortium meeting. From the interview with a supply chain manager at Laing O’Rourke, it is clear that change propagation is unwanted and there is a need to understand its effects on the system. The company employee stated the need for a tool to assess change propagation effects at the early stage of the design process.

Laing O’Rourke particularly focuses on customer choice in different kitchen layouts and dimensions. The complexity of the kitchen assembly process of a module is determined by whether they contain a kitchen, an appliance, a utility cupboard, or a combination of the three. A module containing a kitchen requires extra work on the finishing line to install the required units and appliances and to make the required electrical and plumbing connections. Modules containing a utility cupboard require extra work due to the high volume of MEP (Mechanical, Electrical, and Plumbing) services in these modules. As a result, the investigation of this project has focused on developing the kitchen assembly process and design. This is because kitchen assembly is one of the governing factors of the complexity of a module, and as such can act as a bottleneck process. For that reason, improvements in the kitchen assembly process will lead to improvements in overall module assembly.

Kitchen assembly is also an area for which little prior work has yet been conducted by Laing O’Rourke, with test modular buildings so far having had kitchens installed using a traditional process. As such, there is a high potential in this area to have an impact on a project. It was also noted that having a system that could model the impact of change propagation on the organisation, and not only in one domain, could be useful in providing insights into the whole system. From the discussion above, change propagation is a problem which affects state-of-art manufacturers across different industries. Hence, there is a need to increase the understanding of manufacturing change propagation. Such a need provides the fundamental motivation for this PhD research. The intention of this research is to develop a method to integrate the manufacturing system domains and elements (i.e. product, process, and organisation) into one system by the efficient use of existing skills and knowledge to examine change and possible change propagation and reduce the system complexity

1.2 Research Gap

Research in reducing the impact of changes for Resilient Manufacturing Systems (RMS) has not been widely undertaken (Zhang, W. and Luttervelt, C.A.,2011; Gu *et al.* 2015). The elaboration of these gaps is detailed in the literatures review section from the selected key published literatures on resilient manufacturing systems (Table 2.2, page 21). Several challenges need to be overcome to map and integrate system domains (i.e. product, process, and organization) from different perspectives:

1. The approaches introduced to improve resilience are mainly about planning matters. Although some studies are using mathematical methods, such as those on a computer network, they are still too specific to apply to the entire system. Some others are focused on modelling for manufacturing and supply chain

systems, but the solutions are still too limited and cannot provide operation strategies which can deal with changes (Zhang and Luttervelt 2011).

2.Increase of system resilience by reducing manufacturing systems complexity by the redesign of the system elements and domains is needed to make the system either more robust or adaptable to change (Abech *et al.* 2006; Hoffmann *et al.* 2011)

3.There is a lack of tools to help system engineers to model a system change, complexity, and changeability of systems in manufacturing systems by using empirical data exception from industrial case studies in the industry. So, visualisation techniques and tools need to be developed to help designers work with the large volume of information that can be generated by the change propagation processes operating on integrated models (Giffin et al.2009).

1.3 Research Questions

The overall aim of this research is to understand how to design a Resilient Manufacturing System (RMS) while the system is subject to change. The thesis aims to highlight the need for a design strategy that is supported by specific selected methods. The main question of the research is summarised as follows:

The Main Research Question:
How can change prediction inform the design of resilient manufacturing systems?

This thesis aims to answer the main question through literature and develop a method by researching the current engineering change management (ECM) methods.The review of manufacturing change management described in Section 1.1 helped to answer the questions.This thesis sets out to answer the main research question by redesigning the current understanding of designing an RMS, modelling and managing changes as described in the literature. To establish an understanding of resilience and manufacturing change management, the first research question (RQ1) can be derived from the main research question:

RQ1: What are the characteristics of a manufacturing system that make it resilient to change?

Systematic literature reviews were conducted in the description study to answer this research question by reviewing the key publications on Manufacturing System Design (MSD), Resilient Manufacturing System

(RMS), Engineering Changes (ECs) and Engineering Change Management (ECM) subjects. Finding the answer to RQ1 led to the definition of the second research question:

RQ2: What is the role of engineering change prediction approaches in the long-term delivery of resilient manufacturing systems?

These questions were answered through a systematic literature search and categorisation and these results were used to identify available RMS methods. While the answer to RQ1 created the understanding of resilience, manufacturing system design (MSD), resilient manufacturing system (RMS), engineering changes (EC), and engineering change management (ECM), the answer to RQ2 delivered the EC methods for RMS.

1.4 The Scope of the Research

This research focuses only on the process of design of an RMS which has to withstand the effects of change propagation. This research aims to investigate the natural principles of change in response to MSD changes. Three interrelated research areas are proposed to simulate the design enhancements to existing manufacturing system (MS) architectures. These research areas involve:

- Construction models of the existing MS architecture design to identify potential improvements.
- Assessment of the complexity of the existing MSs to establish a reference standard when making decisions to redesign the existing architectures.
- Generating a methodology to redesign the MS to better design solutions at different levels of detail in a set of data (in terms of elements).

The direct stakeholders of this research are the system engineer, process engineer, managers and researchers involved in activities in the design of the RMS.

1.5 Chapter Summary

This chapter has introduced the research area of this thesis. It has summarised the background and motivation of designing manufacturing systems, resilient manufacturing systems (RMS) and change management for RMSs. This chapter has also presented the research questions to be addressed in the thesis and described the structure in which the work is presented. This thesis is structured in nine chapters that is illustrated in Figure 1.1 regarding the main stages of the research methodology discussed in more detail in Chapter 3. In the next chapter, the literature review for this PhD research is discussed in further detail.

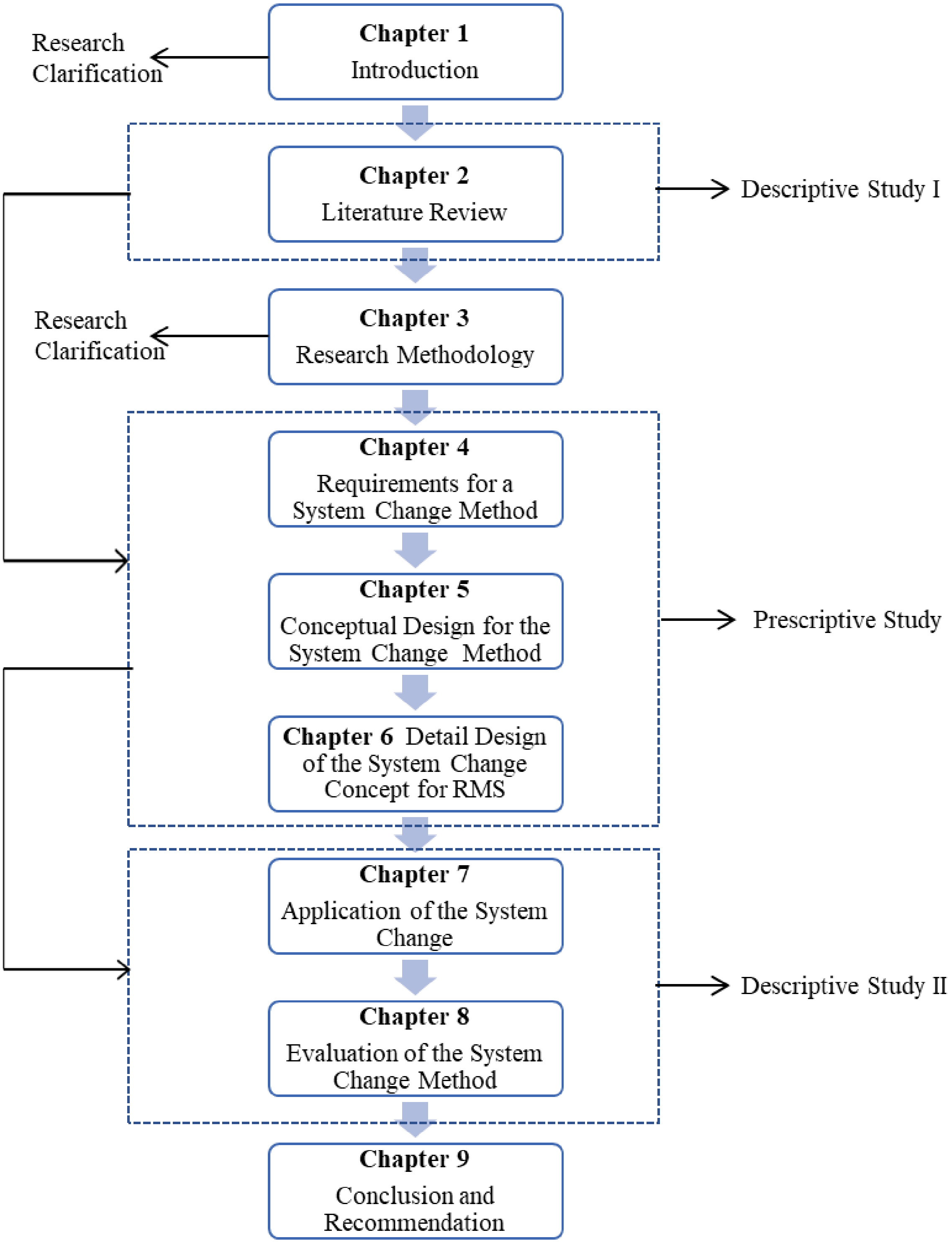


Figure 1.1: Overall structure of the thesis in the context of the design research methodology

2 Literature Review

2.1 The Need for Resilience

The previous chapter highlighted the research area of this thesis. It has also answered the main research question and the two supported questions to be addressed in the thesis and described the structure in which the work is presented. Therefore, one of the aim of this research is to explore an appropriate system change method for designing a Resilient Manufacturing system (RMS) and two research questions (RQs) are framed, RQ1: What are the characteristics of a manufacturing system that make it resilient to change? And RQ2: What is the role of engineering change prediction approaches in the long-term delivery of resilient manufacturing systems? This chapter addresses those questions by reviewing the literature on resilience, manufacturing system design, resilient manufacturing systems, engineering change, engineering change management, and engineering change models.

The chapter consists of seven sections. Section 2.2 discusses resilience in the literature. Section 2.3 explores resilience in the context of the manufacturing system. Section 2.4 presents guidelines for manufacturing system design (MSD) and designing a resilient manufacturing system (RMS). Section 2.5 presents the modelling of system changes. Section 2.6 re-visits the research questions. Lastly, Section 2.7 summarises the chapter.

2.2 Research on Resilience

The Oxford English Dictionary defines “resilience” as “the elasticity and act of rebounding or springing back and the capacity to recover quickly from difficulties”. The term resilience was used for the first time in ecological systems, introduced by Holling (1973). Holling (1973) defines the word resilience for ecosystems as a measure of the ability of the systems to absorb changes and still persist in their functionality. Holling (1973) focuses on maintaining the existing function of the system by absorbing influences. Further resilience research was undertaken in the study of the dynamics of ecological systems by, for example, Gunderson and Holling (2000), Walker *et al*. (2004), Fiksel (2003) and Folke (2006). Resilience in engineering first appeared as a new approach for both system design and system safety (Holling *et al.* 2002). One of the first publications on resilience as applied to engineering was "*Resilience Engineering: Concepts and Precepts*" (Hollnagel *et al.* 2007). The authors developed the basic concepts behind resilience engineering in order to cope with the complexity of the real world.

The idea of resilience has been applied in a variety of settings (e.g., psychology, biology, ecology, agriculture, safety management, information technology, business, and engineering). However, the term does not include specified concepts which have been broadly shared: different approaches and definitions are created by different authors. The literature review explores books, journal articles and conference papers. “*Google Scholar”* was used with a keyword search such as “Resilience”. 120 papers were selected to examine resiliency from different viewpoints. The most cited 18 papers are listed in Table 2.1 which have a direct link to the concept of ‘resilience' and which were thus considered for review. The table gives a diverse definition of resilience and also highlights the characteristic resilience behaviours by different authors and contents.

Table 2.1: Definition of resilience in the different disciplines

Author	**Content**	**Characteristics of Resilience**	**Resilience definition**
Carpenter *et al. 2001*	Ecology	Sustainability Self-organisation Adaptability Persistence	Resilience is the amount of change the system can experience and still remain within the same domain; the amount to which the system is capable of self-organisation and the system can build the capacity to learn to adapt.
Holling *et al. 2002*	Biological and Ecological	Adaptability Absorption	Resilience is the number of disturbances that a system can absorb before it changes state.
Fiksel 2003, Walker *et al*. 2004	Ecology	Adaptability Absorption	The capacity of a system to absorb a disturbance and reorganise while experiencing change while retaining the same function, structure and identity.
Folke *et al.* 2010	Ecology	Adaptability Transformability	Resilience is the ability to remain within a stability domain, continually changing and adapting yet remaining within critical thresholds.
Shadbold *et al.* 2011	Agriculture	Adaptability Transformability	Resilience is the capacity of a farming system to adapt to change in the environment and maintaining productive capacity in face of variability in industry-related factors.

Table 2.1: Definition of resilience in the different disciplines *continues.*

Author	**Content**	**Characteristics of Resilience**	**Resilience definition**
Zhang and Luttervelt 2011	Safety Management	Adaptability Recovery	Resilience is the ability of a system to keep or recover quickly to a stable state, allowing it to continue operations during and after a major accident or in the presence of continuous significant stresses.
Khan *et al.* 2009	Safety Management	Adaptability Absorption, Restoration, Recovery	Resilience is the ability of systems, infrastructures, government, business, and citizenry to resist, absorb, and recover from or adapt to an adverse occurrence.
Ahmed and Kanike 2007	Information systems	Adaptability Absorption Recovery	Resilience refers to a system's capability to 'provide, and maintain an acceptable level of service in the face of various faults and challenges to normal operation to absorb shocks, avoid failures, and recover rapidly.
Bahamra *et al*. 2011a	Organisational	Adaptability Vulnerability	Resilience is a function of both the vulnerability of a system and its adaptive capacity.
Herman *et al*. 2011	Psychology	Adaptability Recovery Vulnerability	Resilience is the overcoming of stress or adversity, and it is thus differentiated from positive mental health.
Hamel *and* Valikangas 2003	Business - Strategic management	Adaptability Re-organisation	Resilience refers to a capacity for continuous reconstruction.
Berkley and Wallace 2010	Electrical and Nuclear	Anticipation Absorption Adaptability Robustness	Resilience is the ability to reduce the magnitude and/or duration of disruptive events and to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event.
Hollnagel *et al.* 2006	Engineering	Adaptability Absorption Robustness	Resilience is an ability to sense, recognise, adapt and absorb variations, changes, disturbances, disruptions and surprises and feedback
Chalupnik, Wynn and Clarkson. 2013	Engineering	Reliability, Robustness, Adaptability Flexibility	The ability of a system, as-built/designed, to do its basic job or jobs not originally included in the definition of the system's requirements is uncertain or changing environments.
Urken *et al.* 2012	Engineering	Adaptability, Robustness Sustainability	Resilience is a dependable system adaptability from a multi-phase process that includes graceful degradation and time-constrained recovery, re-stabilization, and prevention of catastrophic failure.
Rydzak *et al.* 2006	Manufacturing/ Production	Robustness Adaptability	Resilience is as a way to deal with uncertainty and disturbances.
Abech *et al.* 2006	Manufacturing/ Production	Adaptability Flexibility Robustness	Resilience is an ability of a system to return to its original state or move to a new one, more desirable, after being disturbed

The definition of resilience in ecology, biology and agriculture contexts is the dynamics of dealing with disturbances, how a system absorbs the impacts of stress or shock and while retaining the same function, structure and identity (Carpenter *et al.* 2001; Fiksel 2003; Walker *et al.* 2004; Folke *et al.* 2010; Shadbold *et al* 2011). The characteristic ability of a resilient system as described in the literature is to resist degradation by absorbing effects (as in *Persistency, Adaptability, Transformability, Self-Organising and Sustainability)*. Ecosystem types of systems have an *adaptive capacity* in response to the influences (Martin-Breen and Anderies 2011). So, the system's ability to absorb the influences depends on the capacity of a system. The capacity of the system responds to changing external drivers and internal processes by a*daptability* behaviour and thereby allows for development within the current stability domain (Folke *et al.*

2010). However, *transformability* is the capacity to create a fundamentally new system (Walker *et al*. 2004) such as computers have been replaced by tablets. The *self-organising* ability also enables the creation of new systems in response to influences, and continual change and adaptation to remain within a stability domain. Additionally, a system is able to sustain resilience through adaptive or transformable system life-cycle properties (*Sustainability*).

Resilience in *safety systems* (e.g. infrastructures, government, business, and community) and *information systems* mainly refers to *adaptability, absorption* and *recovery* which are linked to preventing, protecting, responding to and recovering missions (Ahmed *et al*. 2007; Zhang and VanLuttervelt 2011). After major harm or destruction to a system, it recovers quickly to a stable state with resilience ability (Khan *et al*. 2009; Zhang and VanLuttervelt 2011). Adaptability and risk-informed planning are critical considerations (planning resilience) in advance and are particularly key in complex safety systems before systems suffer undesired consequences (Zhang and VanLuttervelt 2011).

However, resilience in the *business environment* usually takes a performance improvement to prompt the work of renewal and refers to an adaptive capacity for continuous reconstruction (Hamel *and* Valikangas 2003). In contrast, at the *organisational* level, system stability is significant for an element to return to a stable state after a disturbance. Similarly, in *psychology*, the vulnerability is central to resilience. The vulnerability of an individual drives resilience by overcoming stress to arrive at positive adaptation, maintaining mental health and recovering from adversity. The adaptive system approach is mainly applied to models of individual dynamics (Herman *et al*. 2011).

The resilience in *Engineering* and *manufacturing/production* systems commonly refers to *Adaptability, Robustness, Reliability and Flexibility* (Table 2.1). Resilience is defined as dependable system adaptability from a multi-phase process that includes recovery, re-stabilization, and prevention of failure (Urken *et al.* 2012). The concept of resilient systems was investigated and extended to the manufacturing/production system; it emerged as the ability of a system to return to its original state or move to a new one, more desirable, after being disturbed in an uncertain environment (Abech *et al*. 2006; Rydzak *et al*. 2006).

The various contexts of research are assessed for resilience descriptions. Although the meaning of the term may change across all of these contexts, the concept of resilience is mainly associated with the capability and ability of a part to return to its original state after a change. Still, a clear definition of resilience is needed for *manufacturing systems* which not only explicitly define, but also describe the characteristics of resilience within the manufacturing system in order to effectively manage changes. Manufacturing system resilience needs to be explored in order to achieve a successful move towards RMS. For this reason, the following sub-sections reviewed: (1) manufacturing system definitions, which is discussed in Section 2.3.1; (2) a deep understanding of resilience in the manufacturing system context which is explored in Section 2.3.2; (3) an appropriate definition of manufacturing resilience and resilience properties, presented in Section 2.3.3.

2.3 Manufacturing Systems Resilience

Research on manufacturing system resilience has not been paid much attention until recent years (Zhang and Luttervelt 2011; Hu and Holloway 2013; Heisel 2013; Gu *et al.* 2015). Resilience in manufacturing systems is defined as a natural behaviour response to a variety of external disruptive events from natural disasters (e.g., hurricanes, earthquakes) to man-made accidents (e.g., terrorism, supplier bankruptcy) (Sheffi and Rice 2005). Many of these studies focus on *supply chain networks* where risk management tools are developed to reduce the impact of supply chain disruptions (Sheffi and Rice 2005). However, tools for designing a resilient manufacturing system (RMS) for customer requests, supplier changes or process change etc. are still missing, although the field of RMS is still growing in both academic research and industrial practice.

2.3.1 Manufacturing Systems

The definition of Manufacturing systems in a comprehensive review of studies published literature are described differently. Manufacturing systems definition in the most related literature with this thesis objective are described for instances: (1) a manufacturing system is a collection or arrangement of operations and processes that are related to each other to produce valuable products (Kim 2002); (2) a manufacturing system as an arrangement and operation of machines, tools, material, people and information to produce a value-added physical, informational or service product whose success and the cost is characterised by measurable parameters (Cochran et al. 2001); (3) a manufacturing system consists of machines, inspection stations, and intermediate buffers, that are interconnected to perform required operations for the end product (Gu et al. 2015). Slight differences are observed in these definitions.

A manufacturing system includes interacting sub-systems and elements. In a manufacturing environment, a reactor or the extraction process could be a sub-system of the overall manufacturing system and elements could be job activities. The interactions between the system elements are defined by material flows and information flows through the system. However, Cochran (1994) differentiates manufacturing systems from production systems. Production systems include the manufacturing system along with additional functions such as product development, marketing, supply chain management, and finance.

In order to define a manufacturing system, probably the best way is to first understand the *system* and *the system approach*. Vaughn *et al*. (2002) describe the system as comprised of elements that interact with one another to do something or perform a specific function. The function of systems cannot be accomplished by the elements of the system alone (Vaughn *et al.* 2002). Naylund and Andersson (2012) address a "holistic" system perspective which means individual elements are viewed not only in terms of their interactions with other elements of a system but in terms of the overall objectives, or functions of the system. The International Council on Systems Engineering (INCOSE) Handbook (2011) defines a system as "an integrated set of elements, subsystems, or assemblies (i.e. people, processes, information, organisations and services, as well as software, hardware and complex products) that accomplish a defined objective".

The main idea in the *system approach* is that the individual of system parts, as well as the relations between the parts, may affect the whole system (Checkland 1999). Seliger *et al.* (1989) define the system in three system aspects which are illustrated in Figure 2.1. (1) The functional aspect (A), which describes the behaviour of a specified system and its understanding. The system is considered as inputs are converted into outputs; (2) the structural aspect (B), which describes the system as a set of elements that are connected by relations (Seliger *et al.* 1989); (3) the hierarchical aspect (C), which considers the system as a part of a larger system in which a complex whole is divided into a hierarchical system (Seliger *et al.* 1989). The challenges in designing manufacturing systems consider a functional aspect as well as the subsystems and elements which include a structural and hierarchical perspective of systems. When applying a hierarchical perspective, the division starts from the largest function and thereafter the system is divided into smaller systems (e.g. subsystems, system elements) until every subsystem only has a few relevant functions (Seliger *et al.* 1989)

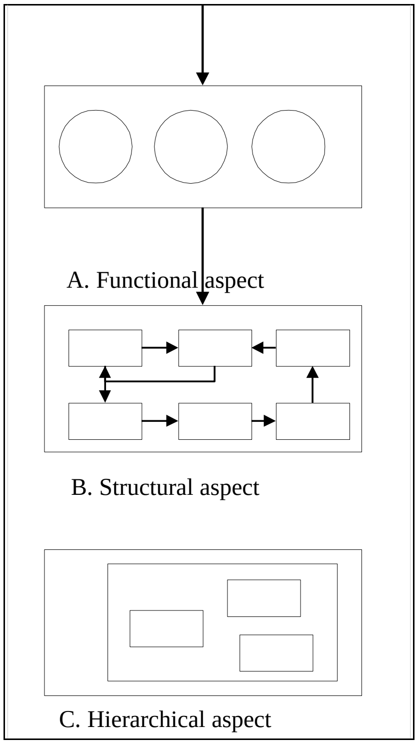


Figure 2.1: System aspects (Seliger *et al.* 1989)

The definition of a system for this thesis is developed as follows:

A system is a group of elements, having interactions and interrelated entities that are surrounded and influenced by its environment.

A manufacturing system includes interacting sub-systems and elements. In a manufacturing environment, a reactor or the extraction process could be a sub-system of the overall manufacturing system and elements could be job activities. The interactions between the system elements are defined by material and information flows through the system. Cochran (1994) differentiates manufacturing systems from production systems. Production systems include the manufacturing system along with additional functions such as product development, marketing, supply chain management and finance. The definition of a manufacturing system for this thesis is the combination of the definitions which are described in this section, as follows:

A manufacturing system is to produce a value-added product by converting input raw materials by processing them. The elements of manufacturing systems are resources that are necessary for this conversion, such as people, equipment, material, and information.

As discussed previously, anufacturing systems are complex systems which involve other subsystems and elements and connections to manufacture the required products (Algeddawey and ElMaraghy 2011). Hence, the manufacturing system should be viewed in a holistic way that utilizes the principles of systems engineering (Vaugen *et al*. 2002; Naylund and Andersson 2012). For instance, Figure 2.2 illustrates a general representation of the manufacturing system elements (product, resource and order) and their connecting domains (process, production, and business) with the purpose of connections (e.g. Planning, Scheduling, Methods) (Naylund and Andersson 2012). As seen in the figure, the structure of a manufacturing system contains elements with different roles as well as their related domains and activities. The key point in Figure 2.2, the structure of a manufacturing system contains elements with different roles as well as their related domains and activities. For instance, in the figure, Products symbolize the manufacturer's offers to its customers. Resources indicate availability to manufacture the products. Orders link to products that are ordered by customers. The process domain represents the capabilities that are needed to manufacture the products. The production domain defines the capacity to manufacture in customer orders. The business domain is responsible for markets in order to the customers obtain thei orders (Naylund and Andersson 2012).

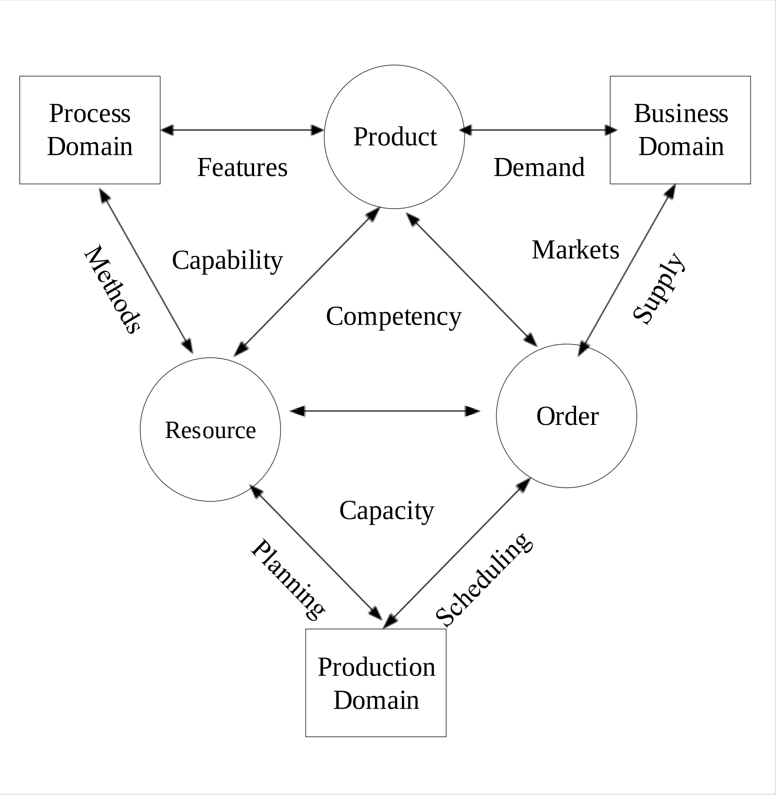


Figure 2.2 Representation of a manufacturing system (Naylund and Andersson 2012)

2.3.2. Resilience in Manufacturing Systems

Complex systems require '*resilient abilities'* to sustain normal operations when faced with internal or external changes (Zhang and Luttervelt 2011) for today's manufacturing systems. Changes in manufacturing systems interrupt normal operation conditions and cause operation cost. Managing the complexities effectively and systematically requires building more resilient systems. In Table 2.2, twenty most relevant research studies have been analysed to understand the characteristic resilience abilities of manufacturing systems in response to manufacturing changes alongside the models or frameworks used to design resilience.

The resilience of the manufacturing systems has been assessed by researchers in various industries and the majority of the papers appear in oil and gas, petrochemical, biofuel production, chemical production, pharmaceuticals (see Table 2.2). Secondly, resilience behaviour is reviewed further in the automotive, aircraft, aerospace industries. In the subject matter, few researchers focus on resilience in machine performance, machine capability, manufacturing performances that refer to the machine's capability to recover its functions after partial damage to lead to successes from failures. The other manufacturing businesses which focus on resilience is *paper tissue manufacturing, office equipment production, distribution process, steel processing*.

Changes can be *predictable* or *unpredictable* and either *internal* or *external* and can influence the manufacturing system's ability to perform its objectives. Internal changes arise due to defective processes within the business. According to the literature listed in Table 2.2, changes can arise internally from various sources such as material shortages, machine reliability and capability, an explosion in a reactor, natural or man-made disruptions changes (e.g. Gardner and Colwill 2016; Heinicke 2014b; Hu *et al.* 2013; Rydzak *et al.* 2006). On the other hand, external changes arise from, for example, production planning scheduling and control, technology changes, networking disruptions, customer preferences, changes in revenues and costs, system design and structural changes (e.g. Thomas *et al.* 2015; Dinh *et al.* 2012; Abech *et al.* 2006; Fiksel 2003).

Fiksel (2003) proposes the concept of resilience as enabling organisational survival and that resilience is to be viewed as a characteristic system property within aircraft and nuclear plants. The author considers that a design system with characteristic resilience takes advantage of properties such as 'diversity, efficiency, adaptability, and cohesion'. Resilience is explored in the context of '*Sustainability'* to improve the manufacturing system conditions and the capability of a business element of adapting to changes (e.g. Gardner and Colwill 2016; Byard *et al.* 2015).

The other key literature in Table 2.2 focuses on both '*Reliability* and *Robustness'* abilities in complex industrial systems. This increased the safety level of systems and the efficiency of organisations. The speed of responding to disturbances is critical to building resilience systems in the high-risk environment. Rydzak et al. (2006) and Zhang and Luttervelt (2011) suggest reliability and robustness properties support long-term functionality and effectiveness of industrial organizations in an uncertain world. In this way, resilience addresses the dynamics of dealing with disturbance and how a system absorbs the impacts of stress or shock and how it re-organizes afterwards. Thomas et al. (2015) and Heinicke (2014b) suggest '*Robustness and Agility'* with respect to the resilient system are properties to be considered in terms of a closed-loop control system in a manufacturing environment Ismail *et al.* (2011) outline an approach that builds on the principle that manufacturing supply chain resilience occurs as a result of the implementation of operational and strategic capabilities. In Table 2.2, the authors argue that manufacturing-based small companies involve the impact of the potential changes on revenues and cost that link into the overall strategy of the company to be resilient when they are both strategically and operationally agile.

According to some of the key literature in the table 2.2, product and process development are potentially high-impact disruption stages, therefore manufacturing systems must be *flexible* to absorb the impact of disruptions and quickly recover to normal conditions (e.g. Gu *et al.* 2015; Azadeh and Salehi 2014). Flexibility is a strategic and operational attribute for manufacturing performance (e.g. Gu *et al.* 2015; Azadeh and Salehi 2014). On the other hand, chemical design and process are complex hazardous technical operations, wherein resilience abilities are described as including *flexibility and recovery* to improve quickly after an upset (Dinh *et al.* 2012). Zhang and Luttervelt (2011) address resilience in engineered systems, referring to their capability to recover their functions after partial damage to achieve success from failures. The authors propose the resilience properties of a manufacturing system as *recovery* and *adaptation* in machine performance and emergency evacuations. Similarly, Madni and Jackson (2009) refer to building resilient systems that are able to avoid accidents by anticipation and survive disruptions through *recovery*, and grow through *adaptation*. Hu *et al.* (2013) introduce a model framework to address the resilient operations of manufacturing networks and solve the optimal operation for downstream storage of serial networks. The authors describe resilience as the ability of an enterprise to survive potentially high-impact disruptive events and which is characterised by the *absorbing capability* of the enterprise and its *recovery capability* such as quick restarting of production.

Hu *et al.* (2013) characterise resilience as including redundancy to reduce the negative impact of change and enable a system to quickly resume production or transportation by redistributing its resources. Such resource redundancy is related to alternative resources, for example, alternative suppliers, to keep the desired operation when the change causes loss of capacity. Gu *et al*. (2015) define resilience as the ability of a system to tolerate potentially high-impact disruptions, and it is characterized by the capability of the system to absorb the impact of disruptions and quickly recover to normal conditions. Their findings show that built-in *redundancy and flexibility* can improve system resilience performance, especially when the disruption is long, or the system has a small number of parallel machines in each stage (see table 2.2).

Table 2.2: Summary of resilient manufacturing systems in the literature

Author	**Characteristic of Resiliency**	**Industry**	**Change**	**Model or Framework**	**The Definition of Resiliency**
Gardner and Colwill 2016	Sustainability	Renewable energy, Military and Aerospace	Critical material shortages	Framework	Resilience: "the capability and ability of an element (in this case a business), to return to a pre-disturbance state after a disruption."
Gu et *al.* 2015	Flexibility Redundancy	Machine capability	Unexpected disruptive events that occur on one machine and causes the machine to be down for a certain period	Bernoulli Reliability Model with Numerical Case Studies	Resilience is defined as the ability of a system to withstand potentially high-impact disruptions and it is characterized by the capability of the system to absorb the impact of disruptions and quickly recover to normal conditions.
Byard *et al*. 2015	Sustainability Agility Flexibility	Various Industries (72 UK manufacturing companies)	Potential business failures	A Framework applied through data analysis and industry survey	Resilience is the ability of a company to be able to return to its original state or to move towards a new desirable state after being disturbed.
Thomas *et al.* 2015	Sustainability Flexibility Adaptability Agility	Aerospace and Automotive	Management and business improvement	Strategic Framework (The conceptual fit model)	Business resiliency is a term used frequently to describe a company's ability to adapt and cope with disturbance.
Heinicke 2014	Agility Robustness	Steel Processing	Production planning and control	Functional Map	The concept of resilience is the ability of a system to cope with change effectively.
Azadeh and Salehi 2014	Flexibility	Oil, Gas, Petrochemical Companies	The efficiency gap between managers and operators	Integrated Framework and Quantitative Data Analysis	Resilience can increase the reliability and safety level in a high-risk environment, the resilience-based system is responding to disruptions and challenges efficiently.

Author	**Characteristic of Resiliency**	**Industry**	**Change**	**Model or Framework**	**The Definition of Resiliency**
Mu *et al.* 2010	Adaptability Transformability	Biofuel Production	Rapid, nonlinear and unpredictable changes from technology	Quantitative Metrics	Resilience is the capacity of a system to maintain structure and function against sometimes large and unexpected disturbance.
Hu *et al.* 2013	Redundancy	Office Equipment Production	Production and Inventory Changes	The framework, A Mathematical Model	Resilience is the ability of a system or enterprise to minimize the effects of disruption.
Dinh *et al.* 2012	Flexibility, Recovery	Chemical Design and Process Operations	Explosion by flammable materials, evacuation and the high reactor temperature	Literature Reviews and Expert Opinions	Resilience, which is the ability to recover quickly after an upset, has been recognized as an important characteristic of a complex organization handling hazardous technical operations.
Phoombop lab 2012	Robustness	Automotive Bodies and Aircraft Fuselages	Frequent Market Changes, Customer Preference, Standard/Regulation, Technologies, Unexpected Disruptions	Stream-Of-Variation (SOVA) Model, Functional Dependence Model, DSM and Task Flow Chain	Resiliency is the ability to deal with faults (abnormal situations) and unexpected changes that emerge throughout the product life-cycle.
Ismail *et al.* 2011	Agility, Flexibility Robustness Responsiveness	Automotive, Construction, Computing, Pharmaceutical, Aerospace	The potential impact of change on revenues and costs	A strategic framework	Manufacturing–based small companies are resilient when they are both strategically and operationally agile.
Zhang and Luttervelt 2011	Reliability Adaptation, Recovery	Email System, Machine Performance, Emergency Evacuation	User Satisfaction And Demand, Resources Availability	Twin-FBS model	Resilience is applied to engineered systems, referring to their capability to recover their functions after partial damage and achieve success from failures.
Hoffmann *et al.* 2011	Adaptable Robustness	Manufacturing Sensors	Design change	A query-based approach that is informed by the successful systems strategy of service-oriented architecture (SOA)	Resiliency is the rapid redesigning of platform-based architecture and is often determined by adaptability and trustworthiness.

Author	Characteristic of Resiliency	Industry	Change	Model or Framework	The Definition of Resiliency
Madni *and* Jackson 2009	Adaptable Recovery Robustness	Various industries	Natural/man-made, external/systematic, single agent/multiagent, short-lived/during disruption	Conceptual framework	Resilience engineering is concerned with building systems that are able to circumvent accidents through anticipation, survive disruptions through recovery, and grow through adaptation.
Karlsson 2008	Optimisation Flexibility Persistency	Automotive	Risk assessment for a business continuity plan	A framework supported with a case study	Resilience refers to the level of persistence of relationships in a system.
Rydzak *et al.* 2006	Robustness Reliability	Refineries and Chemical Plants	Internal/external stress, Machine reliability	System Dynamics Models	Resilience refers to the dynamics of dealing with disturbance, how a system absorbs the impacts of stress and how it re-organizes afterwards.
Allen *et al.* 2006	Adaptability Robustness Recovery	Paper Tissue Manufacturing	Structural changes and major innovations	Multi-Agent Modelling	The ability of resilience is to recover from mishaps, but as a proactive, structured and integrated exploration of capabilities within the system to resist and prevail against unforeseen events.
Abech *et al.* 2006	Adaptability Robustness	Oil Distribution Plant	Major System Failure (i.e. Explosion)	Monitoring changes with a knowledge-based approach	Resilience is the capability to adapt to handle disrupting events especially those that challenge the base of plans and procedures
Carvalho and Machado 2006	Adaptability	Production System	Planning and Scheduling Production Systems	The Fuzzy Logic Theory	Resilience is the ability to return, rapidly, to the initial stage or to an improved one, more desirable, after being disrupted.
Fiksel 2003	Diversity Efficiency Adaptability Cohesion Sustainability	Aircraft Nuclear Plants	Organisational Changes	A Theoretical Systems Design Protocol	Proposes the concept of resilience enabling organisational survival and that resilience is to be viewed as an inherent system property rather than an abstract goal

2.3.3 Comparing Resilient Manufacturing System Lifecycle Properties

The key resilience literature for manufacturing systems has been comprehensively examined and listed in Table 2.2. The finding is that resilience is achieved through eight characteristics: robustness, adaptation, flexibility, agility, sustainability, reliability, recovery and redundancy (Figure 2.3). In order to define the meaning of resilience and the characteristics of resilience in the manufacturing system context, the resilience properties must be structured by considering manufacturing system reactions to change or the ability of manufacturing system to change.

Figure 2.3: Characteristics of resilience in manufacturing systems from the literature

Sustainability, Reliability, Recovery, Redundancy

Reliability and resilience are both frequently seen in a system, however, their responses in a system towards changes is different. Reliability is associated with system performance where systems are either functional or failed. Reliability may be the goal of a system; resilience may be realistic cooperation that reflects the nature of changes. *Sustainability* and resilience are both used to describe a system in terms of life-cycle analysis and structure analysis (Carpenter *et al*. 2001). However, sustainability is about the achievement of the system to continue to function in the future (Chalupnik *et al.* 2013; Urken *et al.* 2012) and tends to focus on preserving traditional methods of resource use (Marchese *et al.* 2018). In contrast, resilience initiatives tend to focus on adapting to new conditions. In addition, sustainability is a broader concept than resilience and the literature mainly consider it in the context of ecological issues (Fiksel 2003) and it may be supported in ways that don’t involve resilience such as risk aversion, crisis recovery, increased efficiency (Martin-Breen and Anderies 2011). Figure 2.4 illustrates how the resilience of a system can impact that system's sustainability and addresses how a resilient system can become sustainable after recovering from disruption through the adaptive element of resilience (Marchese *et al.* 2018).

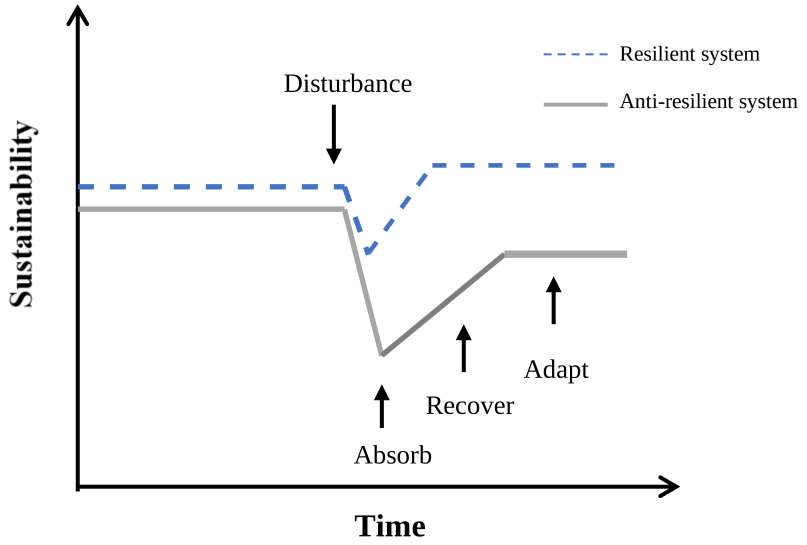


Figure 2.4 Representations of the Resilience and Sustainability, Recovery and Adaptation (Marchese *et al.* 2018)

Recovery is one of the adaptive elements of resilience which resilient systems can build to tolerate impact disruptions through the capability of the system to absorb the impact of disruptions (i.e. a capability of speed increase) (Gu *et al.* 2015). In engineering research, the concept of resilience is rarely used to focus on a system's recovery (Fiksel 2007). *Redundancy* is also different from resilience. Redundancy is related to putting alternative resources in place in response to changes rather than a system being able to quickly gain stability and adaptability by itself, which resilience implies. This thesis, therefore, does not consider resilience as system life-cycle properties of sustainability, reliability, recovery, and redundancy.

Adaptability, Robustness, Flexibility, Agility

These concepts are often confused, and they are characteristically different, and which strategy would work best depends on the manufacturing system. According to the key literature, it is essential to distinguish that *robustness* and *adaptability* are different from *flexibility* and *agility*: the ability to change movement (flexibility/agility), ability to quickly gain stability (robustness) and ability to self-organise (adaptability) are system behaviour to response changes. However, flexibility and agility are strategic characteristics of systems which have their roots in robustness and resilience (Jackson, 2009). Fricke and Schulz (2005) classify the aspect of changeability in a diagram with these four system life cycle properties (Figure 2.5). The clear difference between the left side and right-side properties is whether external influences are necessary to change the system.

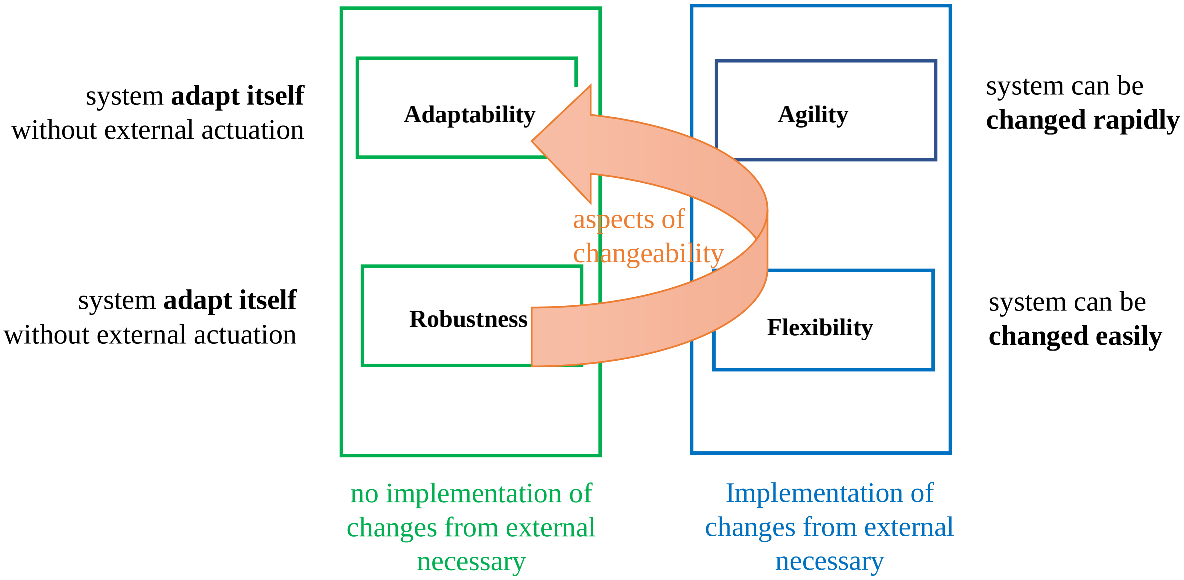


Figure 2.5 Aspects of changeability with four engineering lifecycle properties (Fricke and Schulz 2005)

A considerable amount of literature about engineering resiliency states that robustness is in a way the foundation for the resilient manufacturing organization (see Table2.2). However, agility enables a reaction to those severe disturbances which cannot be tolerated by the robustness of a production system **(**Heinicke 2014). Many illustrative examples compare a wide range of these lifecycle properties. For instance, Heinicke (2014) demonstrates in Figure 2.6 that the differences between the robustness with minor disruption of the system and disturbances that require a quick reconfiguration of the system are based on its agility property. Agility refers to a quick reaction to unexpected changes and thus is similar to flexibility (Ivanov and Sokolov 2013). Resilient behaviour combines two dimensions: agility, which expresses *reactive strategies*, and robustness which suggests *proactive strategies*. Manufacturing systems need to be more proactive in rapid or planned changes. Flexibility or agility can be seen as the characteristic capability to transform a current direction to adapt to changes, whereas robustness refers to the ability to tolerate such changes without adapting.

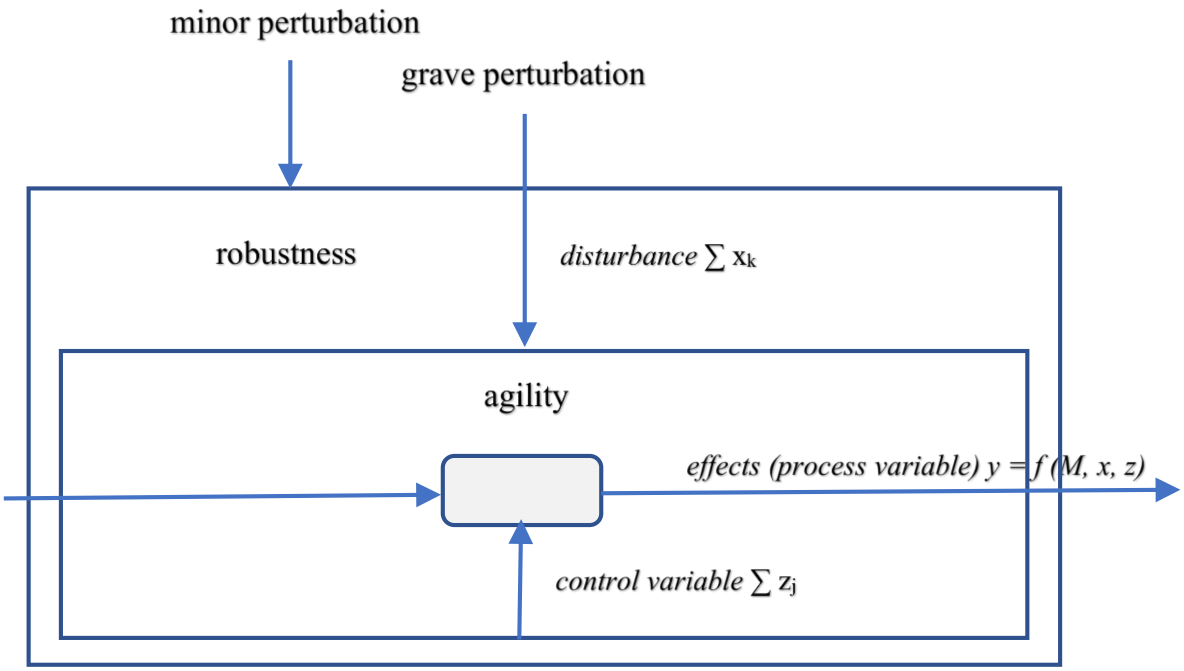


Figure 2.6.: Comparison of robust and agile behaviours (Heinicke 2014)

A r*obust* system can effectively maintain a given set of capabilities in response to external changes to deliver desired functions in spite of changes in the environment or internal variations (Ross *et al.* 2008. *Adaptable* and *flexible* systems are often differentiated by whether the *change agent* is within the system or whether it is internal or external changes to the system (Ross *et al.* 2008). A flexible system is usually modified from outside the system by an agent (McManus, 2008). An adaptable system, on the other hand, may undergo self-modification and be continuously adaptive. *Flexible* designs thus enable a system to be modified to meet different needs and, relating to concepts from ecological literature, achieve different states.

As seen that in Table 2.2, it can be interpreted that robustness is in a way a foundation for resilient organisations. The ability to change and adapt is therefore linked with the attributes of resilience. Chalupnik *et al.* (2013) compare robustness and adaptability which is shown by an explanation on the right-hand side in Figure 2.7. The ability to survive (robustness) is likely to be more important in a business setting than the ability to change course (flexibility or agility).

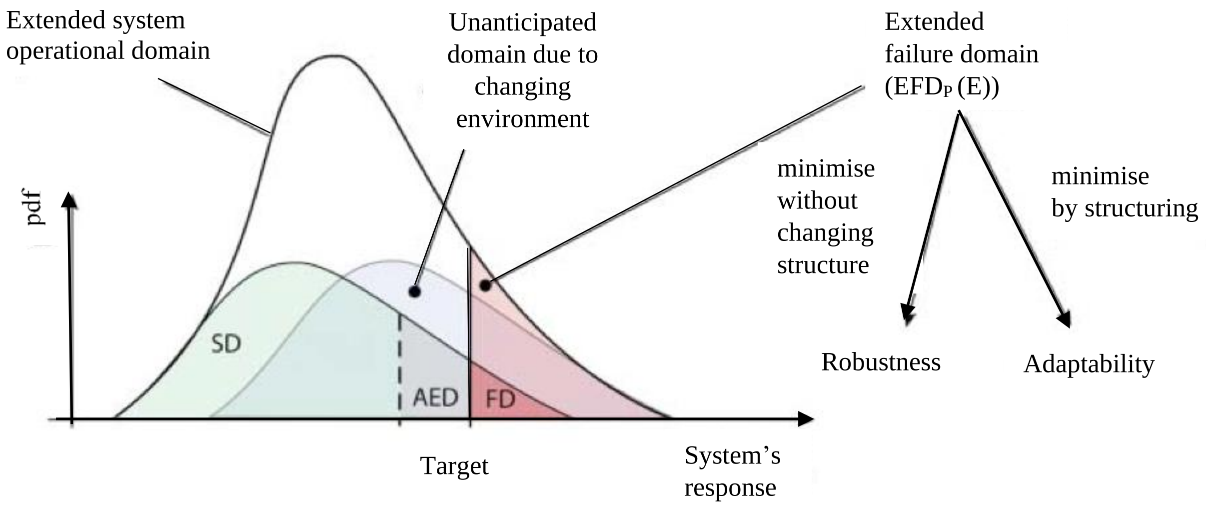


Figure 2.7: Comparison between robustness and adaptability (Chalupnik, Wynn and Clarkson 2013)

In conclusion, *robustness* and *adaptability* come very close to the term of resilience in the manufacturing system context. Due to the operational/strategic effects of the manufacturing systems considered here, the terms of flexibility and agility are not within the scope of resilience in this study. A manufacturing system can behave resiliently if it is properly functioning with regard to changes such as technological innovation, changes in customer needs, new legislation (Hollnagel *et al.* 2007). The key literature describes the resilience behaviour in the relationship between change reaction and system performance under the change. RMSs need to quickly return to their previous or improved or more desirable state through *changeability* behaviour after disruptions (Fricke and Schulz 2005; Ross 2006). Frequent changes on such as customer preference, standards/regulation, technologies, structural changes and major innovation within the manufacturing environment require robustness or adaptable ability to deal with change effects quickly and efficiently. The *integrated* and *restructuring* capabilities of the system keep resisting changing and succeeding to change towards robust or adaptable properties (e.g. Hoffmann *et al.* 2011; Madni and Jackson 2009). While a variety of definitions of the term resilience in a manufacturing system context has been suggested, this thesis adopts the definition first proposed by Hoffmann *et al*. (2011):

> **Resiliency** is the ability of manufacturing systems to respond to change through a rapid redesign using an architectural approach and determines the ability and robustness of the whole manufacturing enterprise

2.4 Manufacturing System Design

Manufacturing systems operate in a constantly changing environment (Whindehal *et al.* 2005). Pressures from globalisation have forced manufacturing enterprises to respond rapidly to changes such as the constant innovation of products, technology or requirements from customer demands, reducing product cycle and cost (Nylund *et al*. 2009). Manufacturing businesses need a strategy to design a robust and adaptable manufacturing system to respond to changes rapidly and efficiently (Hamraz *et al.* 2013). In order to achieve these changes, a manufacturer needs to understand the interrelationships among the different system elements and integrate these properly with the rest of the manufacturing system elements through system design (Cochran *et al.* 2001; Vaughan *et al*. 2002).

The definition of the *system design* is the planning of the overall set of elements and actions establishing a system, together with the rules for their relationships in time and capacity (CIRP, 1990). Design of manufacturing systems includes defining the problems, objectives and outlining the problem-solving and detailed design of proposed manufacturing systems for decision-making (Bellgran and Safsten 2004). Some systems are very complex and hard to design and operate because they have elements, and those elements interact in complex and sometimes unpredictable ways. It takes a long time for a manufacturer to learn all the interactions that are known, and even longer to find the hidden ones (Benkamoun *et al.* 2014).

Cochran *et al.* (2001) define manufacturing system design (MSD) as a means to understand: (1) the relationships between high-level system objectives (i.e. increasing customer satisfaction, reducing system throughput time) and the interrelationships between design decisions (i.e. equipment design and selection, system layout), (2) the interrelations, and dependencies among various elements of a system design that determine its ability to meet high-level requirements and objectives. A similar approach but the different interpretation is framed in Figure 2.8 by Vaughan *et al*. (2002). The authors divide MSD into two parts, the top half representing the manufacturing system *infrastructure* design (including the decision making or strategy formulation activities such as Business Unit, Corporate Level, Stakeholders) and the lower half the *structure* design (including the detailed design, piloting and modification of the manufacturing system). The infrastructure part includes detailed MSD.

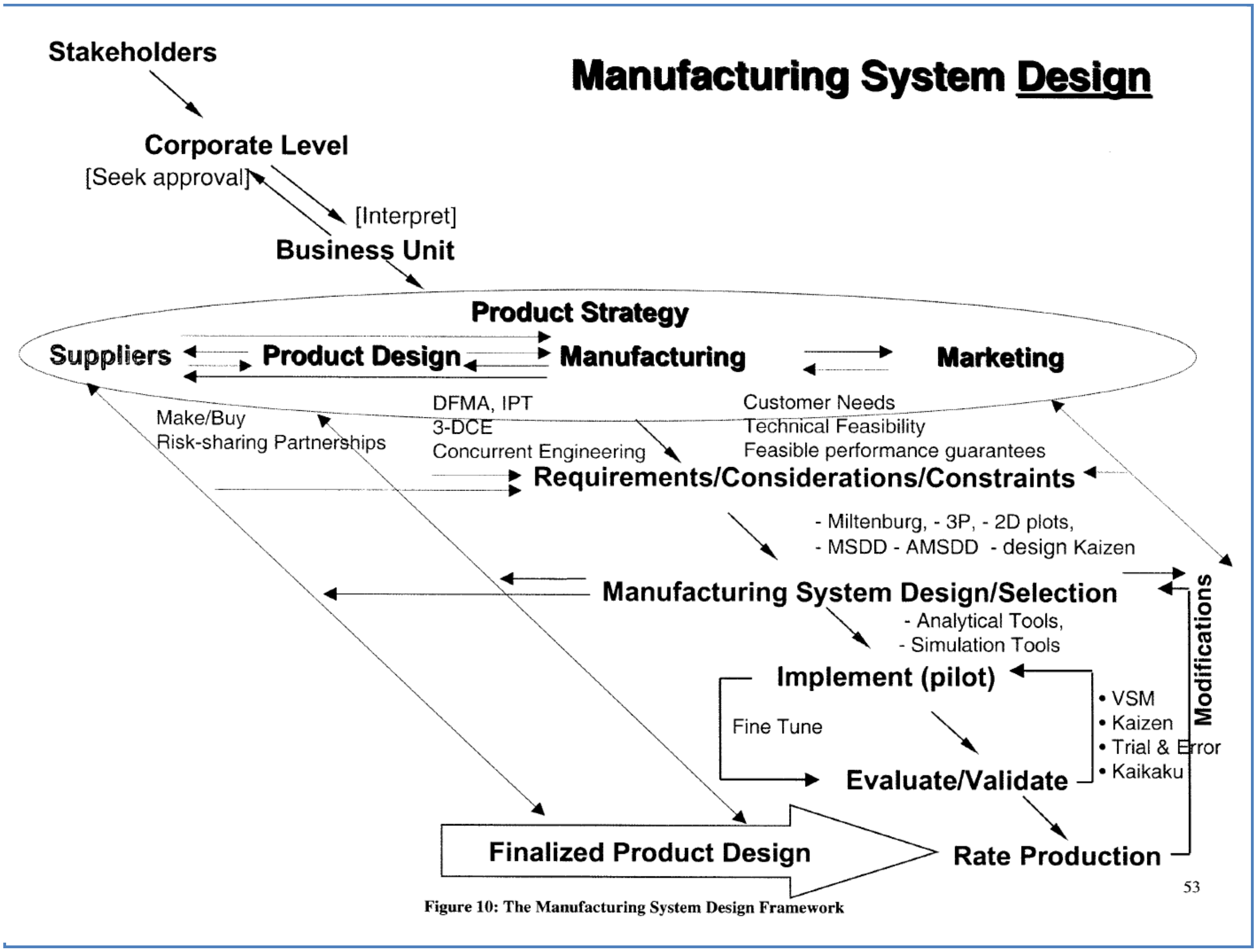


Figure 2.8: Representation of the manufacturing system design (Vaughan *et al.* 2002)

All definitions of MSD show that a holistic approach is needed to enable the design of a manufacturing system, and this covers all subsystems and elements as well as the relations between the elements (Bennett and Forrester 1993). A systematic representation of MSD is of benefit to integrate the system elements functionally. Evaluation of MSD elements and the effective communication of those elements across the MSD domains need *an integrated approach* which could greatly increase the effectiveness and efficiency of the MSD (Cochran *et al.* 2001; Kim 2002; Naylund *et al.* 2009). The following section, therefore, discusses challenges in MSD by reviewing all aspects of operating a manufacturing system that is necessary to run a business.

2.4.1 Challenges in Manufacturing System Design

Manufacturing systems engineering is significantly affected by advances in technology alongside the low-cost target of companies (Gershwin 2006). The change requirements lead manufacturers to look for a better systematic way of rapidly and constantly adapting to new innovative technologies and to be more responsive to changing global markets. Designing a manufacturing system to achieve a set of strategic objectives involves making a series of decisions over time (Hayes and Wheelwright 1979; Cochran *et al.* 2001). Making these decisions requires an understanding of the interactions among various elements of manufacturing systems. In order to support the company's business strategy, designing a manufacturing system is a difficult challenge in practice. The challenge is to understand the detailed design of manufacturing systems (Cochran *et al.* 2001). Liu *et al.* (2009) raise a discussion about the challenges of designing systems of resilience from both *theoretical* and *practical* viewpoints. Gershwin (2006) describes three main *practical challenges* in manufacturing system design as (1) a lack of a decent understanding of the complex system in a practical way; (2) developing good computational tools, and (3) obtaining the required data.

Implementation of a change may become ten times costlier in terms of time and resources invested to plan. (Clark and Fujimoto, 1991; Fricke and Schulz 2005). The challenge is that the time, cost, and resources that need to be allocated to effect the change are dependent on its potential impact (Eckert *et al*. 2004; Wickel and Lindemann 2015). Due to rapid changes in recent market demands, reducing product cycle and improving quality highlight the importance of MSD. Ceglarek and Jin (2004) describe the challenges are related to manufacturing system failures and quality problems during the downstream phase as (1) lack of accurate methodologies for predictability of process performance during early product development stages; (2) system failures and long fault recovery during a ramp-up phase; and (3) lack of advanced maintenance and system evaluation methodologies of complex manufacturing systems. Thomas *et al.* (2015) also highlight the methodological challenges in some of the previous frameworks/models where the lack of integration of business improvement methods results in an incomplete strategic view. A methodological approach can support identifying the architectural constraints and the relationships between system elements and other architectural properties in designing resilient systems systematically (Thomas et al. 2015)

Consequently, based on the literature, manufacturing systems design has two main challenges (Figure 2.9): (A) *Financial* and (B) *Technical.* The first financial challenges in *responding to customer need* lead to frequent new product introductions and product enhancements which may require restructuring and architecting of manufacturing systems with quality improvement and these are expensive and time-consuming. The second financial challenge is *industry needs* which are: (1) practical techniques to assess the performance of manufacturing designs, (2) experts to understand manufacturing complex systems. The third financial challenge is *manufacturing system failures* (i.e. failures in material or information flow cycle). On the other hand, the technical challenges are (1) complexity, (2) changeability which is reviewed in detail in Section 2.5.1.

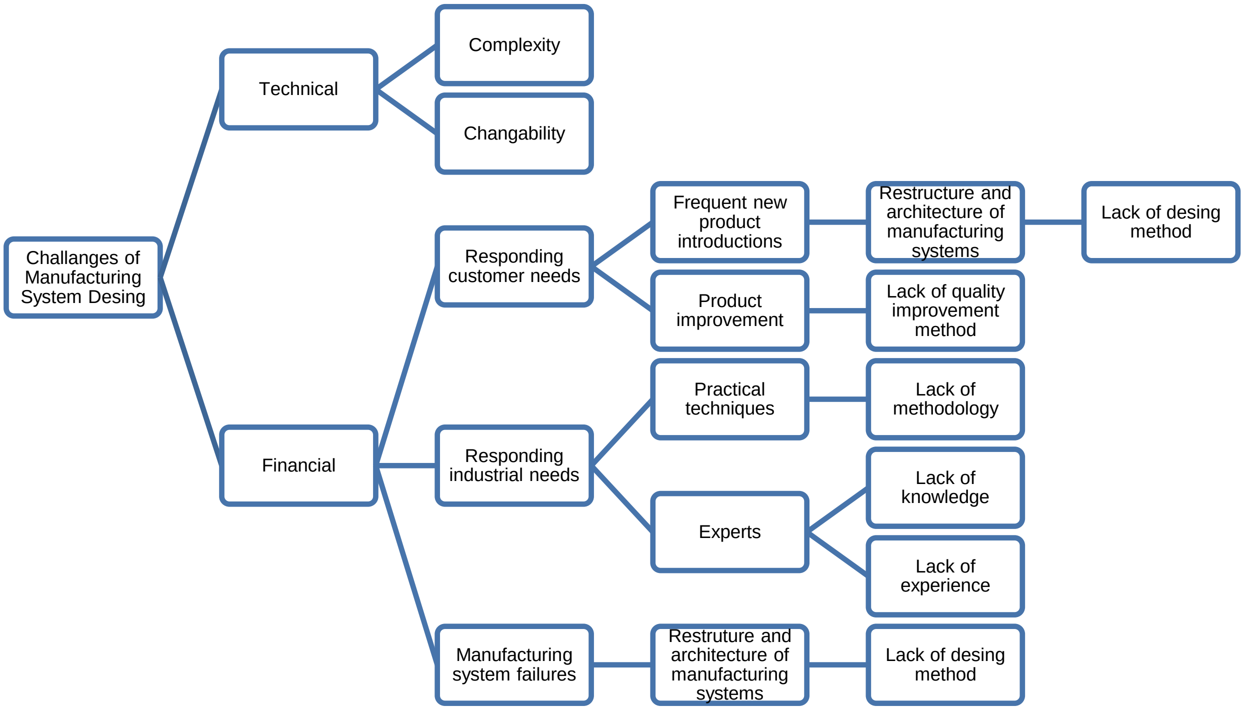


Figure 2.9: Challenges in manufacturing system design

Improving manufacturing efficiency by Adaptive artificial intelligence (AAI) to leverage advanced concepts such as machine learning and predictive maintenance is out of the scope of this thesis. In addition, using digital technology in a manufacturing environment such as Industry 4.0 to optimize the manufacturing system is out of the scope of this thesis. This thesis focuses on designing a resilient manufacturing system to achieve the challenges of manufacturing changes. In order to meet these challenges, this thesis is planned to address three points: (1) understand the manufacturing system design process (Section 2.4.2); (2) understand designing an RMS (Section 2.4.3); (3) explore a model/framework used for designing an RMS (Section 2.5)

2.4.2 Manufacturing System Design Process

The term *process* is defined by the Business Dictionary (2018) as "sequence of interdependent and linked procedures which, at every stage, consume one or more resources (employee time, energy, machines, and money) to convert inputs (data, material, parts, etc.) into the output. These outputs then serve as inputs for the next stage until a known goal or end result is reached". The manufacturing system design (MSD) process integrates many elements into a smoothly functioning system, which is a critical step in system design (Cochran *et al*. 2001). ElMaraghy (2009) classifies the combination of manufacturing systems into four levels: the system, factory, machine and product. Each level has a related set of activities as part of the MSD process. A fundamental part of the design process is the combination design activity. A strategic decision needs to be taken to arrange design activities in order to design systems well and to understand their behaviour (Benkamoun *et al.* 2014).

A system design process provides a conceptual solution to the system development requirements (Framinan and Ruiz 2010). A critical step in the system design process is to map physical solutions with their functional requirements (Benkamoun *et al.* 2014), for instance, multi-domain system integration for customer requirements. Usually, a system design process can be broken down into two parts: (1) the description of elements of a system and their relationships (what it is called the architecture of the system), and (2) the detailed design of these system elements (Framinan and Ruiz 2010)

Due to the complexity of the interconnections of system parts when changes happen, the manufacturer may be unable to understand systems and their behaviours properly. Thus, there is a need to understand structural complexity. Structural complexity is subjective and requires experienced users of the system (Crawley *et al.* 2004). Architectural design is a way to understand and manage complex systems. An architecture framework increases the representation of a system and a systematic design process across different physical and functional viewpoints in a frame that may support understanding of the complexity

Architectural Design of Systems

The system architecture is the conceptual model that defines different views of a system (structural, behavioural). The system architecture can consist of system elements and sub-systems with their relationships and constraints between them (Alleman 2002). Jackson (2010) defines in his book: architecture as a structure in terms of elements, connections and constraints of a *product, process, or element*. Ulrich (1995) describes *product architecture* as a collection of three parts within the physical domain: (1) the arrangement of functional elements; (2) the mapping from functional elements to physical elements*;* (3) the specification of the interfaces among interacting physical elements. Levis (1999) differentiates the *process architecting* with four types of architecture based on system requirements: (1) *functional architecture* (representation of activities or functions that are needed to accomplish the system's requirements), (2) *physical architecture* (representation of physical resources and their interconnections), (3) *technical architecture* (the physical architecture that includes the arrangement, interconnections, and interdependence of the elements, to achieve the system requirements), (4) *dynamic operational architecture* (how the elements operate and interact over time while achieving the goals).

The impact of any *engineering change* depends heavily on the system architecture, its complexity, and the degree of innovation present within the design (i.e., past experience may not predict performance). Most assessment tools focus on supporting changes to a given design but do not tie the impact of these changes to system performance (Jarratt *et al.* 2011; Eckert *et al.* 2004). In recent years, several studies in engineering change management have been conducted to address the challenges of manufacturing system design. The studies are limited to the application of developed models for changes in redesigning system architecture. A model needs to assess key performance, changes within system architecture, and design to the new optimal solution (Rydzak *et al.* 2006; Hu 2013)**.**

Nadge *et al.* (2012) discuss the representation of *architectural design process* under three topics: (1) modelling of the dependency; (2) assessing the impacts of engineering changes in terms of complexity in the redesign, process yield, and cost; (3) redesigning the system by using the design task sequence generated. One design task can be dependent on other design tasks; and so, changing the architectural design can be very challenging in terms of early architectural decisions or on the integration of new solutions into existing architectures. Therefore, this thesis aims to develop a novel approach to design manufacturing systems that allows a co-evolution of architectures of manufacturing systems.

The process of creating architecture often follows a *process of decomposition*, in which a top-level concept of the system's required functions is broken down into sub-functions, and is further broken down into subsystems capable of performing the sub-functions (Cochran *et al.* 2001). A methodological approach needs to decompose and analyse system architecture in a systematic way, for instance using Design Structure Matrix (Browning 2001) and methods for mapping (e.g. Axiomatic Design) tools. In architectural system design, the hierarchy high-level decomposition of the system requirements to create separate manageable parts that can be worked on independently. A major challenge is to understand the many interactions between parts of the hierarchy. These interactions may cause problems during the integration of the system in a new design stage (Crawley *et al.* 2004).

Hierarchical Decomposition of System Architecture

The use of hierarchies is a means of system structuring. The assessment of hierarchical decomposability of a system helps to understand the requirements for building the hierarchical model. Hierarchies are a well-known concept for managing complexity (Jones 1969). Likewise, Simon (1981) clarifies that complex systems almost always have a hierarchical structure; otherwise, they would be difficult to understand. The simple structure of an aspect of engineering design (i.e. products, process and people) is hierarchical.

Marden *et al.* (2009) propose to divide the control of manufacturing system design (MSD) into hierarchically ordered layers which structure the functional decomposition into subsystems, which can then be easily further decomposed but also integrated and managed in bigger systems as well. In the layered structure specification, the particular subsystems logically represent some layers (e.g., planning and planning control layer). Different structure types of architecture representations help the designer to capture and analyse the system from a different perspective. This thesis considers *hierarchical architecture* which defines the influences within the layers of manufacturing systems consisting of different physical elements such as informational or material with different functionalities. Figure 2.10 represents three hierarchical levels in the physical manufacturing system (Scholz and Reiter 2007).

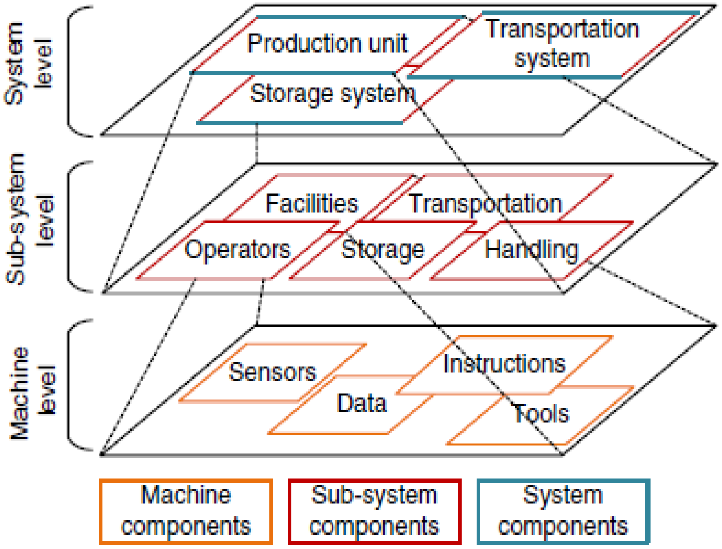


Figure 2.10: Physical hierarchal levels illustration (Scholz and Reiter 2007)

Architecture's ability to influence the functions and connected system life-cycle properties drive resilience (Crawley *et al.* 2004). Resilience from an architectural perspective is the capability of a system to maintain its functions and structure in the face *of internal* and *external change* and absorb change to continue its functionality. However, the architectural design of a resilient system is limited in response to ongoing internal and external changes and a crucial factor is to determine *resilience characteristics* (robustness or adaptability) of systems (Codes and Hulsmann 2013). Three key aspects of future system design which must be met by the design of system architectures are that: (1) the system should be able to be changed quickly and effortlessly; (2) the system should be robust or adaptable towards changing environments; (3) the complexity of the system should be represented (Fricke and Schulz 2005). Consequently, a deeper understanding of changes and change behaviours will help the designer to structure an RMS. The next section reviews findings from the key literature about the operational resiliency models and frameworks.

2.4.3 Designing a Resilient Manufacturing System

The design of system life cycle properties like resilience means preparing systems for an expected or desired performance during changing requirements. This must be considered in the early stages of the product design (Kissel and Lindemann 2012). A system architect determines the system life cycle properties intentionally or unknowingly by converting the stakeholders' needs to technical specifications. System life-cycle properties can transform a company's business strategy in the phase of architectural design (Haskins *et al.* 2010). Gao (2010) presents an approach for modelling and analysing the resilience characteristics. The concept is to examine a system network. The system performs a function and even when the network is reduced, still the system carries out the same function.

Research on designing resilience in engineering systems is relatively rare, and mainly focused on the organisational concepts and qualitative analysis of system resiliency rather than intended at providing quantitative estimation models (Zhang and Luttervelt 2011; Heinicke 2014b, Fraccascia *et al.* 2017, Ivanov *et al.* 2017, Ungar 2018, Caputo *et al*. 2019). The approaches introduced to improve resilience are mainly about planning matters. Although some studies are using mathematical methods, such as those on a computer network, they are still too specific to apply to the entire system. Some others are focused on modelling for manufacturing and supply chain systems.

Key findings relevant to considering the design and development of an operational resiliency model are provided in Table 2.2 (Section 2.3.2). A review of frameworks/models from Table 2.2 highlights the following limitations from the RMS literature:

- Few frameworks are developed as a result of industry collaboration. Most were developed from an analysis of secondary academic literature.

- Mainly the frameworks and models are focused on the application of a single example towards achieving supply chain resiliency only. A model that effectively connects the key elements and strategies into one framework within a manufacturing system is missing.
- Only a few models focus on the application of tools and techniques for resilience at an operational level, and there is little focus on integration with the strategic objectives of the business.
- Although the developed frameworks are new, they did not entirely verify the business improvement by created strategies for manufacturing operations.

An analysis of the wider literature relating to resiliency shows that little information exists about designing a resilient manufacturing system. Largely, the literature focuses on resilience from a theoretical standpoint. Research on designing an RMS model/framework and subsequently implementing its effectiveness is limited. This thesis thus focuses on the concept of designing an RMS to achieve to answer the main research questions as mentioned before. The aim of the thesis is as follows: (1) to present the concept of resilience in the context of manufacturing systems along with a new conceptual model of them, (2) to present strategies for designing and managing an RMS. A systematic representation of MSD can help manufacturing engineers and designers to capture and examine changes in the interrelationships among the different elements of a system for decision-making. The following section, therefore, provides a theoretical investigation of modelling change within MSD. A systematic way is then presented to examine the connection between manufacturing system domains and elements to predict the impact of change.

2.5 Modeling System Change

As established in Chapter 1, manufacturing systems are a constantly changing environment (Whindehal *et al.* 2005); accordingly, manufacturers need an efficient way to examine changes because many manufacturing industries are subject to a high level of change that requires considerable time and cost to implement (Cahlarek and Jin 2004). Eger *et al.* (2003) argue that a significant cause of the problem in managing change originates from a lack of understanding of the connectivity between products and process in the industry. The key to successful change management lies in understanding the state of design and the connectivity between parts of the design (Reddi and Moon 2009).

Eger *et al.* (2007b) address the impact of changes in the domains of *product, process, organisation and External factors.* Likewise, Myklebust (2002) divides a manufacturing system and service design into three key domains: *product domain, process domain* (a manufacturing process), and *resource domain* (organisation) as shown in Figure 2.11. The links between these domains in a project and wider business implications are not equally understood by all members of a change team. Making a change in one of these domains are manageable processes in most cases. These three dimensions or domains are suggested to the analysis of design processes that integrate manufacturing systems and services (Myklebust 2002; Haq *et al*. 2011; Vashanta *et al.* 2012).

The point in figure 2.11, the integrated design and manufacturing process can be modelled to manage changes (Myklebust 2002). Process Domain, which characterises the set of processes, considered by the process planning activities. This domain contains also mechanisms for resource selection and the connections to the product domain. The product domain which characterises the part geometry, raw material and technical characteristics of the part which will be addressed by the process planning activities. As seen in the figure, the process domain connects product data with the organisation domain. Decisions of production change can more easily be visualised to a designer. The designer will get production knowledge structured to view manufacturing processes. Organisation Domain, which characterises the available resources e.g., machine tools, fixtures, tools etc. in given potential shop floor(s). The organisation domain must support the feasible processes in the process domain (Myklebust 2002).

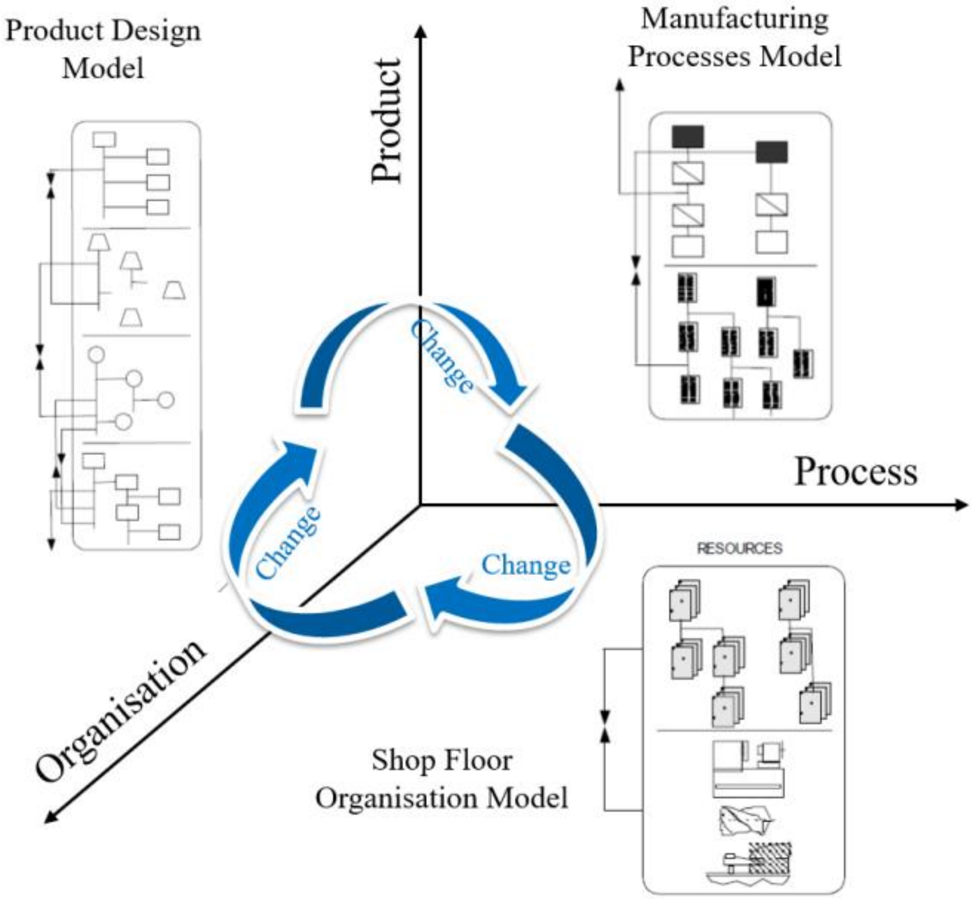


Figure 2.11: A design manufacturing model (adapted from Myklebust 2002)

Ahmad *et al.* (2013) demonstrate *an integrated model* to capture and manage changes and change propagation within manufacturing systems. Integrated models increase the understanding of a manufacturing system structure to manage changes systematically. The integrated model for manufacturing systems consists of manufacturing elements which are connected through the process, production, and organisation domains (Naylund *et al.* 2009). Integrating design and development activities with products and production activities into one system enables existing skills and knowledge to be used more efficiently

To model a system change, complexity and changeability of systems are explored in the following subsection. To better understand change management in a manufacturing environment, subsection 2.5.2 reviews engineering change (EC) and engineering change management (ECM) in the related literature. Accordingly, a comprehensive literature review for the modelling and management of change in subsection 2.5.3 aims to choose the most suitable model for this thesis. Lastly, subsection 2.5.4 provides an understanding of change prediction and the change prediction method (CPM).

2.5.1 Complexity and Changeability

Complexity

The Business Dictionary (2018) defines complexity as "consisting of many diverse and independent but interrelated and interdependent elements or parts linked through many interconnections". Exploring the design requirements for complexity, it is crucial to understand first *complex systems*, *sources of complexity*, *Complex system structure and behaviour*, *controlling and managing complexity*. Complexity in a manufacturing environment is categorised in different viewpoints. For instance, Weber (2005) simply classifies complex manufacturing processes in three parts: (1) complexity of manufacturing parts; (2) complexity in assembly; (3) complexity in costs due to the product range, whereas ElMaraghy *et al.* (2012) differentiate manufacturing enterprises into design, manufacturing and business standpoints such as (1) complexity of engineering design and the product development process; (2) complexity of manufacturing processes and systems; (3) complexity of the business and market, as illustrated in Figure 2.12. The researchers agree that the complexity of a system increases if more sub-systems or elements exist, and with more connections in between them. The scope of complexity may be classified as (1) part, (2) product, (3) system elements and (4) sub-system.

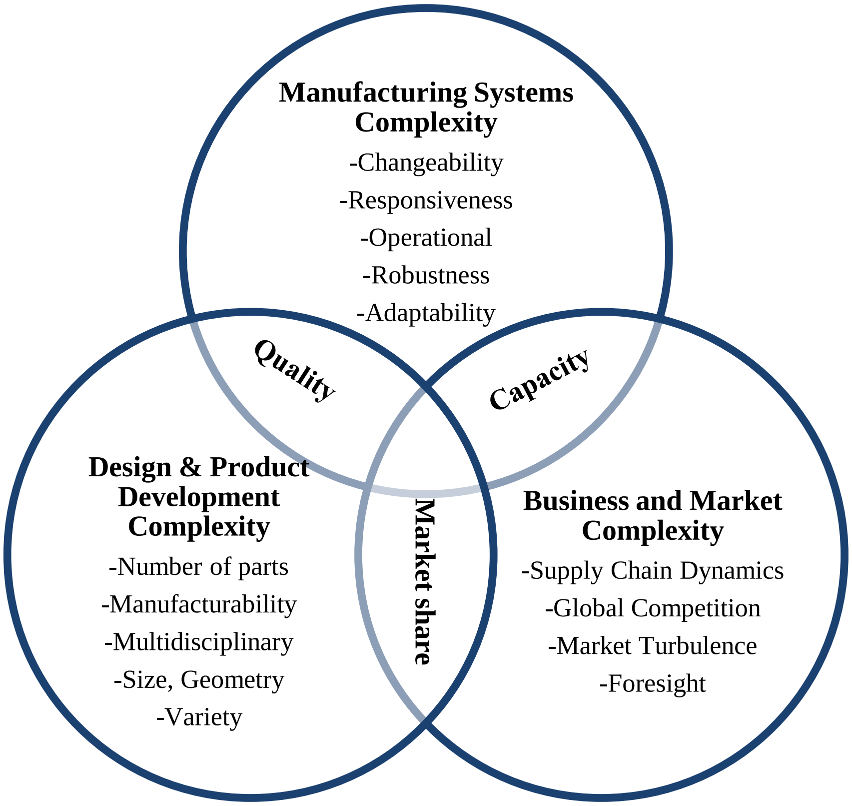


Figure 2.12 Complexity of the design & product development, manufacturing and business & market (adapted from ElMaraghy *et al.* 2012)

Source of complexity

The complexity of manufacturing, technological and engineering systems increases due to constant changes in product design, processing technologies and manufacturing systems. Managing and controlling complexity in manufacturing businesses requires the understanding of the sources of complexity and, accordingly, developing appropriate methodologies. Earl *et al.* (2005) specify the potential source of complexity in the design process with four domains: (1) *product*; (2) *process;* (3) *designer and* (4) *user*. However, the complexities in design often arise from the relations between these four domains and their elements. Complex products, processes and manufacturing systems cost more when designing, implementing, planning, operating, controlling and maintaining systems. A complex product is much harder to control all the relevant parameters of, and their impacts on each other (Fricke *et al.* 2000). Suh (1990) addresses two types of complexity that are linked with *products* as (1) complexity by information and (2) complexity by connectivity. The author states that managing the amount of information and connectivity within elements is associated with the complexity of the design process. ElMaraghy *et al.* (2006) discuss the manufacturing product range, customer demands and their effects as a source of increasing *product complexity* which propagates throughout its life cycle.

Differently, Danilovic and Sandkull (2002) address the source of complexity in project management context as *technology, people, and functionality*; also, they differentiate the origins of complexity by *internal and external reasons.* A comprehensive classification of the types and source of complexity is put forward by Weber (2005) which is illustrated in Figure 2.13. The author splits product/systems and process complexities into five dimensions and links them to the elements of the technical strategy of companies (Weber 2005; Maurer 2007).

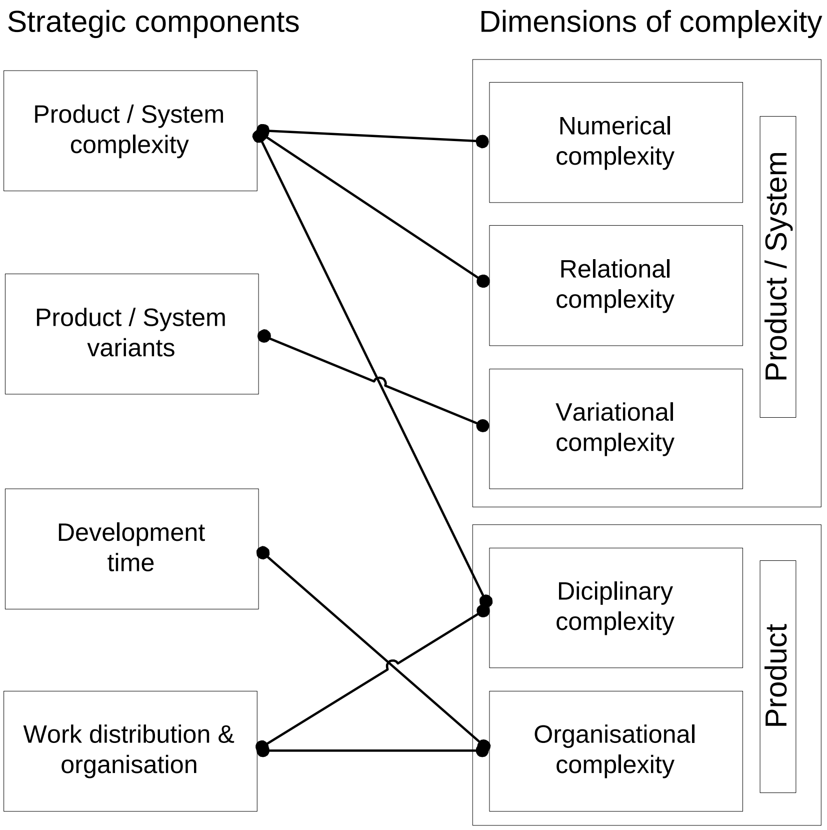


Figure 2.13: Strategy and dimensions of complexity (Weber 2005; Maurer 2007)

Complex system structure and behaviour

Complex systems show properties that appear from the interaction of their parts and which cannot be predicted from the properties of the parts. Complexity in a system is always connected with (1) the connection of system elements, (2) their influence on the system, and (3) the system's connections with its external surroundings. How these connections occur and how they allow the system to change (by creating new structural paths and structures) need to be understood (adapted from Business Dictionary 2018).

Weaver (1947) summarises two kinds of complexity in design: (1) structural (organised); (2) behavioural (disorganised). Likewise, Eckert *et al.* (2004) describe complexity in two areas: (1) the structural complexity of parts and connections; (2) the dynamic complexity of behaviour. It can be said that complex systems may be dynamic because they are changing and evolving. A question arises as to how the different elements of connectivity define constraints on behaviour. Holland (1998) simply provides an answer that understanding 'emergent' behaviours between connected elements are a crucial concept for understanding complexity. Simon (1981) describes *structural complexity* as the organisational structure of a complex reality. The author also argues that the ultimate structures of a complex system have to have a *hierarchical nature* which is essential for any complex system practically decomposable but not fully decomposed into separate, independent parts (Simon 1981). A hierarchical breakdown of a system provides a useful structure to a complex problem, especially support the discovery of hidden dependencies between elements and systems.

In a complex system, the elements are connected through linking factors such as *geometry, material, function, and behaviour* so changing any one of these factors may require a change in numerous other factors within the system (Eckert *et al.* 2001, 2004). The connectivity between parts is a static setting whereas dynamics represent behaviour (Eppinger *et al.* 1994). ElMaraghay *et al*. (2012) address engineering complexity in two domains: (1) engineering complexity in *the physical domain*; (2) complexity in *the functional domain* e.g., the axiomatic design complexity theory. For instance, Suh (2001) and Summers & Shah (2010) promotes the idea that **c**omplexity must be defined in the functional domain as a measure of uncertainty in achieving a set of tasks.

The manufacturing system itself is a product to be designed, manufactured or redesigned and it has its lifecycle (ElMaraghy *et al.* 2006). Jarratt *et al*. (2004b) state the complexity of a product can be measured by the connectivity among a product's elements and their interaction. Managing a complex manufacturing system and an MSD require a very high level of decomposition to break into more subsystems, process steps, workers, machines, inspections, assembly steps and a robust control system (Suh 2001; Vaughn 2002). Reducing complexity requires a thorough understanding of connectivity within systems.

Controlling and managing complexities

Clarkson *et al.* (2001a) propose that an effective system for controlling complexity can predict the impact of change. Existing products adapt to a new requirement through change prediction which helps shorten system cycles time. Thus, the possibility of controlling change dependencies in product development may allow more comprehensive adaptations, as the resulting consequences can be quickly identified (Lindemann *et al.* 2009). The changes resulting from such adaptations may have an unexpected impact on several interconnected elements which may create iteration loops. However, manufacturing systems are designed to satisfy functional requirements and customer demands in a robust and adaptable manner. A systematic approach is needed to manage and control complexity when interacting with systems containing multiple domains, e.g., interrelations of components, processes, and people. Papakostas and Mourtzis (2007) present a novel approach for modelling the adaptability of a manufacturing system using a mathematical model for quantifying the adaptability and robustness of a system using real manufacturing data. The main objective is to quantify the ability of a manufacturing system to adapt to requirements and to establish different operational policies for adaptability, reducing the complexity of any system by minimizing the number of dependencies (ElMaraghy *et al.* 2012). Lindemann and Maurer (2007) suggest a matrix-based approach such as the *multi-domain matrix (MDM)* for analysing complex systems involving of interdependencies between several domains.More information with regards to MDM can be found on section 2.5.4 Connectivity Models. The purpose of this thesis is to link between manufacturing system complexity and strategic manufacturing objectives and then to design robust or adaptable manufacturing systems. Two key points result from analyzing the literature when designing resilient manufacturing systems:

1. Multi-layered hierarchical decomposing of a system into its smallaer parts (sub-systems) and an elements towards system architecture is basically representing the degree of complexity.
2. Capture dependencies between systems domains and elements.

Complexity can be linked to changes. The nature of change behaviour increases the complexity of system design by creating additional connectivity within system elements (Eckert *et al.* 2005). Changeability is desirable in complex engineering systems. The next section explores understanding changeability behaviour within manufacturing systems to manage complex systems systematically.

Changeability

Wiendahl *et al.* (2006) state changeability have become a key characteristic of manufacturing system design (MSD) in recent decades. The authors define changeability as “the characteristic to accomplish early and foresighted adjustments of the manufacturing structures and processes on all levels to change impulses economically”. In the literature, products with good changeability are sometimes described as “*easy to change”* (e.g. de Weck 2007). The *motivation for changeability* over a system lifecycle is categorized into three major drivers described by Fricke and Schulz (2005): (1) dynamic marketplace; (2) technological evolution and (3) variety of environments. These drivers suggest two key aspects of system architectures: they must be able to be changed easily and rapidly, and they must be insensitive or adaptable towards changing environments (Schulz *et al.* 2000). Ross *et al.* (2008) refer to the main concept of changeability as a combination of three things, change agents, the effects of change and change mechanisms. Changeable systems enable value transfer over different stages of system lifecycle (Ross *et al.* 2008).

The literature addresses semantic and conceptual topics associated with changes, which could be reduced by using effective system life-cycle properties. ElMaraghy and Wiendahl (2009) define a system life cycle process with two changeability phases, a design and implementation phase and a performance phase. Fricke and Schulz (2005) suggest *Design for Changeability* (DfC) as a solution strategy to address the changes to build the following four concepts into the entire design process and the product: Robustness (Taguchi 1993), Flexibility, Agility and Adaptability. This suggests that the term 'changeability' can be used to point toward 'robustness and adaptability' only in this research.

Changeability in manufacturing system design places many challenges on the stakeholders (Francalanza *et al.* 2014). Establishing a changeable system design process needs the development and the deployment of changeable system strategies in the industry. A changeable manufacturing system design addresses the results of the functional activities of product design, process planning and planning decisions which occur concurrently and continuously. Designers can assess manufacturing system structure and activities from the different perspectives such as: "Functional View, Changeability View, Change Enabler View, and Object View". These views are represented in Figure 2.14 (Francalanza *et al.* 2014). This research focuses on the changeable manufacturing system as a robust, adaptable and architectural approach.

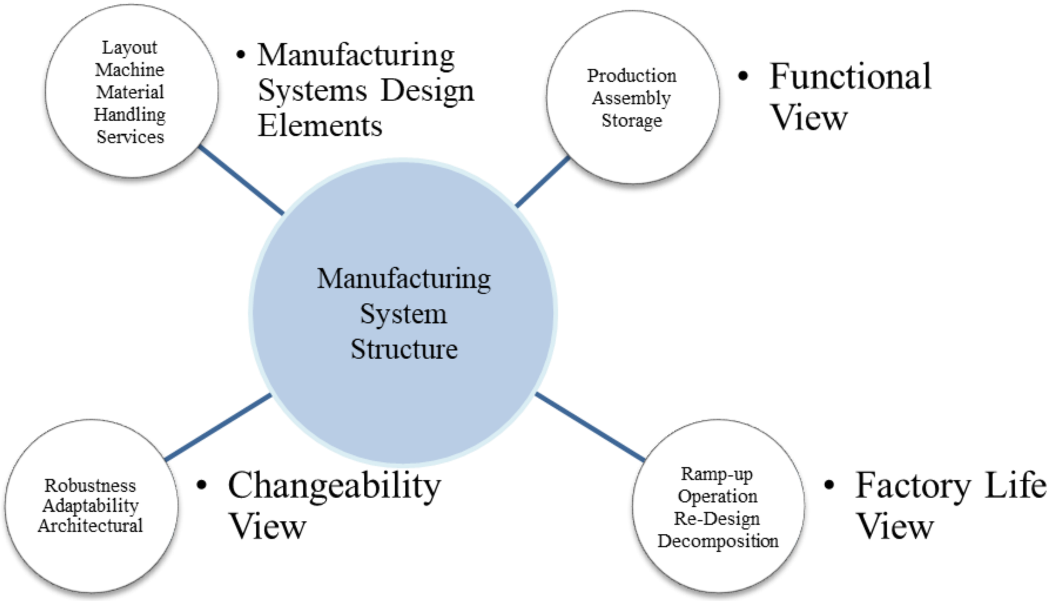


Figure 2.14: A viewpoint of changeable manufacturing system structure (adapted from Francalanza *et al.* 2014)

Shuh *et al.* (2009) propose *an object-oriented design technique* for changeability based on four steps: (1) identify, (2) analyse and classify the dynamic change drivers, (3) specify the manufacturing system, and (4) control the complexity of manufacturing systems. However, the technique is highly dependent on the real-world validation of the changeability. Ross *et al.* (2008) state designing systems for changeability can be achieved if there is an approach in the quantification of changeability. Koh *et al.* (2012) examine the changeability of complex engineering systems by five ways: (1) the initiating points of change; (2) the direct propagation of change; (3) the indirect propagation of change; (4) the likelihood of change; and (5) the impact or effort of change. The technique developed uses a matrix-based approach and the change prediction method (CPM) described by Clarkson, Simons, and Eckert (2004) to model the direct and indirect change dependencies between system elements. System changeability is subsequently estimated by analysing the likelihood and impact of potential changes

This research outlines changeability as an attribute and enabler to robustness and adaptability at various stages of a manufacturing enterprise. The measures of changeability as an attribute are not well defined. (Windehal *et al*. 2006). Further research should focus on the appropriate engineering change models within a manufacturing enterprise. This thesis concludes the following based on the literature:

3. A change model/framework is needed to analyse connections of system elements to predict change risks with direct and indirect change propogations.
4. A change model/framework is needed to design a changeable system through achieving robustness and adaptability (resilience) by quantifying and reviewing connections between the system elements.

This research thus aims to develop an appropriate system change method in manufacturing environment through understanding engineering change (EC) and engineering change management (ECM) concepts, which are addressed in the next section.

2.5.2 Engineering Change (EC) and Engineering Change Management (ECM)

Engineering Change (EC)

This section describes an EC meaning, explores when EC processes occur during the system life cycle and discuss the elements that make up the characteristic EC process. ECs are defined differently in many design contexts. The existing definitions for EC related to this research and frequently cited papers are listed in Table 2.3.

Table 2.3: Existing definitions of engineering change

Authors	**Definition**
Wright 1997	‘An engineering change (EC) is a modification to a component of a product after that product has entered production’
Huang *and* Mak 1999	‘Engineering changes are the changes and modifications in forms, fits, materials, dimensions, functions, etc. of a product or a component.’
Terwiesch *and* Loch 1999	‘Engineering change orders (ECOs) - changes to parts, drawings or software that have already been released.’

Jarratt *et al.* 2004c	'An engineering change is an alteration made to parts, drawings or software that has already been released during the product design process. The change can be of any size or type; the change can involve people and take any length of time.'
Hamraz 2013	'ECs are 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.'

Wright (1997) defines ECs as 'a modification to a component of a product after that product has entered production'. Huang and Mak (1999) explore the term *modification* in more detail by clarifying that these concerns forms, fits, materials, dimensions or functions of a product or component. Also, Terwiesch and Loch (1999) include a product's software; however, these Jarratt *et al.* (2004) consider a change in product development. Jarratt *et al.* (2004) utilise the definitions of Huang and Mak (1999) and Terwiesch and Loch (1999) and add the time aspect to ECs with people involved and taking the length of time. Hamraz (2014) describes a definition of EC taken from Jarratt *et al.* (2004c) taking structural, behavioural and functional aspects. The definition valid throughout this specific thesis is based on that from Jarratt et al. (2004). A definition of ECs adopted for this research is provided by Jarratt *et al.* (2004):

> **Engineering changes** are modifications in forms, fits, materials, dimensions, functions, drawings or software of a product that has already released during the manufacturing design process. Engineering Changes include the connected process changes and can be of any size or type, can involve people, and can take any length of time.

Management of EC may insufficient due to determination and involvement of all change and process elements within the design process. For instance, people, organizational structure, technology and processes are important supports of change and must interact properly to manage its complex nature. The next subsection provides a definition of ECM which has been extracted from the most related literature.

Engineering Change Management (ECM)

The management of change in manufacturing systems addresses the ECM and assigns it to the manufacturing domain in the literature (Koch *et al.* 2016). Jarratt *et al.* (2004a) describe ECM is as the organizing and controlling of the process of making modifications to a product. Based on these definitions, the term 'Manufacturing Change Management (MCM)' is defined as 'organizing and controlling the process of modifying manufacturing (e.g. adaptation of plan, select, implement and control manufacturing changes'. In this perspective making modifications in manufacturing such as production elements, manufacturing suppliers, or policies come under manufacturing change.

A system-based model for MCM developed by Koch *et al.* (2014) considers the manufacturing elements and their relations for the MCM-domain. Each element can be a sub-system itself and contains hierarchically arranged elements and their relations. As shown in Figure 2.15, the model is divided into two segments (1) MCM and (2) ECM which are interconnected and operate individually. Both segments comprise the same kind of elements: change management process, change itself, and the object of change. In addition, their connections are linked by change cause and the supporting framework (Koch *et al.* 2014).

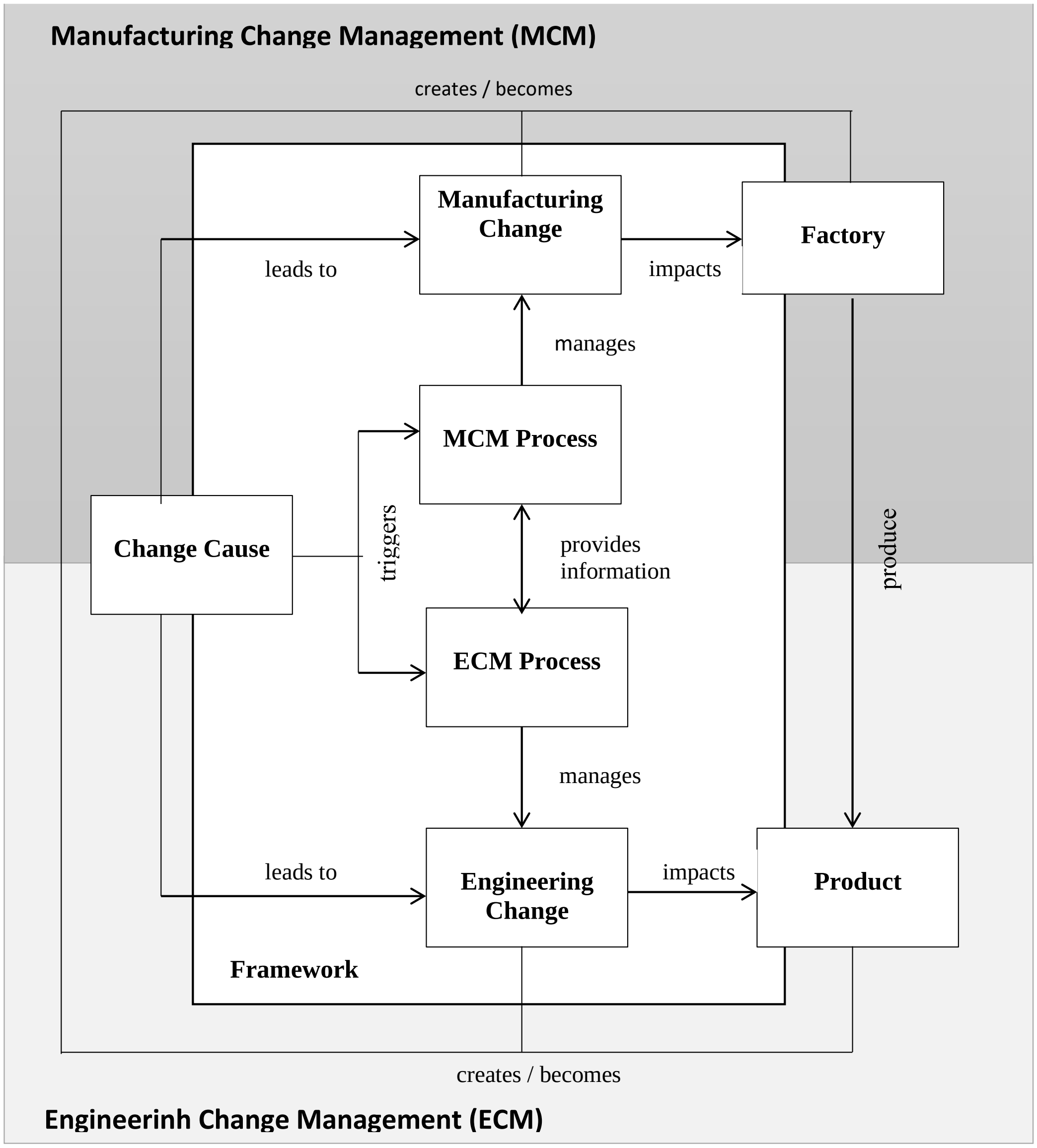


Figure 2.15: A context model for manufacturing change management (Koch *et al.* 2016)

Engineering change management (ECM) has been defined as the process by which an organisation proposes, evaluates, implements, and audits changes (Huang and Mak 1999). ECM deals with the evolution of a design which is consistently changed to satisfy customer requirements, correct design problems, and meet a good engineering solution. Any company involved in the design of complex manufacturing systems must perform ECM to deal with the desire and need for *design changes* (Clarkson *et al.* 2004). The definitions of ECM in the related literature share the same ideas that the objects of observation (change in manufacturing) deal with different procedures to better cope with change. The ECM definition that is used in this thesis is adopted from Huang and Mak (1999) as this one includes the design changes aspect of an engineering system or product.

Engineering change management (ECM) is the process by which an organization proposes, evaluates, implements and audits changes to the design of an engineering system or product.

Engineering Change Process

The literature describes a change management process in a system engineering context: the direction of requesting, defining, planning, implementing, and assessing system changes to support the processing and traceability of changes. Ulrich and Eppinger (2010) propose a generic *product development process* and Jarratt *et al.* (2004c) add *engineering changes* in the product design and development process which needs to be controlled and managed. In this way, an engineering change processes arise in the design and production of the product, which is illustrated in Figure 2.16.

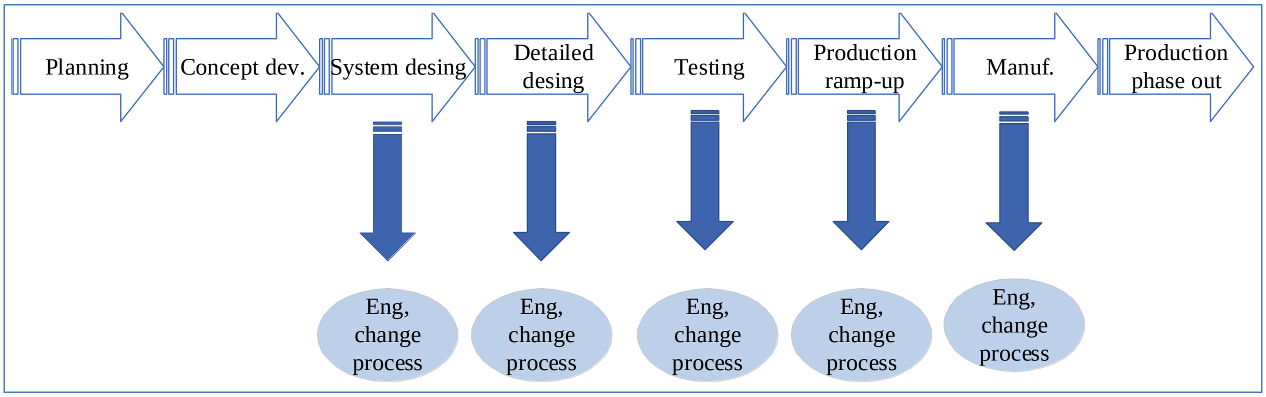


Figure 2.16: Engineering change process (Ulrich and Eppinger 2000; Jarratt 2004)

Jarratt *et al*. (2004) propose a generic change process as illustrated in Figure 2.17 which suggests a determination of the complete life cycle of ECs. The authors present the *6- Steps* process organised into three stages and the change process initiated by a change trigger. In *Step 1*, a request outlining the reason, priority, type, and extent of change is created by the change initiator and sent to a design team. In *Step 2*, possible solutions to the change request are explored. The impact and risk of implementing each solution are then assessed in *Step 3*. This is followed by a review session conducted by an EC team in *Step 4*. In *Step 5*, the selected solution is implemented either immediately or at a later given date. The timing of change will depend on various factors, such as the nature of the change. Caution should also be taken to ensure that relevant documentation is updated. Finally, in *Step 6*, the change should be reviewed to assess if the planned objectives have been achieved. The two most likely iterations and four possible breakpoints, at which the change process can be brought to a stop by the control mechanism, are marked in the process map. Possibly the most critical step is *Step 4*: the selection and approval of a solution by the team due to choosing an accurate solution. In this phase, various evaluations have to be made by the EC team to come to a decision.

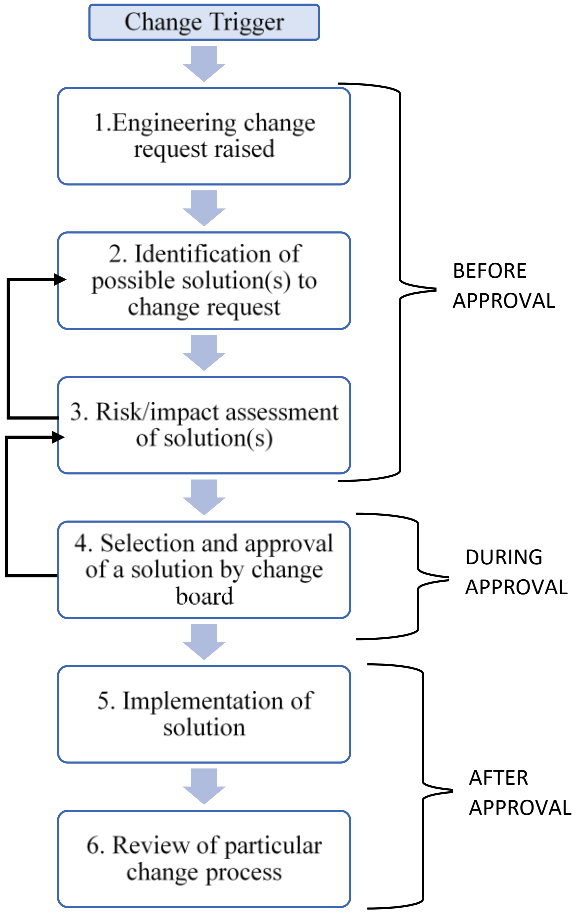


Figure 2.17: A generic engineering change process (Jarratt *et al.* 2004c)

ECs are not always managed as requested (Huang *et al.* 2003) or there may be changes that are sometimes not suitable for the application. Huang and Mak (1999) reveal that about 90% of the manufacturing companies surveyed agreed that the most important attribute of a formal EC management system is to have *a well-structured guideline* to improve issues such as poor communication among parts which are involved in the product development process. A more general set of EC guidelines is suggested by Terwiesch and Loch (1999) in their four key strategies to reduce the negative impacts of ECs: (1) avoid unnecessary changes; (2) reduce the negative impacts of an EC; (3) detect ECs early; and (4) speed up the EC administrative process. Completely avoiding ECs in a system not preferred as ECs provide the chance of improving the product's quality or being innovative.

The source of engineering changes

A change request may occur at any stage in the engineering system lifecycle. Designing a system may continually change to meet stakeholder requirements and successfully respond to the requirements. Change management capability depends on types or the source of changes, for instance, the internal (e.g. manufacturing) and external (e.g. supplier) elements becoming involved in the process. Changes may thus occur *externally or internally* (Eckert *et al.* 2004). The authors specify two sources of change: (1) *emergent changes* and (2) *initiated changes*. Emergent changes are triggered by problems with the design and development of a product, which are illustrated in the top half of Figure 2.18. Some of the motivations for emergent changes are product quality, design and manufacturing. In contrast, initiated changes are triggered from an outside source such as changing requirements from customers or a change carried out for process-related reasons, and is represented in the lower half of Figure 2.18. Some of the motivations for initiating a change are customer requests, legislation, new technology, and marketing.

Understanding EC effects to unplanned parts of a design are crucial. Changes may propagate, so what is meant by change propagation? The following sub-section provides a review of the definition as well as characteristics of change propagation in a design context.

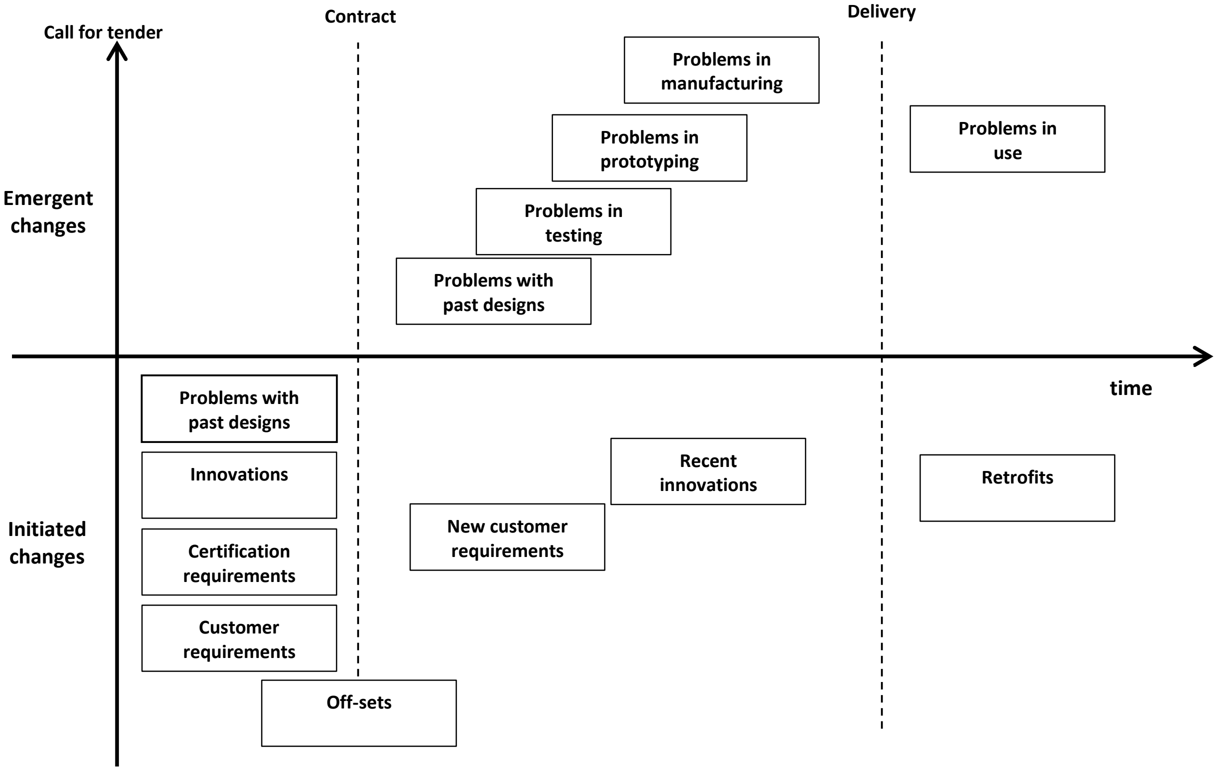


Figure 2.18: Source of change during the design process (Eckert *et al.* 2004)

Change Propagation

Propagation is a key potential impact on a system or product while implementing engineering changes (Fricke *et al.* 2000; Clarkson *et al.* 2001). The impact of change propagation occurs within the design process as well as other downstream and upstream processes, thus causing unwanted time delays. Change propagation is an occurrence by which one change initiates a series of other changes (Clarkson *et al.* 2004). Jarratt *et al.* (2004) argue that change propagates mostly due to *three key assumptions* which are also the inspiration of the CPM technique: (1) the dependency between elements that share significant levels of interaction; an assessment of dependency between elements potentially should identify more possibilities of change propagating than an assessment of connectivity; (2) the presence of constraints on elements interactions is part of the design; the assessment of constraints on design provides a good indication of the paths along which a change is likely to propagate; (3) Insufficiencies in the change process such as system knowledge and experience, design decisions, communication efficiency. Likewise, Terwiesch and Loch (1999) recognise three significant relations which can lead to propagation within manufacturing systems:

(1) between elements and the system; (2) between elements within the same subsystem; and (3) between elements in different subsystems.

One particular aspect of changes in engineering design is their risk of change propagating through a system. There are dependencies within the system and thus a change to one part of the system will trigger subsequent changes in other parts which create change propagation (Yang and Duan 2011). For example, Clarkson *et al.* (2004) explain that a change made to the blade of a helicopter would require an important redesign of the entire aircraft, because of the functional dependence of the rest of the aircraft. The ECM process of an organisation cannot avoid that possible propagation effects when evaluating and implementing a change to a single part of a system. Particularly as product designs become more and more complex and elements are increasingly linked to each other, both *directly and indirectly* (Giffin 2007); changes to one part are more likely to call for a change in at least one other element.

Eckert *et al.* (2004) describe EC propagation as “the process by which a change to one part or element of an existing system configuration or design results in one or more additional changes to the system when those changes would not have otherwise been required”. Meanwhile, Koh *et al.* (2012) define EC propagation as “the process by which an EC to parts of a product results in one or more additional ECs to other parts of the product, when those changes would not otherwise have been required”. Both Eckert *et al.* (2004) and Koh *et al.* (2012) describe EC propagation as a process by which an EC leads to more additional ECs in other parts of the product which wouldn’t have been required if it wasn’t for the initiating change. Based on both definitions of EC propagation, the following description was generated for this thesis:

> **Engineering change propagation** originates from the relationships or dependencies between elements, parameters, functions, etc., and describes the process by which a change to one part or element of an existing system architecture or design results in one or more additional changes to the system, when those changes would not have othervise been required,

Types of change propagation

Eckert *et al.* (2004) classify change propagation into two types: e*nding and unending change propagation.* Ending change propagation means that the change finishes within the required time (see Figure 2.19). In contrast, unending change propagation cannot be finished on time The authors distinguish between three potential effects of EC propagation as illustrated in Figure 2.19:

1. *Ripples* are propagation paths with a constantly reducing number of ECs. Change ripples are most likely when only a few elements are affected and the change propagation effects are manageable.
2. *Blossoms* are propagation paths with a growing number of ECs at the beginning that can be carried to a close within predictable time limits. Change blossoms consist of a higher number of essential changes which are even so still predictable.
3. *Avalanches* are unending propagation paths with a growing number of changes. They are frequently the result of major unpredicted emergent changes which are not defined in the problem scope. Terwiesch and Loch (1999) refer to this propagation type as a *snowball effect.*

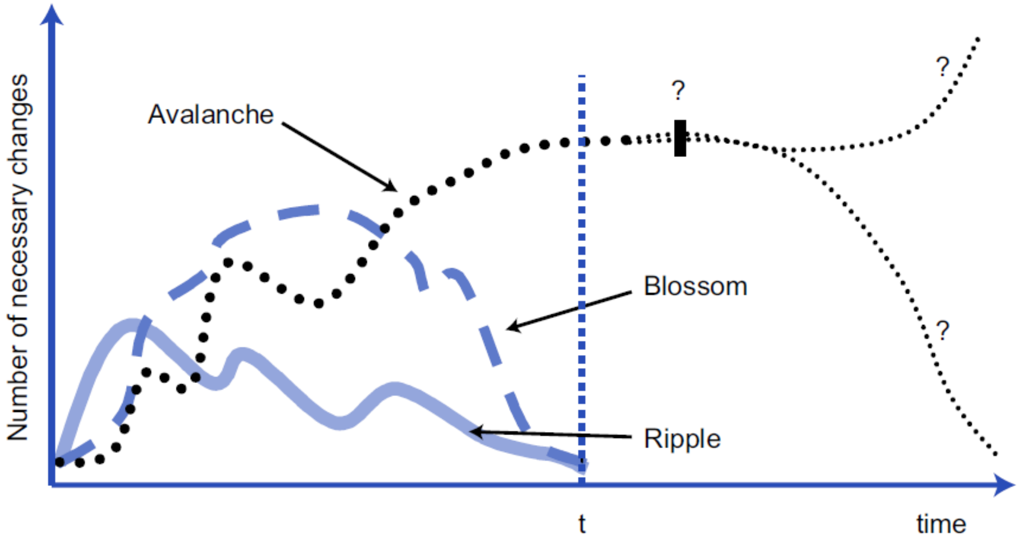


Figure 2.19: Types of change propagation (Eckert *et al.* 2004)

ECM literature refers to dependency-based models for managing and controlling these possible effects of change propagation (Ollinger and Stahovich 2004). The change of a sub-system can dramatically turn into an expensive redesign that requires adaptations to a wide range of elements (Jarratt *et al.* 2002). Clarkson *et al*. (2001) highlight a company's capability to manage change can be significantly affected by their understanding of the connections between different parts of the product or system the impact on the propagation of change. The accurate prediction of change propagation is challenging in risk management of the redesign process (Clarkson *et al.* 2001). Additionally, the impact of a change may become more expensive. So, it is essential to be able to predict the risk of change propagation by analysing change behaviour at the early stage of design (Clarkson *et al.* 2001).

A correct assessment of change impact on a system is challenging given the involvement of many elements. The system must be decomposed into understandable and manageable representations of the parts (Ariyo *et al.* 2007a). This research aims to model an MSD process and defines the fundamental principles that could help the designing of an RMS in the presence of change. Modelling the system supports capturing and managing changes and change propagation within manufacturing systems in a systematic way. Subsequently, the following subsection reviews the selected methods or frameworks for the modelling and management of changes which are most related to the aim of this research.

2.5.3 Methods for Management of Changes

Assessing change impact and predicting the change propagation within a system design requires an effective change management supporting tool. ECM literature focuses on various methods for change management. In a review of the literature, Hamraz *et al.* (2013a) identify 54 methods of supporting change management. Most literature is based on product structure models (networks, graphs, matrices), which describe the dependency of elements on each other. Ahmed *et al.* (2013) identify 23 methods to focus on cross-domain approaches (i.e. requirements, function structure, component structure, detail design process, including parameters and tasks) for change impact assessment. Koh *et al.* (2010) compare 24 methods to enable a cross-domain analysis of change propagation by assessing the capability of the modelling techniques. Additional approaches use product attributes or design constraints to design the relations between elements or enhance the model by adding different levels (Cohen *et al.* 2000; Ollinger and Stahovich 2004; Ariyo *et al.* 2007a).

Reasonably, modelling change within manufacturing systems supports designers in the decision-making process through the risk assessment of change impact. Analysing the relations and patterns of changes increases the understanding of the system. A systematic dependency method with multiple levels of analysis allows greater insight into the connections of system elements. Accordingly, ECM methods such as *a dependency analysis method* and *change propagation analysis method* can describe the connection between system elements and domains and translate them into a system (Olmez *et al.* 2018b). This thesis focuses and classifies the ECM methods in two aspects to assessing the complexity and changeability of manufacturing systems: (1) methods for managing complexity and (2) methods for assessing changeability.

1. Methods for managing complexity

Chen and Li (2005) propose *The Change Favorable Representation (C-FAR)* model as a representative model for controlling and reducing design change propagation. Fundamentally, C-FAR is a matrix which computationally determines the effect of one attribute to another by using its matrix relationship of a product (Chen and Li 2005). The method is structured in three steps: (1) a redesign problem integrates constraints (physical or behavioural) and functions (interrelations). These relations are captured in the binary so-called design dependency matrix; (2) alternative redesign solutions are developed; (3) the best and least redesign solution is selected. C-FAR uses an existing product information model to model change representation, propagation, and qualitative evaluation. Unfortunately, product information may not always be available during the design process. This model may appropriate for small and relatively simple products due to its computational complexity (Clarkson *et al.* 2005).

Matrix-based system representations can increase the understanding of system complexity by presenting a holistic view of connectivity. The most recognized the matrix model is the Design Structure Matrix (DSM) which models the design and structure (architecture) of a system (Eppinger and Browning 2012). Steward (1981) was the first to introduce DSM, which can be applied to represent the interactions between design requirements for the product, process and organization. The DSM has become increasingly popular in planning product development, project planning and management, systems engineering, and organizational development (Browning, 2001). Mapping the design process accurately in a DSM is challenging because dependencies are difficult to capture among the different domains, and the DSM cannot directly define in an exact state.

Maurer (2007) has taken the *Design Structure Matrix* (DSM) approach further to model whole systems consisting of multiple domains, each having multiple elements, connected by various relationship types and this is termed the *Multiple Domain Matrix (MDM)*. An MDM consists of DSMs and DMMs (Domain Mapping Matrix). The MDM allows a system's structure to be analysed across multiple domains, condensing every single analysis into one DSM that represents multiple domains at one time. Based on the MDM approach, Pasqual and de Weck (2011) propose a *multi-domain change propagation network* model including the product, change (process), and network domains. Here, the product domain is a network of the elements; the change domain, a network of change requests; and the social domain, a network of people. The authors suggest using existing tools and metrics for change examination within these networks.

Suh (2001) introduces the theory of *Axiomatic Design*, which is considered the domain in the product design stage when changes in the physical domain elements. However, the changes in the functional domain and their effects on the physical domain have not been considered. Guenov and Barker (2005) and Janthong (2011) used the *Axiomatic Design Matrix* (DM) to estimate the effects of changes by mapping the layers of design parameters (DP) to functional requirements (FR).

Another multi-layer method proposed by Fei *et al.* (2011b) supports tracing change propagation between the functional requirement layer and the physical structure layer. The authors suggest further work in method development to assess design change impact. Any changes in product development need to be assessed for impact on time, risk and cost (Fei *et al.* 2011b). In industry, there is a strong need for experienced designers to make an accurate assessment of the impacts of these design changes.

Rouibah and Caskey (2003) suggest a change method which is a network model of parameter interdependencies. The method assesses the effects of EC throughout the design process of several companies. Information on dependencies between parameters, parts, documents and roles must be created in advance based on experience in similar products. Changes in the structure of systems must also be recorded during the design process (Rouibah and Caskey 2003). However, new parameters and their dependencies are not covered because they are not defined previously.

2. Methods for managing changeability

Kocar and Akgunduz (2010) propose *the Active Distributed Virtual Change Environment (ADVICE)* method to use visualisation (graphical) and data mining techniques to represent the product. The techniques support uncovering dependencies between product elements while examining the EC requests. A designer can capture and predict the potential change propagation through the impact on the change database with these techniques (Kocar and Akgunduz 2010). The critical part of the method is the creation of *a virtual platform* before change analysis, which highly influences the design solution.

CPM–HoQ is suggested by Koh *et al.* (2012) which is integrated the House of Quality and the Change Prediction Method for the different change options. Each change option is assessed on its effect on product attributes so that the best change option can be chosen by the designer. The change may propagate between elements due to the physical structure of the product. Initially, the method was developed by Hauser and Clausing (1988) as a conceptual map that provides functional planning. Koh *et al*. (2012) only add the roof of the HoQ, a triangular matrix, in their method. The roof specifies the dependencies of different product parameters to understand the interchanges among them. The method needs a broad set of change options. However, the roof model only symmetrical connections, but is not able to map asymmetrical connections like a multi-domain matrix. The approach is also limited to the assessment of attribute performance and does not consider the impact of implementing redesign structures.

Redesign IT developed by Ollinger and Stahovich (2004) addresses the key assignments of change propagation in developing redesign plans of a product. The tool aims to accomplish redesign objectives which are (1) to define physical quantities referring to both physical assets of the product's elements and operations; (2) to introduce constraints on quantities describing design requirements on quantities; (3) to establish relations between quantities describing how a change to one quantity influences other quantities.

The authors specify the quantities and the direction in which these quantities have to be adapted to achieve a specified performance objective (Ollinger and Stahovich 2004). The tool helps the designer to understand the possible consequences of a redesign by indicating the key product parts that will be affected by a change. However, the application of the tool is limited to a specific redesign goal, during the redesign of a specific function.

An approach proposed by Morkos *et al.* (2012) assesses interdependencies between documented requirements with keyword analysis by using *a binary DSM*. The requirement pairs share at least one keyword and the binary DSM identifies possible propagations when a requirement is changed. The authors observe the specific set of requirements that are not directly connected (Morkos *et al.* 2012). Thus, to manage a change properly, the indirect connections must be considered if requirements are to be met successfully.

The *analytic network process (ANP)* method was developed by Lee *et al.* (2010). The method is the integration of informal and unstructured disconnected relationships with structured online workflows. This method determines how semantic web knowledge can characterise and share many types of EC-related information in a context. The method determines both (1) the likelihood of each element in a product and (2) whether the changes propagate directly or indirectly to other elements. This two-level analysis accomplishes a similar result to CPM, through a more difficult and probably more time-consuming data collecting process.

Rutka *et al.* (2006) develop the *Change Propagation Method (CPA)* to support the decision-making process of ECM at the design stages. The model collects information on dependencies between product elements and identifies the impact and risk of changes. However, the model captures the dependencies between the systems but ignores the dependencies between the product attributes and the systems. Due to the ignoring of the attribute-element dependency on a product, the model needs more involvement of experienced designers to define changes and product attributes in detail.

Reddi and Moon (2009) propose that changes may propagate differently between elements dependent on the type of changes (e.g. material, shape, and geometry). The dependencies are valued on differently (i.e. low, medium, and high). The model uses a database of potential propagation steps. Each entry in the database includes an initiating element and type of change (ToC). However, the implementation of a model too complex system is very dependent on the model's level of detail. Tang *et al.* (2010) also suggest a similar approach, which is a *DSM-based EC management system***.** Tang et al. (2010) focu on knowledge management to define the property of dependency (e.g. material or geometry), and dependency strength of two elements. The technique includes three different domains to support the modelling of ECs. It maps the interactions between product, process and organisation elements and domains. Change propagation paths are shown graphically, drawing on the concept of the CPM. The overall risk sources are considered and visually illustrated with scatter graphs. The main objective of this method is to increase the traceability of ECs across these three domains during product development. However, the assessment of change propagation effects on the product attributes is not considered.

The change prediction method (CPM) developed by Clarkson *et al.* (2001), which is a matrix-based change method, uses a design structure matrix (DSM) to model connections between elements in a complex product. Each connection is qualified with the likelihood and impact of a change in one element propagating to the others along the dependencies presented. By outlining all possible propagation paths, CPM displays the likelihood and impact of propagation between all elements through a created matrix. Clarkson *et al.* (2004) achieved notable success with CPM in predicting change propagation in a few real-world scenarios at Westland Helicopters (a UK company).

The 15 existing engineering change methods drawn from a broad literature review listed in Table 2.4 . The methods address managing complexity and changeability by predicting change prorogation in designing an RMS. The capabilities of the tools were assessed in two categories: (1) *managing complexity*; and (2) *managing changeability*. To assess the tools strategically and effectively, these two suggested categories are divided into multi-layered hierarchical structuring (decomposing architectural systems), dependency analysis, direct/indirect change prorogation, risk analysis, quantifying connections and results, visualising change propagation, and change modelling capability. The Table 2.4 compares and evaluates the methods with rating scale in Poor (1), Fair (3), Average (5), Good (7), Excellent(10). The sum assessment results of managing complexity and managing changability are stated on the right side of the two categories which support to compare the methods adequatly.

The weighted sum results on managing changeability shows that CPM (sum assessment result 33) is the most suitable of all methods. On the other hand, as Table 2.4 shows, some of methods score as better as the CPM in certain managing changeability criteria. CPM (sum assessment result 8) is one of the lowest score within the 15 methods in the managing complexity. Followed by C-Far (sum assessment result 25), Chen &Li (sum assessment result 20), Redesign IT (sum assessment result 20) and ADVICE (sum assessment result 20). Similarly, for managing complexity, DSM/MDM (total number 17) has the highest best score.

However, according to results of DSM/MDM is not able to manage changeability (sum assessment result 16).

Acknowledging the difficulty of such a detailed scoring under the condition of various amount of available information for different methods, the results of this assessment are indicative rather than definitive. Making adequate comparisons is quite difficult due to the different information being available for each method. In addirion, the scoring has been assessed by only one person and so might be affected by subjective decision and experience of the assessor. It should be emphasized 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 assessors.

Table 2.4: Engineering change management tools for predicting change propagation.

No	**Method**	**Author (s) and year of publications**	**Key themes highlighted**	**Managing Complexity**		**Sum assessment result**	**Managing Changeability**				**Sum assessment result**
				Hierarchical Decomposing System Architecture	Dependency analysis		Direct/ Indirect change propagation	Risk analysis of change	Quantifying connections and result	Change modelling capability	
1	ADVICE	(Kocar and Akgunduz 2010)	A simulated environment for ECM.	◕	◑	12	◑	◔	◕	◑	**20**
2	Axiomatic Design	Suh *et al.* (2007)	Total likelihood of an element causing change is equal to be the sum of the likelihood of a causing change to each other element.	◕	◑	12	◔	◔	◑	◔	14
3	C-FAR	Cohen *et al.* (2000)	Indicating possible change propagation and an evaluation of the change influence.	◕	◑	12	◑	◑	●	◑	**25**
4	Chen and Li	Cheng & Li (2005)	Pattern-based redesign planning	◑	◑	10	◑	◑	◔	◕	**20**
5	CPM - Change Prediction Method	Clarkson *et al.* (2004)	Change Prediction Method based on numeric component DSMs and stochastic propagation analysis.	◑	◔	8	●	◑	●	◕	**33**
6	ΔDSM	Morkos *and* Summers (2010)	EC propagation due to requirement changes.	◕	◕	12	◑	◑	◔	◔	16
7	ECMS - Engineering Change Management System	Tseng *et al.* (2008)	Evaluating a design change and distributed manufacturing operations in a collaborative manufacturing environment.	◑	◕	12	◑	◔	◑	◑	18
8	FACP - Functional Analysis of Change Propagation	Flanagan *et al.* (2003)	Searching for possible change propagation paths through the link between functions and elements, to evaluate them and to select the optimal one.	○	◑	6	◑	◑	○	◑	16
9	ANP (Analytical Network Process)	Lee *et al.* (2010)	Relative change impact analysis using analytic network process	◑	◑	10	◑	◑	○	◔	14

10	DSM/ MDM – Multi-Domain Matrix	Danilovic &Browning 2004; Maurer &Lindemann 2007)	A system's structure to be analysed across multiple domains.	●	◕	**17**	◑	◑	◔	◔	16
11	Fei *et al.*	Fei *et al.* (2010)	Model-driven and knowledge-based method	◔	◑	8	◔	◔	○	◑	12
12	Redesign IT	Ollinger and Stahovich (2001)	Model-based reasoning to generate and evaluate proposals of redesign plans	◕	◑	12	◑	◑	◔	◕	**20**
13	REDM - The risk in Early Design Method	Grantham Lough *et al.* (2006)	Reducing dependence on expert knowledge (by using a more automated risk generation)	○	◕	8	◑	◕	○	◑	18
14	Reddi & Moon	Reddi and Moon (2009)	Rules recursively map elements /change type pairs onto possible direct and indirect propagation effects.	◑	◑	10	◕	◑	○	◑	18
15	Rouibah & Caskey	Rouibah *and* Caskey (2003)	Change propagates through parameter with links to elements, people, and documents.	◔	◔	6	◑	◑	○	◕	18

Rating Scale

○	◔	◑	◕	●
Poor (1)	Fair (3)	Average (5)	Good (7)	Excellent (10)

The Methods Selected for this Research

In the remainder of this section, the multi-domain matrix-based system change method is adopted which applies a systematic process to the modelling of designing an RMS: The Change Prediction Method (CPM) described by Clarkson *et al.* (2004) and Multi-Domain Matrix (MDM) described by Maurer (2007) is used as a method for this thesis. This research aims to use a change prediction-based method, which captures the factors that may influence the design of an RMS (Olmez *et al*. 2018b). A multi-domain change propagation model can support the assessment of connectivity. Here, the MDM and CPM are chosen for several reasons:

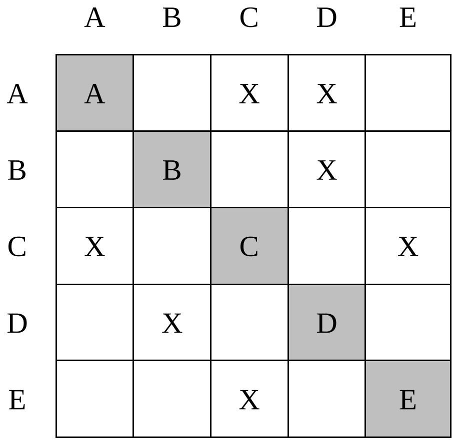
- The network structure of the process is modelled in all its aspects. This way, most process models can be converted into an MDM with the information concerning their structure.
- Capable of decomposing and integrating different domains; this way, it is possible to check how well-aligned the different structures that are modelled (e.g. product, process and people).
- Display the qualitative design information in MDM.
- CPM is capable to model the dependencies between element pairs to quantify and visualise the overall risk of change propagation.
- CPM provides a vision to different stakeholders through the combined risk matrix which supports the decision making of change management in the manufacturing industry.

2.5.4 Connectivity Model

1. Design Structure Matrix (DSM)

Design Structure Matrix (DSM) is a matrix to model the design and structure (architecture) of a system (Eppinger *et al*. 2012). Steward (1981) was first introduced DSM, which can be applied to represent the interaction between design requirements for product, procss and organization. The DSM has become increasingly popular in planning product development, project planning and management, systems engineering, and organizational development (Browning, 2001). DSM reflects the interaction between similar tasks in the form of N-order square matrix. Tasks form a matrix with the same ordered sequence as the matrix rows and columns (Mengqi 2012).

As shown in Figure 20, a DSM a square matrix presents the system elements (the shaded cells along the diagonal) and their interactions (the off-diagonal marks). One reads across an element's row to see its inputs and down its columns to see its outputs. For instance, the DSM in Figure 2.20 shows element A receiving inputs from elements C and D and providing an output to element C.



	A	B	C	D	E
A	A		X	X	
B		B		X	
C	X		C		X
D		X		D	
E			X		E

Figure 2.20: A DSM showing five elemts of a system and their relationship

This research is particularly interested the advantages of the DSM for System Architecture Modeling Browning (2009) highlights in his book; DSM is only one important tool in a system designer's or modeler's tool kit to represent architectural modeling and the some advantages of DSM; The structured arrangement of elements and interactions can meaningfully represent a fairly large, complex system in a relatively small space. DSM provides a system-level view that can support optimal decision making and help focused on particular elements.

A complementary form of DSM to overcome its characteristic single-domain limitations is known as *Domain Mapping Matrix (DMM)* (Becker *et al*). A DMM is very similar to a DSM. However, since columns and rows of the matrix represent the same domain, a DSM has to be symmetric along the diagonal elements and is always square, whereas a DMM is non-symmetric along the diagonal and is always a rectangular matrix. In a DMM each row represents design intent from one domain and each column represents design intent from another domain such as organization, customer requirements, and processes can be linked with each other. The DMM method can be used to represent the mapping between design functions and subsystems, and the mapping of subsystems to critical component types. (Oduncuoglu & Vince 2011).

2. Multi Domain Matrix (MDM)

The challenge is to map the process accurately in a DSM because dependencies are difficult to capture, and the DSM cannot be directly defined in an exact state(Giffin at al. 2009). The MDM extends the capabilities of the DSM by integrating multiple domains and enabling the deduction of indirect dependencies (Furtmeier and Tormmelien 2010) within domains and across domain boundaries. In this thesis, an approach towards a matrix-based system model is presented which applies a systematic process to the modelling of a whole system. The resulting multi-level system elements and the hierarchical system decomposition can be used to simulate manufacturing system property changes and their propagation throughout the system.

a Multiple Domain Matrix (MDM) as presented in Figure 2.21 is to illustrate the flow of connection. A MDM is an incorporation of Design Structure Matrices (DSMs) and Domain Mapping Matrices (DMMs. DSMs are square matrices which serve to model the asymmetrical dependencies between inputs of a provided domain. In difference, DMMs are non-square matrices which link related connection across different domains. When these matrices are linked together into a MDM as shown in Figure 2.21, the outcome is a square matrix which models the dependencies within and between different domains. The diagonal of the MDM are DSMs and the rest of the areas are DMMs. For example, Square 2 lies on the diagonal of the MDM and thus is a DSM which examines the dependencies within the Process domain. On the other hand, square 1 does not lie on the diagonal of the MDM and hence is a DMM which examines the dependencies between the Process domain and the required Organisation domain. More details on mapping between domains can be found in [Danilovic and Browning, 2007].

	Product	Process	Organisation
Product	1	2	▨
Process	3	4	▨
Organisation	▨	5	▨

Figure 2.21: An illustration of a Multi Domain Matrix (MDM)

2.5.5 Change Prediction

The change prediction literature in system design discusses that change propagates between two elements of a system if there is a dependency between them. Eckert *et al.* (2006) mention correcting change prediction by identifying *the knock-on effects of changes* and *a change prediction process*. Predicting the knock-on effect of changes is to determine or estimate whether a particular change could propagate. Change prediction process involves two main challenges: *risk assessment* and *propagation paths* (Eckert *et al.* 2006). Computation of change risks of using CPM technique addresses these challenges. Risk of change propagating between two elements is computed through the combination of all the branches in such a tree. To overcome the challenges of predicting change risk within a system, multi-layered hierarchically structured system descriptions can be used to support risk assessments. Understanding change prediction in a systematic way can be categorised in three aspects to the research aims of this thesis: (1) to define strategies or theories used in predicting change propagation; (2) to identify change prediction needs; and (3) to describe the CPM technique.

1. Strategies / Theories used in predicting change propagation

Eckert *et al.* (2006) propose that the capability to predict the impact of the change is relatively dependent on the degree of understanding of the nature of interactions between product elements. The authors present two strategies for the prediction of change propagation through knowing the nature of connections between elements (as illustrated in Figure 2.22): (1) *Depth-first search*: exploring with the analytical approach the effect of the change, (2) *Experience-based heuristic search*: using the experience of the designer. Another change prediction strategy is presented by Hollnagel and Woods (2006) who refers to potential pathways through which a change to one element may lead to change in another. In this way, there are risks associated with overdependence on the experiences of experts in predicting potential propagation paths.

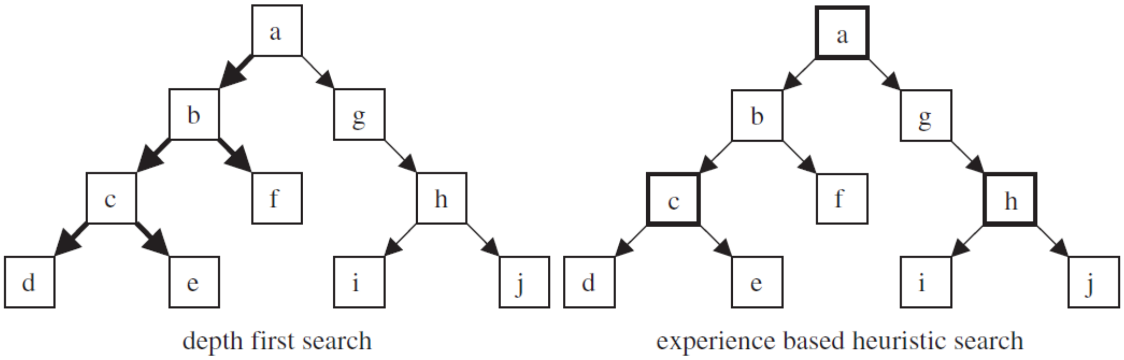
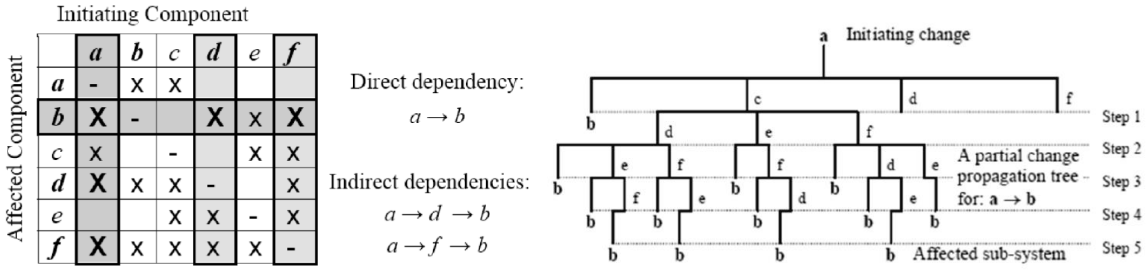


Figure 2.22: Reasoning strategies on change prediction (Eckert *et al.* 2006)

Jarratt (2004b) addresses two objectives of change prediction to support designers and managers in decision making while *creating change implementation process plans*: (1) assessing the consequences of a change, such as estimating the risk associated when making a change (see also Clarkson *et al.* 2001); (2) identifying the system elements that may be affected when making a change. Eckert *et al.* (2006) argue that probabilistic and deterministic predictions are not practical due to the many sources of uncertainty. However, tools can provide an estimation of possible propagation paths, which are often derived from assessments of system properties and the relation between system elements. The types of dependencies between system elements are an important factor when assessing a change of design system (Ariyo 2011). Clarkson *et al.* (2004) categories two types of dependencies. Figure 2.23 (a) illustrates the difference between the two types of dependencies, and Figure 2.23 (b) give the routes of a propagation tree between sub-systems a and b.

1. *Direct dependenc*y is a type of interaction that arises between two elements only. The interaction between the elements is a result of the architecture of the chosen system. A direct dependency refers to the propagation of change between end-to-end sub-systems.
2. *An indirect dependency* exists between any two elements if it requires at least one intermediate element for changes to propagate between them. The change will not propagate between two indirectly connected elements.



	a	b	c	d	e	f
a	-	x	x			
b	X	-		X	x	X
c	x		-		x	x
d	X	x	x	-		x
e			x	x	-	x
f	X	x	x	x	x	-

(a) (b)

Figure 2.23: (a) Direct and indirect dependencies, (b) Partial change propagation tree (Clarkson *et al*. 2004)

The dependencies between the structural elements are identified through the knowledge of designers. The change prediction method has some advantages; it helps the designer to predict the affected elements by changing initiating elements and to estimate the likelihood and impact of the change. These dependencies can be characterised qualitatively (Cohen *et al.* 2000; Furtmeier and Tormmelien, 2010) and/or quantitatively (Clarkson *et al.* 2004). Elements within the complex system also have hidden dependencies which may cause change propagation. These dependencies arise from long chains of connections and constraints on both the system's design and its implementation process. Exceptionally, change may propagate between connected elements despite their not being directly connected. Change propagates because the overall system goal is not achieved. Hidden dependencies also need to be modelled to for the prediction to be successful.

2. The needs for change prediction

A change prediction technique should be capable of meeting the following requirements while predicting change propagation and meeting the research objectives of this thesis.

- A multi-level risk estimation method should enable consistent *decomposition of systems* to a manageable level which is useful for change propagation assessments.
- A multi-level risk estimation method should enable consistent *estimation of risk* across all hierarchy levels of the system description.
- A technique for *propagation path investigation* should support investigations into alternative paths along which a change may be allowed to propagate.
- A propagation investigation technique is required to account for both *the direct and the indirect dependencies* as well as hidden dependencies that exist between elements.
- A prediction technique is required to draw attention to elements critically subject to the effects of proposed changes.

The next section assesses the Change Prediction Method (CPM) against these requirements.

3. The Change Prediction Method (CPM)

Clarkson *et al.* (2004) introduced the CPM (Change Prediction Method) for predicting change propagation risks based on product or system connectivity models which are presented in a Design Structure Matrix (DSM). A connection between two elements means a change initiator can affect the change recipient in a directed matrix. The system connectivity models are structured by modelling the system elements and dependencies between elements, forming a matrix-based representation that allows visual identification of high risks in the element architecture, supporting designers in making decisions about whether changes can be implemented or not.

CPM supports identifying risks of emergent changes resulting from knock-on effects from other changes before these changes are implemented. So, an assumption can be made that if one element is changed, this can only have effects on directly connected elements. These changes can, in turn, again affect another directly connected element (knock-on effects). Each connection includes a direct change likelihood value that captures the probability of a change propagating from the initiating element of the effect to the receiving element. Likelihood and impact values on a connection specify how much of the initiating element has to be changed when a change propagates through this element's connection. In this way, CPM creates a computation of risk by using the system of the likelihood of impact data.

The CPM method has been part of other research projects. Jarratt (2004b) introduced connection types as a way to reason about change dependencies between elements and applied the method in several industrial contexts (Eckert *et al.* 2004; Jarratt *et al.* 2004b). Flanagan *et al.* (2003) looked into how to integrate functions into the basic change prediction model. Similarly, Hamraz (2013) used CPM by integrating functional reasoning with change prediction. The author modelled a product as a network of its functional, behavioural, and structural attributes, and then assessed change propagation as it spreads between the elements along with the connections of the network.

Keller (2007) developed a change prediction methodology for the assessment of change impact with the CPM, which involves three key stages as shown in Figure 2.24. These are (1) construction of a model (Data Gathering); (2) computation of change risks (Compute Risks) and (3) assessment of change requests (Analyse Risks). In *stage 1*, the collected data are modelled using a DSM (Steward 1981). In *stage 2*, the CPM technique estimates the risk associated with change propagating between a pair of elements using a risk computation algorithm developed by Clarkson *et al.* (2004). The estimate is assessed concerning the average design effort associated with making a change. The output of the computation process is referred to as *a combined risk* (The Forward CPM algorithm calculates the combined risk of change propagation from element a to element b, which is presented in Appendix 6). The combined risk represents the other influential factors accounted for when estimating risk values. In this thesis, the term *risk* is used only to refer to this combined risk estimate. In *stage 3*, change requests are analysed by using risk estimates and identified connections of elements. The risk estimates indicate process-related implications of change as the average risk involved in making a change, while the direct connections indicate product-related implications by identifying potential propagation paths (Keller 2007).

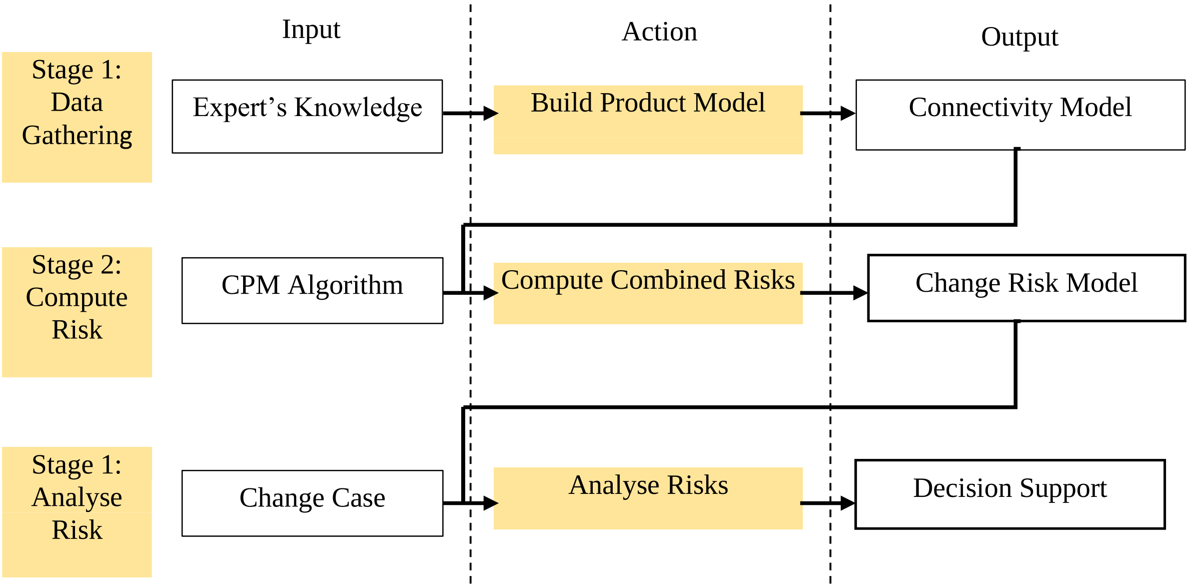


Figure 2.24: A methodology for change prediction (Keller 2007)

Another change prediction methodology was developed by Clarkson *et al*. (2004), illustrated in Figure 2.25. The methodology supports the decomposition of a product into a set of systems and sub-systems and their related dependencies. Those dependencies are quantified and risk of change propagation is presented in a DSM, where risk is defined as the product of the likelihood and impact of change propagation. CPM developed at the Engineering Design Centre (EDC) in Cambridge (UK) accompanies the engineering change process in three steps. The approach is structured in three stages: *an initial analysis: a case by case analysis;* and *the actual redesign*. The first step is the *initial analysis*. It includes the construction of the product model, the combining of the dependency matrices and the CPM algorithm computing the predictive likelihood and impact matrices to develop *a product risk matrix*. In the second step, an analysis of the specific case contributes to identifying, initiating, and predicting changes with direct dependencies. The result of the case analysis is a case risk plot which presents the predicted likelihood and impact of change effects to compare the risk of change to different elements. The last stage represents the *redesign* of a prototype product through the predicted change.

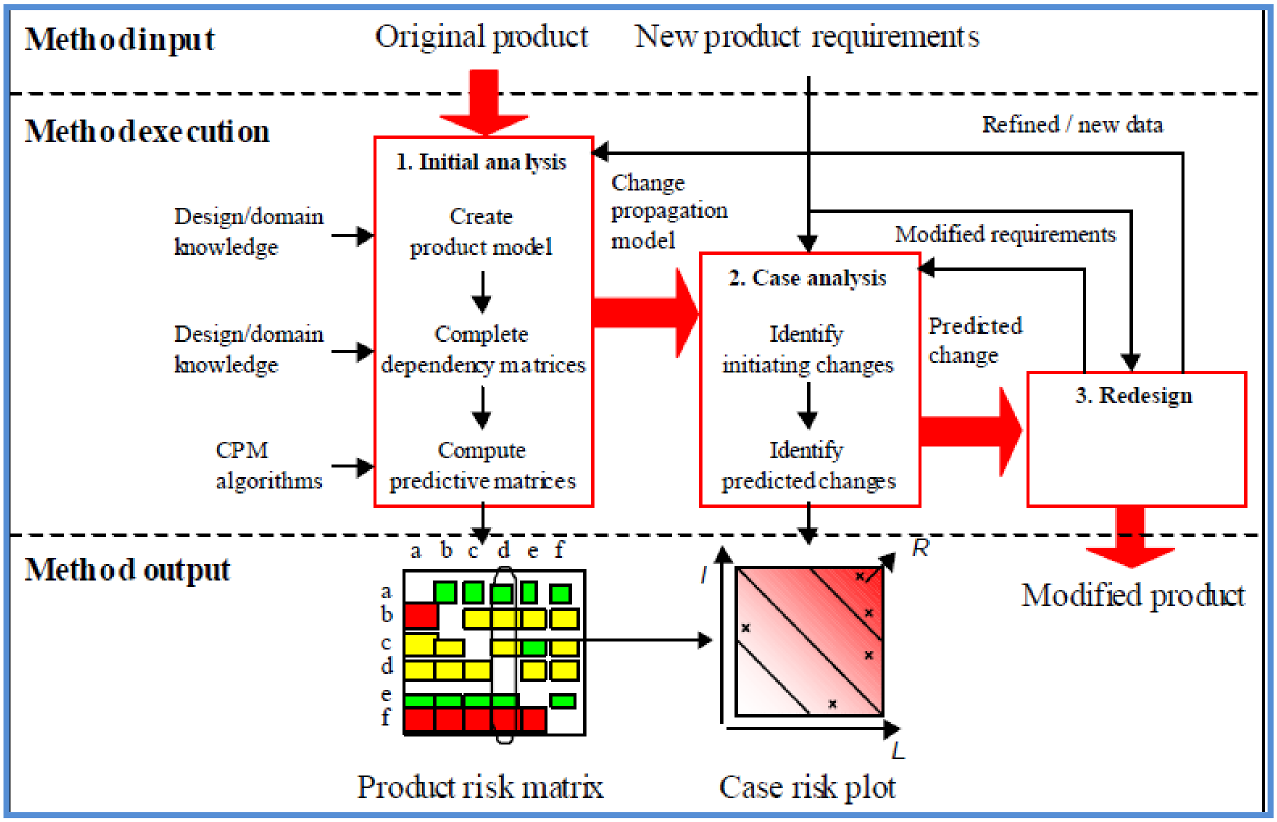


Figure 2.25: The change prediction methodology (Clarkson *et al.* 2004)

Clearly, the change prediction methodology of the product shows that CPM has the potential to identify and manage changes within a manufacturing system. The CPM can be applied within a single domain or across multiple domains and can also identify the impact on specific decision criteria. The main limitation of the proposed CPM method is that the quality of the analysis results depends on the accuracy and completeness of the information stored in the model (Rutka *et al.* 2006). Since all relevant information is usually distributed over many domain experts and knowledge bases, capturing all information can be very time-consuming. Thus, it is necessary to maintain the right balance between time spent to create a model and time spent using the model.

2.5.5 Literature Gaps

Six main gaps have been identified from the selected key published literature on resilient manufacturing systems (Table 2.2, page 22):

1. Some frameworks have been developed to deal with a broader resilience purpose in manufacturing business. However, manufacturers do not fully focus on creating resilience at an operational level.

2. More empirical studies are needed to develop, understand and validate any association between resilience and the manufacturing system.
3. Assessment of manufacturing changes in real manufacturing systems is not broadly supported by a quantitative model or software tools.
4. Future empirical studies need to take into account what has worked, to get a deeper understanding of how resilience occurs.
5. Current research on manufacturing systems has largely been carried out in a range of complex workplaces (such as oil and gas, nuclear power plants, the automotive industry). There is a lack of empirical studies from modern high-risk businesses such as in the construction industry.
6. There seems to be very little literature available which identifies manufacturing systems in the application and implementation of manufacturing resiliency and resiliency models, tools and techniques to achieve robust and adaptable systems.

The main contributions of this thesis to address the literature gap on resilience within manufacturing systems are: (1) a strategically focus on resilience increasing robustness and adaptability supported by a quantitative model or software tools, and (2) the provision of an empirical study that focuses on the operational level to achieve a resilient manufacturing system.

2.6 Revisiting the Research Questions

This thesis proposes to the answer the research questions by first investigating the current understanding of resilient manufacturing systems (RMS), their management and support methods, and subsequently developing and evaluating a broad method for modelling and analysing RMSs based on the initially established knowledge. Thus, at first, two questions, RQ1 and RQ2 were derived from the main research question (How can change prediction inform the design of resilient manufacturing systems?)
(Chapter 1). RQ1 and RQ2 have led the systematic literature review on RMSs and existing support methods that have been presented in Chapter 2. While RQ1 explores the motivation, categories and significance of RMSs, RQ2 considers how they are currently modelled and analysed to understand the relevant properties and capabilities but also potential limitations of existing approaches.

RQ1: What are the characteristics of a manufacturing system that make it resilient to change?

RQ2: What is the role of engineering change prediction approaches in the long-term delivery of resilient manufacturing systems?

Systematic literature reviews were conducted within the Descriptive Study 1 of Research Methodology to answer these research questions by reviewing the key publications on Resilience, Manufacturing System Design (MSD), Resilient Manufacturing Systems (RMS), Engineering Changes (ECs) and Engineering Change Management (ECM), and ECM methods. Finding the answer to RQ1 led to the definition of the second research question. The answers to RQ1 and RQ2 provided both a motivation and a useful basis for the development of a comprehensive approach to designing an RMS and led to the formulation of four other detailed research questions, RQ3 to RQ6. RQ3 concerns requirements for a method to design an RMS, which were extracted from the investigations of RQ1 and RQ2. The resulting requirements were continuously revised when carrying out industrial studies (Chapter 7). The answer to RQ3 (Chapter 4) delivered the requirements for a system change method for designing an RMS and an evaluation of current EC methods against these requirements. The evaluation of EC methods identifies potential limitations and the conceptual design of an RMS, which refer to RQ4 (Chapter 5). This concept was expanded in detail by exploring RQ5 (Chapter 6). Lastly, RQ6 explores the application to practice and asks for an evaluation of the developed method (Chapters 7 and 8).

RQ3 What are the requirements for the system change method to be used in the context of designing a resilient manufacturing system?

RQ4 What are suitable concepts for a system change method to support the delivery of resilient manufacturing system?

RQ5 What are the detailed elements required to understand the chosen change method concept for resilient management system?

RQ6 How well does the developed system change method perform in real case studies?

2.7 Chapter Summary

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

Section 2.1 The need for Resilience gives direction on reviewing the literature on resilience, manufacturing system design, resilient manufacturing systems, engineering change, engineering change management, and engineering change models.an appropriate system change method for designing a Resilient Manufacturing system (RMS) to answer two research questions. Section 2.2 Research on Resilience assess the various contexts of research for resilience descriptions and investigates a clear definition of resilience for manufacturing systems which not only explicitly define, but also describe the characteristics of resilience within the manufacturing system in order to effectively manage changes. Section 2.3 Manufacturing System Resilience explors in order to achieve a successful move towards RMS. For this reason: (1) manufacturing system (MS) definitions, which is discussed and a definition of a system and MS are developed for this thesis; (2) a deep understanding of resilience in the MS context which is explored in literature; (3) an appropriate definition of manufacturing resilience and resilience properties are described.

Section 2.4 Manufacturing system design identifies requirements: (1) to present the concept of resilience in the context of manufacturing systems along with a new conceptual model of them, (2) to present strategies for designing and managing an RMS. *Section 2.5 Modelling system change* explores to model a system change, complexity and changeability of system;. to better understand change management in a manufacturing environment,; engineering change (EC) and engineering change management (ECM) in the related literature.; a comprehensive literature review for the modelling and management of change to choose the most suitable model for this thesis. *Section 2.6 Revisit the research questions* describes the answers to RQ1 and RQ2 and a useful basis for the development of a comprehensive approach to designing an RMS and led to the formulation of four other detailed research questions, RQ3 to RQ6.

This chapter formed the basic understanding for this research, upon which all the following chapters can build. Thus, it has answered the first and second research question. (1) Robustness or adaptability may be the key system life-cycle property for a manufacturing system that makes it resilient to changes. (2) In overview, it was learned that manufacturing changes and their propagation are essential for manufacturing system designs and that support for managing changes is provided by ECM methods. The next chapter reviews current research methodologies to select the most suitable methodology for this research project to answer research questions 3.

3 Research Methodology

3.1 Chapter Overview

This chapter reviews well known research methodologies used for design research and selects the most appropriate method for this work. Thus, the right methodology is a key factor in delivering high-quality research work. This chapter reviews well-known research methodologies which are used for design research. The research methodology supports systematically addressing the research questions described in Chapter 2. This chapter also explores the main scientific research challenges that any researcher faces during the research process. The remainder of this chapter is structured as follows: Section 3.2 investigates the research challenges; Section 3.3 reviews the common research methodologies for design and the selected research methodology for this research; and Section 3.4 summarises the chapter.

3.2 Research Challenges

Desing research can be a paticularly challanging process. s. Eckert *et al.* (2003) review some practical challenges of design research, which is subject to unpredictable requirements and objectives such as (1) procedures for industry-supported research; (2) having practical applications; (3) reliable and validated tools; (4) creating reports from projects; (5) achieving effective contributions; (6) achieving independence in own research, and achieving in large-scale, long-term results; (7) achieving results in a realistic time. Research in the context of designing resilient manufacturing systems (RMS) is subject to difficulties. Some of the research challenges in this research study are described below.

Methodology in Design

Applying design methodology in real industrial cases is challenging process. Especially the limitations in current research methodologies with regards to a clear definition of the research purposes, problems and procedure at an appropriate level of detail. The time limitation was especially challenging for manufacturing design research. The timing of case studies weren't fit appropriately within this PhD projects. The time limitation provides a particular challenge in this study in justifying the work empirically.

Establishing a Case Study

The key challenging factors when establishing the case studies in this research is lack of user availability prevents the gathering of information from interviews so that the researcher has to extract information from documents. Due to this, inappropriate information is sometimes collected. In addition, running the empirical study is required additional skills to understand the methodology of research, such as understand the patterns of the methodology, observation skills, and analytical assessment skills.

Achieving Stakeholder Engagement

Engaging with stakeholders within the manufacturing system was difficult due to the limited time available to develop a relationship and provide opportunities for discussion.

Data Collection

Having a close model link to the change system and estimating the probabilities are significant challenges. Ensuring the availability of precise information is challenging when developing the system change method. Even though acquiring accurate data is difficult, this is somewhat mitigated as the task is risk area identification, not exact quantification. Data inaccuracies mean that risk prediction for the second case study is also inaccurate.

Method Validation

This research was undertaken as an academic research project collaboration between the Engineering Design Centre (EDC) and two industrial manufacturing companies: UOP Honeywell and Laing O'Rourke. The most up-to-date version of the CPM tool has been used in this thesis, applying it to several change requirements. Nevertheless, the CPM results should be assessed against historical change cases. Due to the Honeywell UOP manufacturing plant in the UK having been closed down, the method application could not be validated in the third case study. However, the evaluation of the method application was made in the first and second case studies.

3.3 Research Methodology for Design

This section reviews design research and some of the common research approaches that are mainly used in design research alongside the research methodology which has been selected for this PhD study.

3.3.1 Design Research

Before reviewing the research methodologies, the role and purpose of design research need to be well-understood. Blessing (2002) defines design research in engineering by integrating two aims to improve the design research process): (1) the formulation and validation of models and theories about the occurrence of design, as well as (2) the development and validation of knowledge, methods and tools founded on these models and theories. Design research, in common, purposes at making design better productive and effective and improving design applications. Design research supports to understand and improve the design process in the industry. Developing effective tools and methods requires understanding and investigation at the various levels of design to see the big picture (Eckert *et al.* 2003).

The primary focuss of research in this thesis are (1) to determine the interaction of the product, process and organisation with the change requirements within a manufacturing system design process, and (2) to systematically capture the interconnection and integration of system elements and system domains. Figure 3.1 illustrates the aims of engineering design research and visualises the various parts that are involved in the design research process. A design research process has to be able to develop and validate knowledge systematically, which requires a research methodology (Blessing 2002). The next section, therefore, describes the most recognised research methodologies within the field of design research, and then selects the most suitable one for the present study.

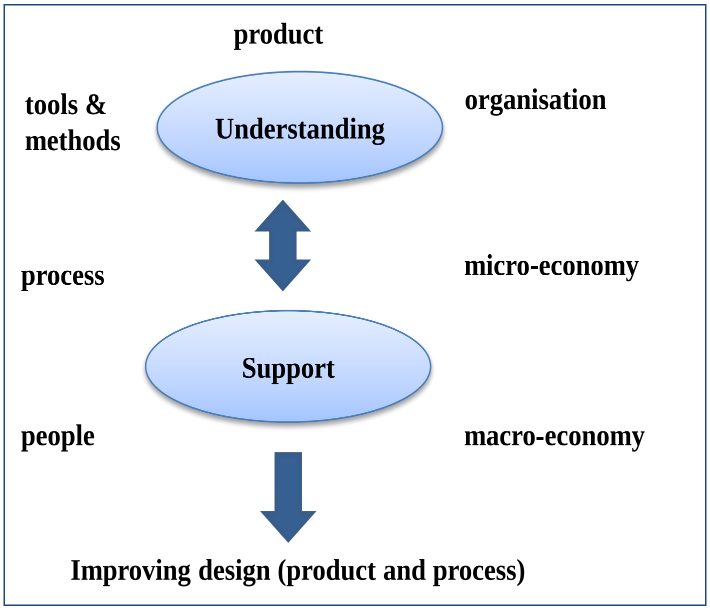


Figure 3.1: Design Research (Blessing 2002)

3.3.2 Common Research Methodologies for Design

The term *methodology* is defined by the Oxford English Dictionary in general terms as *"*a system of methods used in a particular area of study or activity*"*. Collis and Hussey (2003) use the term methodology for the overall approaches to a research process. Blessing and Chakrabrati (2009) describe a research methodology as a systematic way that helps to develop and validate knowledge. Hence, a research methodology is needed for research by providing a roadmap.

The importance of knowing the methodology of the research is to develop disciplined thinking, to observe the field objectively, to evaluate and use research results for action and enable the researcher to make rational decisions (Kothari 2004). The methodology provides an appropriate approach and specific techniques to make research more effective and efficient in achieving the research goals (Blessing and Chakrabarti 2009). Methodologies for design research lead to the formulation of hypotheses and to finding the answers to the research questions through descriptive and prescriptive studies (Duffy and O'Donnell 1999; Eckert *et al.* 2003; Blessing and Chakrabarti 2009). In the following section, design research methodologies were reviewed to select the most suitable one for this research.

Six-step design research methodology

This design research framework was proposed by Duffy and Andreasen (1995) and consists of six steps of methodology (Figure 3.2). This approach argues that a design problem should be supported by literature and design practice from industry to improve design performance. The role of the literature is to develop a hypothesis, formulate a research problem, and develop a solution for the design problem. The design problem is used to generate the hypothesis which is described in a research problem. After that, the solution and formal evaluation is generated with the design practice and then documented. Note that the six-step design research methodology is a linear process and doesn't provide any possible iteration to support refinements to the research.

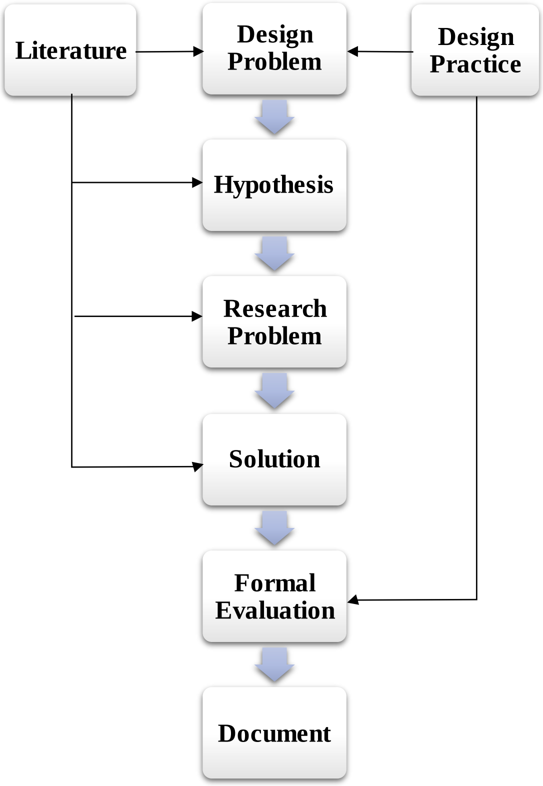


Figure 3.2: Six-step design research methodology (Duffy and O'Donnell 1999)

Grounded Theory

An example of a systematic research methodology is Grounded Theory, first introduced by Glaser and Strauss (1967), and Glaser (1998) for design research. Grounded theory is a methodological approach to build a theory with the qualitative data analysis that is largely used in Social Science research. The theory proposes the constant comparison between data analysis and the developed hypotheses. It is divided into four steps.The data collected with (1) *codes*, (2) *categories* (3) *patterns*, and (4) developing a *theory* based on the analysis results in stages 1 to 3. It should be noted, however, that while Grounded Theory is well used for creating theories, this methodology is context-based explanatory research and is more commonly associated with the social science viewpoint. In addition, this theory develops a model at increasing levels of combination that may not be suitable for manufacturing design research.

Spiral Theory (The eight-fold model)

The eight-fold model or the spiral of applied research was introduced by Eckert *et al.* (2003) to support design research. The eight-fold model categorises design research into four critical phases as illustrated Figure 3.3: (1) empirical studies of design behaviour; (2) the development of design theory; (3) the development of design support tools and procedures; and (4) the introduction of support tools and procedures. Separate evaluation after each phase is also required. The spiral indicates that every phase is followed by reflection and evaluation. The spiral of design research does not prescribe a methodology or knowledge within engineering design research but provides a methodology for other analytical disciplines such as psychology and sociology (Eckert *et al.* 2004).

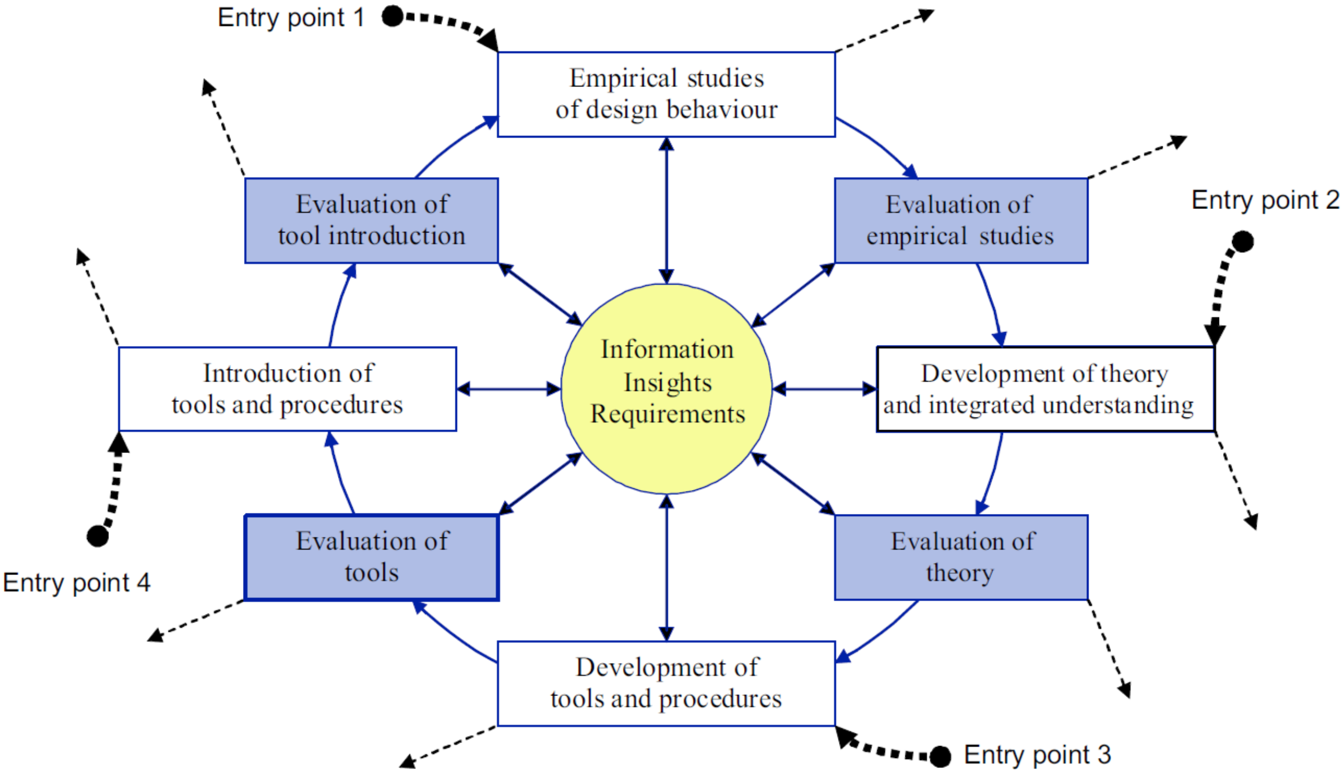


Figure 3.3: The Spiral of Applied Research: the eight types of research objective (adapted from Eckert *et al*. 2004)

Design Research Methodology (DRM)

The most recognised and specialised methodology for design research in engineering is the Design Research Methodology (DRM) first developed by Blessing and Chakrabarti with Professor Ken Wallace at the Cambridge Engineering Design Centre. Since then, it has gone through continuous development as documented in numerous publications (e.g. (Blessing and Chakrabarti 2009). The DRM proposes a framework and offers direction to researchers in guiding their research to achieve specified success criteria as well as its aims and objectives (Blessing *et al*. 1995). Specifying success criteria and metrics are described at the beginning of the research (Blessing and Chakrabarti 2002). However, the validation phase may not be descriptive and should also question the criteria established at the beginning; iterations are possible between description and prescription.

DRM describes basic requirements, main outcomes and deliverables for each of the four research stages (as shown in Figure 3.4). Initially, in the *Research Clarification* goals and hypotheses are defined and research questions are developed by reviewing the literature. The *Descriptive Study I* involves reviewing existing empirical studies and/or undertaking exploratory case studies. Accordingly, a reference model is developed to understand the problem systematically in the *Prescriptive Study* by identifying and assessing influences which are likely to affect the research study. Furthermore, success criteria are defined and evaluated in the effects of the design model. The model is then evaluated concerning functionality and consistency (support evaluation). Finally, the *Descriptive Study II* evaluates whether the developed model can be used for the planned state (application evaluation) and whether it is useful in contributing to achievement (success evaluation) (Blessing *et al.* 1995).

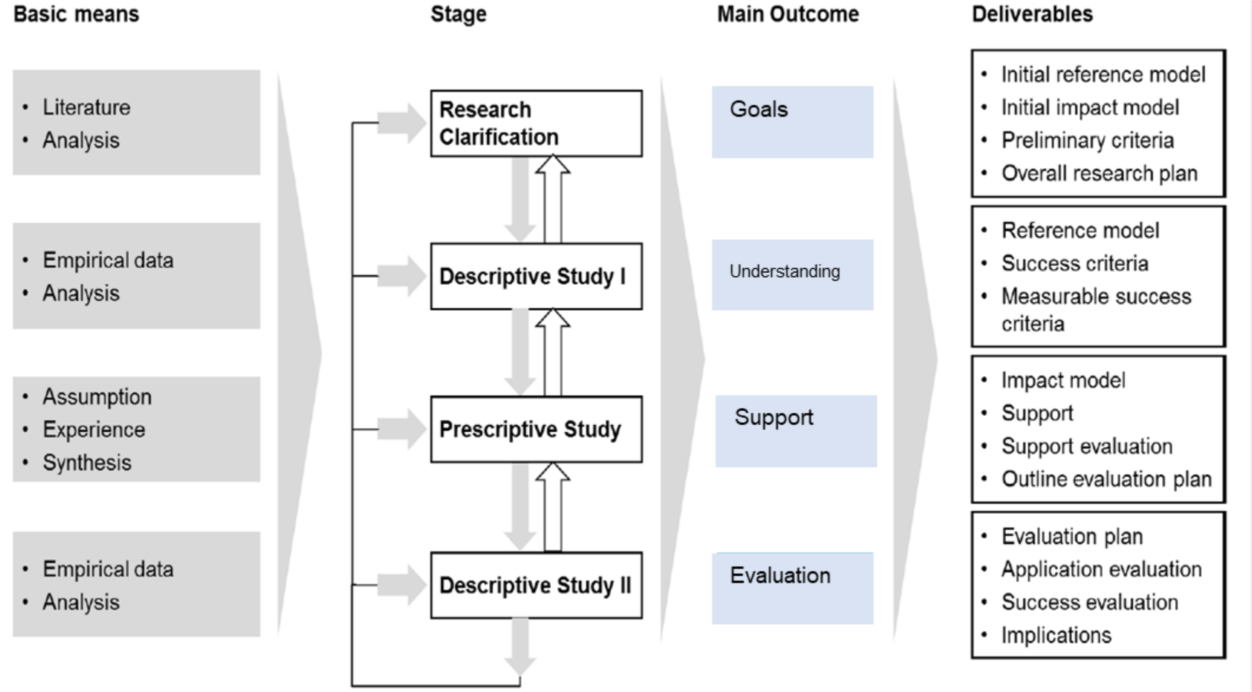


Figure 3.4: The Design Research Methodology (DRM) framework and connections
(adapted from Blessing and Chakrabarti 2002)

In contrast of the described research methodologies, in the step-wise, the Design Research Methodology (DRM) sets up the phases of descriptive and prescriptive research to any project without considering the different natures of research projects. DRM supports the need for formulating measurable success criteria; the importance of descriptive studies to increase our understanding of design processes for a researcher; the systematic development of design and the various types of evaluation; this is expected to improve the industrial changes of manufacturing system (see Figure 3.4).

3.3.3 The Methodology for this Research (DRM)

The Design Research Methodology (DRM) has been selected for this research study (Blessing and Chakrabarti 2009) due to its detailed elaboration including methods, deliverables and potential iteration ability. An in-depth study of a research project may require a comprehensive study or a review-based study that only a literature review is conducted at this stage., Blessing and Chakrabarti (2009) develop seven design research types Table 3.1). The first four are recommended for PhD projects, however, research projects of Type 5 and 6 are highly desirable but often unattainable in PhD projects due to time and resource constraints. Although, research projects described as Type 7 involve a comprehensive study involving three of the DRM stages. The other types are preferable but resource-consuming, potentially going beyond the scope of a PhD (Table 3.1). In Table 3.1, a *comprehensive study* states that a combination of literature review and additional work done by the researcher (e.g. empirical study) is carried out for the specific stage. An *initial study* indicates that only the initial steps related to a given stage are performed in preparation for use by others. The broken arrows point to possible next steps.

Type 5 is selected as this project's scope. Despite the limited existing support work, it was likely that adequate literature could be reviewed to gain an understanding of the subject of resilient manufacturing systems (RMS). In the following, the research is reviewed in each DRM stage.

Table 3.1 Types of research projects and their focuses on design research methodology (DRM) (adapted from Blessing and Chakrabarti 2009)

Type	**Condition for employment**	**Research Clarification**	**Descriptive Study I**	**Prescriptive Study**	**Descriptive Study II**
1.Comprehensive study into criteria	Success and measurable success criteria are little understood.	Review-based	Comprehensive		
2.Comprehensive study of the existing situation	Criteria can be established, but a better understanding of the existing situation is necessary to identify the most relevant factors to address.	Review-based	Comprehensive	Initial	
3.Development of support	Understanding of the existing situation obtained from the literature review and reasoning is sufficient to start the development of support.	Review-based	Review-based	Comprehensive	Initial
4.Comprehensive evaluation	Support already exists, but an evaluation of its application is not available.	Review-based	Review-based	Review-based Initial/ Comprehensive	Comprehensive
5.Development of support based on a comprehensive study of the existing condition	The aim is to develop support, but the understanding of existing condition is not enough	Review-based	Comprehensive	Comprehensive	Comprehensive
6.Development of support and comprehensive evaluation	The understanding of the existing situation obtained from the literature review is sufficient, and the project resources allow formal evaluation of the support.	Review-based	Review-based	Comprehensive	Comprehensive
7.Complete project	Little prior research has been conducted in the area of interest, yet indications are that the area has potential.	Review-based	Comprehensive	Comprehensive	Comprehensive

Figure 3.6 shows a broad view of the DRM stages with related research questions within the structure of this thesis.

2. **Research Clarification:** This stage started with exploring manufacturing and engineering design literature to focus on designing resilient systems and change management in resilient systems to understand the key subjects in the fields. Frequent discussions with the thesis supervisor and with industrial contacts (UOP Honeywell and Laing O'Rourke) have supported the development of this research project (for instance, enabling the management of change while implementing the company's specific operation system by designing a resilient manufacturing system in Honeywell UOP). Accordingly, research questions and scope, and also the first two detailed research questions, which directed the Descriptive Study-I, were formulated and an overall research plan was developed. The results of this stage have been outlined in Chapter 1 and further discussed in this chapter.
3. **Descriptive Study-I:** A systematic literature review on RMS and existing supported engineering change methods was conducted based on the Research Clarification which increases the understanding of the research problem in-depth within a typical design organisation using a reference model and theories. Descriptive Study-I was achieved through the research supervisor and company interviews with an extensive literature review. Motivated by the lack of research in the field of design manufacturing systems and methods, the literature review was conducted within a broad field of engineering design and EC methods and included modelling and simulation Some of the findings were presented in Chapter 1 under the research background and motivation. The outcome of Descriptive Study-I attempted to address the research question 1 and 2 engineering change methods which are drawn from a broad literature review. However, more research regarding the requirements of the method is needed to understand the problem at hand.
4. **Prescriptive Study***:* Based on the Descriptive Study I, the design requirements were developed for a comprehensive evaluation of a system change method to answer *research question 3* (Chapter 4). The requirements were derived to develop a suitable design concept to support the delivery of RMS, which addresses *research question 4* described in Chapter 5. The conceptual description of the method was then converted into detailed definitions which can be specified in practice and implemented computationally, resulting in the proposed SCM (Chapter 6). The detailed elements and the detailed application of the analysis toolbox were defined to understand the chosen change method for RMS which provides the answer to the *research question 5*.
5. **Descriptive Study-II** comprises the stages of applying and evaluating the method in an industrial setting. The proposed method is verified by applying it to three case studies in real-time and reviewing the outcome (Chapter 8). This implementation addressed *research question 6* and enabled validation of

the research via application in industry. The modelling framework and software tool was validated by application to three industry cases, which extended the approach as part of the novel research (Chapter 8). In each case, a different user applied the approach over several months to support two system improvement cases in collaboration with Laing O' Rock and Honeywell. It has thus been possible to evaluate the approach within its intended application context. During this stage, the supervisor and industry interviews supported empirical studies wherein the method and the design concept was applied to industry. In addition, through many informal discussions with experienced researchers, this was combined with an objective evaluation of the usage of the CAM software.

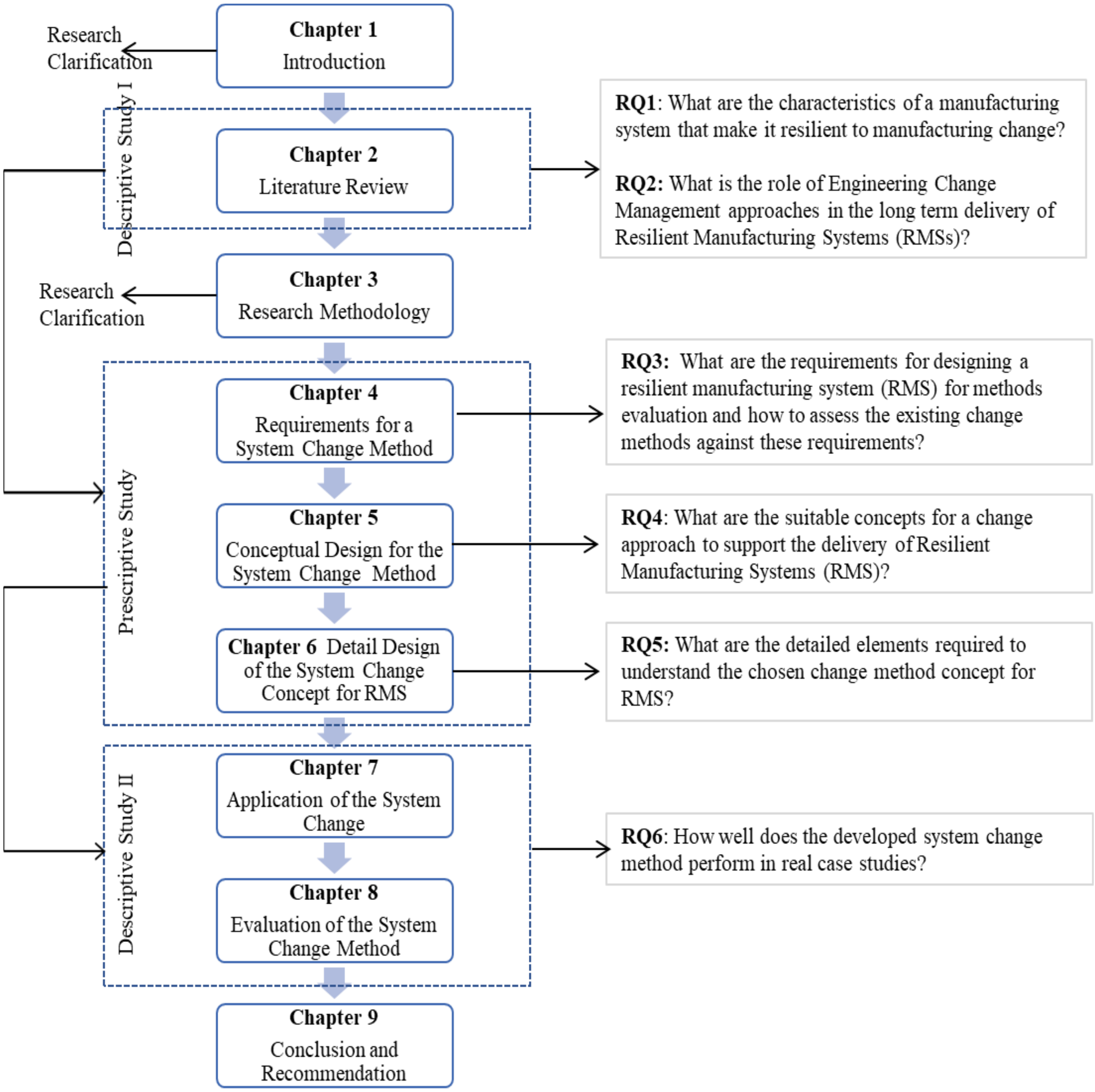


Figure 3.5: The research questions and the adopted methodology to address the content of the thesis

3.4 Chapter Summary

The general methodological challenges of this research are discussed in this chapter. Design Research Methodology (DRM) was adopted as a research methodology which provides a systematic direction to both the theoretical and empirical parts of this research project. It structures design research, taking it through from empirical studies of design to the introduction of new methods.

4 Requirements for a System Change Method

4.1 Chapter Overview

This research has established the requirements to develop a system change method (SCM) for designing resilient manufacturing systems (RMSs). Chapter 2 explored the potential engineering change management (ECM) methods based on comprehensive literature analysis and understandings from industrial case studies. Using the change method development process illustrated in Figure 4.1, this chapter identifies the method requirements for assessment of the six ECM methods with the highest potential. This chapter relates to the key research question RQ3: What are the requirements for designing a Resilient Manufacturing System (RMS) for method evaluation and how should the existing change methods be assessed against these requirements?

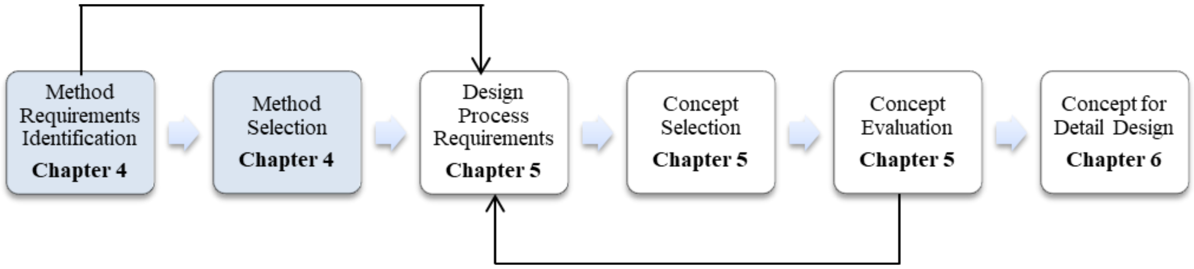


Figure 4.1: The System Change Method (SCM) Development Process

Hereafter, the chapter is structured into three remaining sections. Section 4.2 presents a requirement identification and information management process to support the generation of a broad list of requirements of Engineering Change Methods (ECM). Section 4.3 describes an assessment of current ECM methods alongside this list of requirements. Section 4.4 summarises the chapter.

4.2 The Identification of Requirements for Engineering Change Methods

The method requirements are critical in the selection of an adequate method (Ulrich and Eppinger 1995; Pahl and Beitz 1998; Otto and Wood 2001; Ullman 2003, Hull *et al.* 2004; Morkos *et al.* 2012). Method requirements are defined against project goals and are often updated due to the iterative behaviour of the design process, (Hein *et al.* 2015). These requirements are frequently caused by changes to stakeholder expectations, so a systematic approach can support better determining the expectations of the stakeholders (Hull *et al.* 2004). It is difficult to predict the impact of any change just based on the available information and how requirements are structured, formalized and documented (Rios *et al.* 2007). Change requirements are expected to occur at any stage of the product lifecycle and may cause undesired uncertainty and complexity within the design process (Clarkson *et al.* 2004).

Despite the researcher focus on the requirement analysis and formalisation of methods and tools (Zhang *et al*. 2014), there is little published on model requirements for designing resilient manufacturing systems (RMS). Nevertheless, the related publications typically describe requirements of the selected engineering change methods (listed in Table 4.3 in Section 4.3). Reviewing this literature wisely supports the recognition of the main structures of the ECM methods that provide a requirement list for a reference method for system change management. A requirement identification process should recognise change progress from conceptual design to detailed design phases (Morkos *et al.*2012).

To develop a comprehensive list of requirements for a system change method, a requirement identification and management process diagram was developed and followed as illustrated in Figure 4.2. The purpose of the diagram is to give a direction to designers regarding capturing the requirements of engineering changes adequately. In the requirement identification process is to develop requirements data from key stakeholders, project objectives, and already developed requirements. The purpose of the diagram (Figure 4.2) gives a direction to assist designers step by step regarding capturing the requirements of engineering changes. The requirements data were developed from key stakeholders, project objectives, and already developed requirements from the related literature. First, the author reviewed engineering changes with stakeholders to clearly understand the purpose of changes, causes of changes, the impact of changes, etc. The selected references are listed in Table 4.1 were analysed to draw up requirements based on the stakeholder's expectations on engineering changes for the purpose of developing a resilience model.

The listed requirements don't have to be perfect at this step, just documented. Each identified requirement was then reviewed, prioritized, de-conflicted into a more refined set of requirements. Followingly, the refined list of requirements was allocated to categorized and validated with the thesis supervisor and EDC researchers. The reviewed and approved requirements are framed into the specific context to help facilitate the understanding of the relationship among requirements in relation to the engineering change (see Figure 4.3). In order to assure consistency of model requirements were evaluated with the support of the thesis supervisor and EDC researchers. Before comparing the current engineering methods alongside the identified requirements (Figure 4.2), the framed requirements were reviewed whether meet the overall objective of the system as well as the stakeholders' needs in the validation step.

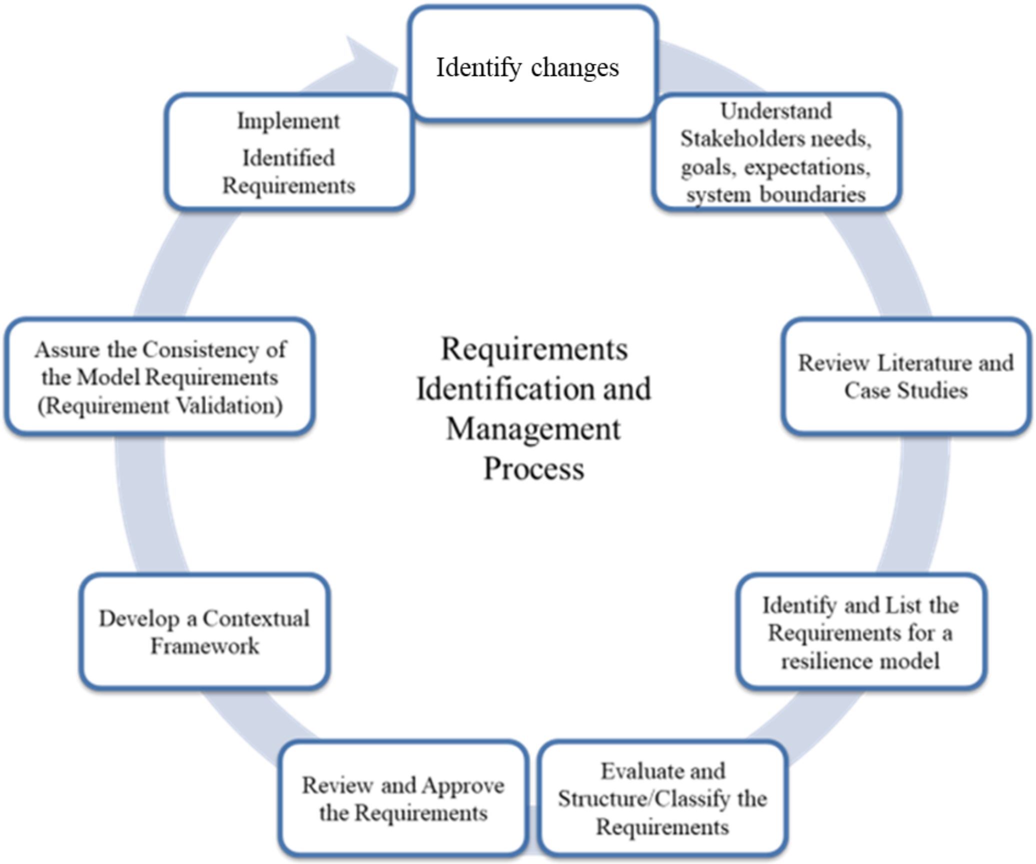


Figure 4.2: Requirements Identification and Information Management Process

Subsequently, the author strategically evaluated the list of 21 requirements into five categories and developed a holistic contextual framework (Figure 4.3). The core of the framework is to define the requirements of a reference model for designing resilient systems. The framework presents the inputs of the five types of requirements, which are *Functional, Operational, Technical, Physical, Model Development.* Functional requirements were considered in the model requirements to see if the systems, changes, and change analysis capability was working as intended. In discussions with the thesis advisor, reviewing system performance and resilience to understand a system's ability to cope with change, model availability, and change-cost impact analysis are vital in the operational view of model requirements. In model development, a visual representation of a system should be considered in the first step in terms of understanding the complex system architecture and the connectivity of system elements. As stated in Figure 4.3, the Eight most common Model Development and Application requirements were gathered from the related literature and listed in Table 4.1.

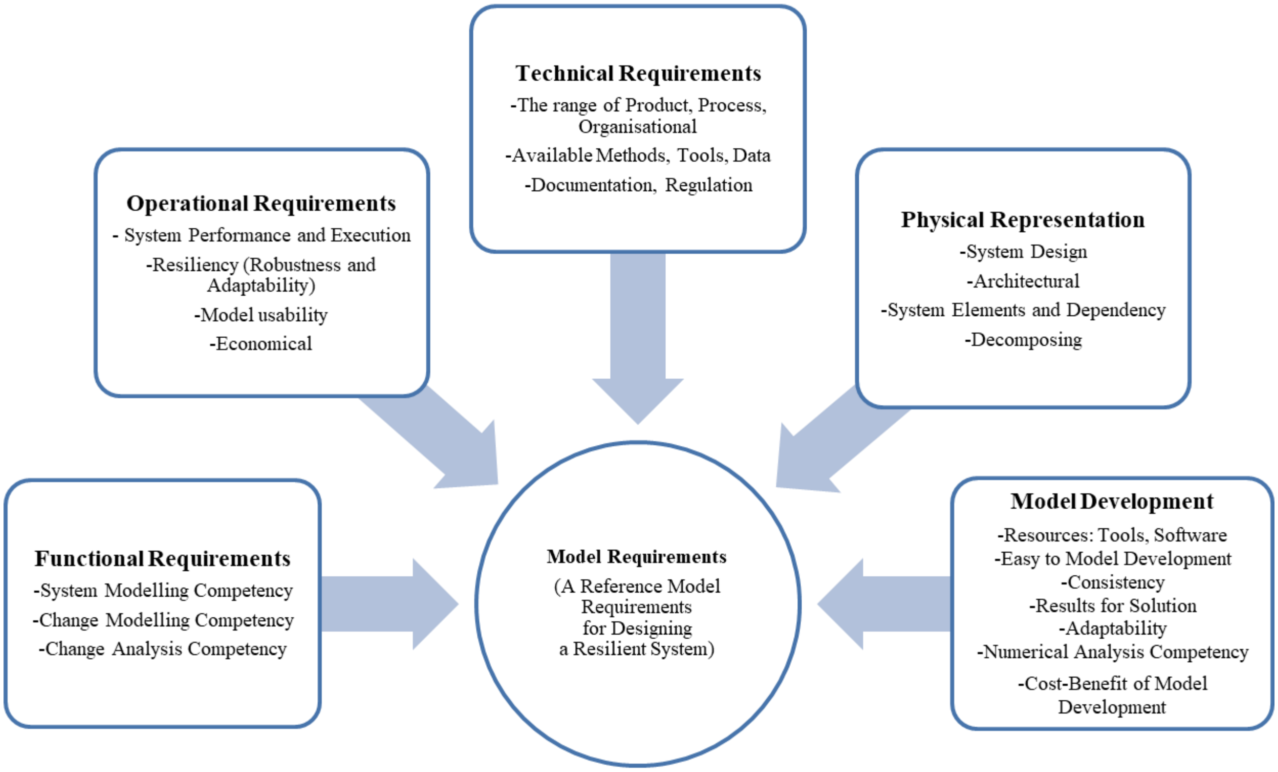


Figure 4.3: A Framework for classifying requirements of a system change method (SCM)

The thesis advisor and author listed requirements with final review and placed them in Table 4.1, with 21 requirements under 5 categories. The table states the related references for the rationale of each requirement. Some model requirements were added from the extensive requirements-based development of an Engineering Change Method (ECM) tool by Hamraz *et al.* (2013b) and Shapiro (2016) transferred from the product-domain and process-domain into the system-domain. In the research literature, other EDC authors (Jarratt 2004; Ariyo 2007; Ahmad 2011; Koh 2011) revived the selected requirements in their PhD thesis but do not systematically represent these.

The 21 requirements were used as criteria to rate a collection of the most influential existing ECM methods (Table 4.2) The requirements are simply grouped into the five categories. Altogether, these requirements ensure that the change method is usable to support the management of engineering changes in the industry (operational requirements), competency of modelling for designers in practice (functional), reliability and availability of the model (technical requirements), visualising system interface (physical requirements), and easy to develop & apply (model development).

Table 4.1: The list of requirements for a reference system change method

No	Category	Requirement	Description of the requirement	Selected References
1	**Functional Representation**	System Modelling Competency	• System design process • Managing system complexity • System domains, elements and interaction • Structural and behavioural viewpoint • Functional system structure • Functional and different level of decomposition • System analysis and design techniques	Wiesner *et al.* 2017 Holder *et al.* 2017 Zhang *et al.* 2014 Vallhagen *et al.* 2013 Morkos *et al.* 2012 Albers *et al.* 2011 Fiksel 2000 Morkos and Summers 2010 Reddi and Moon 2011b Ulrich 1995
2		Change Modelling Competency	• Model changes in system life-cycle properties • Structural changes (adding removing activities) • Modelling capability • Change propagation capability • The range of different changes covered • Predicting change propagation capability	Clarkson *et al*. 2004 Koch *et al.* 2016 Hein *et al.* 2015 Ahmad *et al.* 2013 Hamraz *et al.* 2013 Wynn *et al.* 2010 Giffin *et al.* 2009 Eckert *et al.* 2004 Jarratt *et al.* 2004
3		Change Prediction Analysis Competency	• Provides analyses to systematically identify high-risk elements and system improvement, • Quantitative an expression of change and constraints. Predicts propagation paths, • Change impact analysis to improve system performance. • Domain base system analysis, dependency analysis	Clarkson *et al.* 2004 Spena *et al.* 2016 Hamraz *et al.* 2013 Koh *et al.* 2012 Yang and Duan 2012 Reddi and Moon 2009 Kilpiner *et al.* 2009 Aryani 2009 Ollinger and Stahovich 2004 Case study experience
4	**Operational Representation**	System Performance and Execution	• Product and process requirements, structure, organisation performance, • Techniques applied during a systems development life cycle • System Execution	Fiksel 2000 Chalmeta *et al.*1997 Case study experience
5		Built Resiliency (Robustness and Adaptability)	• The system capability to recover their functions after partial damage to lead to successes from failures, • System ability to cope with change	Gu *et al.* 2015 Zhang and Luttervelt 2011 Fiksel 2000 Case study experience
6		Model Usability	• Identify changed elements, read imposed change risk to other elements, • Accessibility, • Perfectibility, • Flexibility. • Multi-tasking	Clarkson *et al.* 2004 Hamraz *et al.* 2013 Case study experience
7		Economic Viability	• Change -cost impact analysis (i.e. material cost, personal cost)	Clarkson *et al.* 2004 Case study experience

8	**Technical Representation**	The range of Product, The process, Organisational.	- Traced throughout the life cycle of product, process, and organisation.	Holder *et al.* 2017 Fiksel 2000 Ulrich 1995
9		Available Information, Data etc.	- Information for System life-cycle. - Sufficient qualitative data from expert interviews. - Results from the different users	Case study experience
10		Documentation, Regulation.	- Requirements are identified, documented, maintained, communicated, validated and tracked throughout the life cycle of a system, product, or service.	Holder *et al.* 2017 Maalem and Zarour 2016 Case study experience
11	**Physical Representation**	System Design	- System Design Process. - System design objects and activities, - System control and recovery. - Complex system representation	Morkos *et al.* 2014 Zhang *et al.* 2014 Vallhagen *et al.* 2013 Rios and Lopez 2007 Gu *et al.* 2001 Fiksel 2000
12	**Physical Representation**	Architectural	- The representation of the desired or existing physical solutions, - Architectural representation. - Functional structure - Process architecture	Hein *et al.* 2015 Benkamoun *et al.* 2014 Nadge *et al.* 2012 Fei *et al.* 2011b De Weck *et al.* 2004 Ulrich and Eppinger 2003
13		System Elements and Dependency	- Modelling element interactions on large systems, - Dependencies between parameters, parts, documents and roles must be developed in advance based on a similar system, - Inter-layer connectivity between domains - intra-layer connectivity between elements	Clarkson *et al*. 2004 Ahmed *et al.* 2009 Bock and Feeney 2013 ElMaraghy *et al.* 2012 Furtmeier and Tormmelien 2010 Rouibah and Caskey 2003 Cohen *et al.* 2000
14		Decomposing	- The systematic use of decomposition, abstraction, and projection allows complexity to be dealt with by making problems simpler - Integrated development tools for a complex solution, - Functional decomposition, - Hierarchical decomposing. - The range of levels of decomposition supported.	Brace and Cheuter 2012 ElMaraghy *et al.* 2012 Fei *et al.* 2011b Marden et al. 2009 Wiesner *et al.* 2017
15	**Model Development and Application**	Resources: Tools, Software	- Expert interviews, documentation and tools to capture data, - Information (from Stakeholders, market analysis, colleagues, expected solution, and designers own documents), - Artefacts information: existing specification, proposed solution, existing product (i.e. benchmark), previous projects, design guidelines, and user guidelines), - MSD is determined based on products and process plans information, quality, and customer satisfaction, - Constraints (i.e. financial and technological) - Simulation, - Organisational information, - Process integration, - Business practice and resources	Hamraz *et al.* 2013 Brace and Cheutet 2011 Kocar and Akgunduz 2010 Hu *et al.* 2011 Clarkson *et al.* 2004 Gu *et al.* 2001 Deno 2001 Cohen *et al.* 2000 Case study experience
16		Easy to Model Development	- Built and analyse the method by any design manager, engineer or researcher, given that a sufficient manual is provided.	Hamraz *et al.* 2013 Case study experience
17		Consistency	- The method application approach ensures that resulting system models are internally consistent and also consistent with other existing system representations and/or the design teams.	Hamraz *et al.* 2013 Kocar and Akgunduz 2010

18		Results for Solution	• Enable the development and testing of alternative solutions • Solution finding capabilities • Solution selection process	Ahmad *et al.* 2010a Ollinger and Stahovich 2004 Koh and Clarkson 2009 Case study experience
19		Adaptability	• A model of an existing system can be adapted to analyse a new one (i.e. existing models can be re-used easily). • The model can easily be changed or updated.	Clarkson *et al.* 2004 Ahmad *et al.* 2010a Hamraz *et al.* 2013 Kocar and Akgunduz 2010
20		Numerical Analysis Competency	• Numerical connection values and algorithm for change risk calculation • Quantitated results	Clarkson *et al.* 2004 Hamraz *et al.* 2013
21		Benefit-Cost of Model Development	• The benefits of method development (e.g., alignment of stakeholders, decision support information development) • Cost of model development (i.e. personnel costs)	Clarkson *et al.* 2004 Hamraz *et al.* 2013 Ahmad *et al.* 2013 Reddi and Moon 2009 Rios *and* Lopez 2007

The main point is to develop a reference change method to manage changes in the manufacturing and supply chain environment effectively and efficiently. Accordingly, the selected method should be applicable, provide valuable solutions and be economical to users. The defined method requirements are addressed to the design process requirements that support the development of a conceptual design for a systematic change analysis process (Chapter 5). The synthesis of the design process requirements and system change method requirements indicate the system change method, which was also checked in the practical relevancy based on the three industrial studies (Chapter 7).

4.3 Comparative Assessment of current ECM Methods

This section identifies and compares different conceptual ideas to fulfil each identified requirement using a comparison table to develop an alternative concept for designing an RMS for changes. The 21 requirements and five categories described in Table 4.2 were used as standards to rate the most capable *6 ECM methods*. These methods were selected from the identified *16 ECM methods* through the literature review (Chapter 2) and consist of ADVICE, C-FAR, CPM, DSM/MDM, Redesign IT, and the methods from Chen & Li. These six methods were carefully reviewed based on the available information which included all publications. The comparison of the methods against the identified model requirements is presented in Table 4.2.

The weighted sum scores show the relative gaps between the methods (Table 4.2). The weighted sum scores mean items with lower loadings on the factor have the same weight as the items with higher loadings. So, all items have the same weight when the factor scores are computed. However, items with higher loadings might have a larger effect on the total factor score and vice versa. For this rating, the related publications were reviewed and a colour shade scale is used from poor (1) to excellent (10) to rate these concepts. For each requirement, weighted sum assessment result (Good + Excellent) are stated at last row of Table 4.2. The colour code rating outcome recommends that CPM (103 in the weighted sum assessment result) is the most suitable of all, followed by the method from DSM/MDM (90 in the weighted sum assessment result), Chen &Li (66 in the weighted sum assessment result) and Redesign IT (56 in the weighted sum assessment result). However, the weighted sum assessment results in Table 4.2 shows that some methods score better than CPM consider weighting some of the criteria. CPM could be improved in terms of System Performance and Execution (requirements 4), levels of decomposition (requirements 14), System Elements and Dependency (requirements 13), and Results for Solution (requirements 18). The MDM method can improve the CPM with regard to physical representation (requremements 12, 13, 14) where CPM has competitive gaps. Furthermore, it can be taken from the rating that for the 15 criteria, the best mark of excellent (5) is not achieved by any method. For each of these methods, a detailed evaluation table was prepared. The detailed assessment of the justification of CPM is shown in Table 4.3. The equivalent tables for the remaining five methods can be found in Appendix 3, 4, 5, 6 and 7.

Acknowledging, the constructing adequate comparisons is quite demanding due to different amounts of available information for different methods. Additionally, the ranking was assessed by only one person, and therefore the assessment might be affected by subjective decisions according to personal experience and might be biased because the rating was led by only one person. Although, this comparison is sufficient for the use in this thesis. For consultancy or other purposes, the assessment could be led by more assessors.

Table 4.2: Requirements identification for Engineering Change Method

No	**Category**	**Requirements**	**Engineering Change Methods**					
			CPM	**DSM/ MDM**	**Chen &Li**	**Redesign IT**	**C-Far**	**ADVICE**
1	Functional Representation	System Modelling Competency	◕	●	●	●	◕	○
2		Change Modelling Competency	●	◔	◔	◕	◕	◕
3		Change Analysis Competency	◕	◔	◔	◕	◕	○
4	Operational Representation	System Performance and Execution	◔	●	◕	◔	◕	◕
5		Built Resiliency (Robustness and Adaptability)	●	◔	●	●	◕	◕
6		Model Usability	●	●	◕	●	○	◕
7		Economic Viability	●	◕	◕	●	○	◕

No	Category	Requirements	Engineering Change Methods					
			CPM	DSM/ MDM	Chen &Li	Redesign IT	C-Far	ADVICE
8	Technical Representation	The range of Product, Process, Organisational	●	●	◕	◕	◑	○
9		Available Information, Data etc.	◕	◑	◑	◑	◑	◑
10		Documentation, Regulation.	◕	◑	◑	◑	◑	◑
11	Physical Representation	System Design	◕	◕	◕	◕	◑	◕
12		Architectural	◑	◕	◑	◔	◕	◑
13		System Elements and Dependency	◔	◕	◑	◔	◑	◕
14		Decomposing	◑	●	◕	◔	◕	○
15	Model Development and Application	Resources: Tools, Software	●	◕	◕	○	◕	◔
16		Easy to Model Development	●	◕	◑	◑	◔	◑
17		Consistency	◕	◑	◑	◑	◑	○
18		Results for Solution	◔	◑	●	◕	◑	◑
19		Adaptability	◕	◕	◕	◕	◕	◑
20		Numerical Analysis Competency	●	◔	◔	◔	●	◑
21		Cost-Benefit of Model Development	◕	◕	◕	◑	◔	◔
Weighted sum assessment result (Good + Excellent)			**110**	**90**	**66**	**56**	**38**	**14**

Rating Scale

○	◔	◑	◕	●
Poor (1)	Fair (3)	Average (5)	Good (7)	Excellent (10)

It is important to note the CPM method has been part of other research projects. Clarkson *et al.* (2004) focused on components and structural interactions between them for change propagation with CPM. The technique has been used in numerous industry case studies with promising results, for instance: 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). Jarratt (2004b) applied the method in several industrial contexts by presenting connection types about change dependencies between elements. Flanagan *et al.* (2003) and Hamraz (2012b) explored how to integrate functional reasoning into the change prediction model. Hamraz (2012b) modelled a product as a network of its functional, behavioural, and structural attributes, and then assessed change propagation as it spreads between the elements along with the connections of the network. Ariyo *et al.* (2008) have improved the approach by developing a hierarchical method which allows 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. Ahmad *et al.* (2013) enhanced the method by incorporating the information domains of requirements, functions, components, and the detail design process. Maier *et al* (2014) applied the technique in the combined effects of progressive iteration, rework and change propagation during the design of interconnected parts in a product architecture.

Some other researchers used methods that are related to CPM techniques. The well-known approach is that the Change Propagation Analysis replaces the direct likelihood and impact values with relations dependent on the type and level of change (Rutka *et al.* 2006). In addition, 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). Another approach which has similarities to the CPM was suggested 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.

Table 4.3 illustrates, the detailed assessment of CPM for five categories and 21 requirements with the rationals for score. The method has excellent score in four categories: One in technical representation of the range of Product, Process, Organisational due to the relative simplicity of technique makes it applicable to products, process, and organization of very high complexity. CPM has better score in three categories of model development and application: Resources- Tools, Software [CAM tool and CPM module are freely available, to capture two matrices (DSMs) can be used]; Easy to Model development [two DSMs with direct likelihood and impact values are elicited]; Numerical Analysis Competency[in numerical connection values and algorithm for change risk calculation].

Table 4.3: Rating and rationales of CPM

No	Category	Requirements	CPM score	The rationals for CPM score
1	Functional Representation	System Modelling Competency	●	Average: system model shows the connections between elements or systems, but at a high level only without hierarchical decomposition.
2		Change Modelling Competency	●	Good: change propagation along with all possible connections; but only at the element level
3		Change Analysis Competency	●	Good: based on estimated direct likelihood and impact values; considering all direct and indirect connections, but limited accuracy and only on the element level
4	Operational Representation	System Performance and Execution	●	Fair: only one level of a system can be executed
5		Built Resiliency (Robustness and Adaptability)	●	Good: quantify and examine the system abilities to engage to change and to demonstrate that different operational policy.
6		Model Usability	●	Good: run calculation; identify the changed element, read compulsory change risk to other elements.
7		Economic Viability	●	Average: the relationship of operational change to cost was highly evident and the commercial importance of effective change management
8	Technical Representation	The range of Product, Process, Organisational	●	Excellent: relative simplicity of technique makes it applicable to products, process, an organisation of very high complexity
9		Available Information, Data etc.	●	Good: expert interviews; basic information; limited use of available information materials
10		Documentation, Regulation	●	Good: documenting by import/export to XML and Excel files and available regulations
11	Physical Representation	System Design	●	Good: manually modified to adapt to other systems
12		Architectural	●	Average: not able to show multiple connection types between elements
13		System Elements and Dependency	●	Fair: capture inter-layer connectivity of system elements and dependency
14		Decomposing	●	Fair: only one level at a time which could be systems or elements but not more detailed levels
15	Model Development and Application	Resources: Tools, Software	●	Excellent: any tools to capture two matrices (DSMs) can be used, CAM tool and CPM module are freely available
16		Easy to Model Development	●	Excellent; two DSMs with direct likelihood and impact values need to be elicited
17		Consistency	●	Good: couple connectivity development without any sources of discrepancy
18		Results for Solution	●	Poor: only predicts change paths and shows no solutions
19		Adaptability	●	Good: existing models can be used to a certain extent and need to be manually modified to adapt to other systems
20		Numerical Analysis Competency	●	Excellent: numerical connection values and algorithm for change risk calculation
21		Cost-Benefit of Model Development	●	Good: low cost (only expert interviews but no buying or programming of tools needed) and high benefit (change model; product model, communication support etc.)

Rating Scale: ● Poor (1) ● Fair (3) ● Average (5) ● Good (7) ● Excellent (10)

4.4 Chapter Summary

Through representing the literature review and industrial experiences, this chapter has identified 21 requirements for ECM methods. These requirements were classified into the five categories relating to (1) functional (2) operational, (3) technical, (4) physical representation and (5) model development. Following this, these requirements were used as standards to evaluate current ECM methods. The rating of six selected methods suggests that CPM is overall relatively the most suitable method, but for some criteria, the standards are established by other methods. Thus, this chapter has responded to the third research question, which is “RQ3: What are the requirements for delivering an engineering method for RMSs? And to what extent do existing change methods satisfy these requirements?” The next chapter plans to investigate a suitable concept(s) for the application of the system change method that meets the requirements for industrial case studies.

5 Conceptual Design

5.1 Chapter Overview

A combination of the Change Prediction Method (CPM) and the Multi-Domain Matrix (MDM) has been selected as the system change method, as discussed in the previous chapter. This chapter develops a design concept to implement the system change method (SCM). The exploration of the most suitable concepts relates to the fourth research question (*RQ4: What are the suitable concepts for a change approach to support the delivery of a Resilient Manufacturing System (RMS)?*). As Figure 5.1 illustrates, the design process requirements support assessing existing concepts to select the most suitable one.

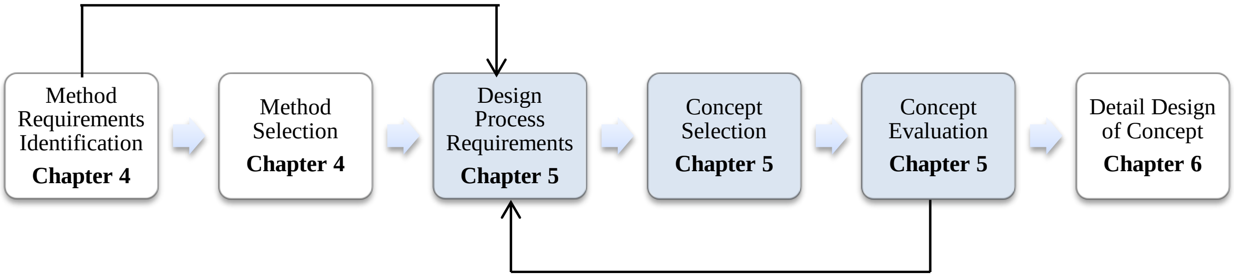


Figure 5.1: The concept development process

This chapter is structured as follows. Section 5.2 presents a systematic concept selection process to decide on the most suitable concept. Then, each step of the selection process is reviewed in Section 5.3 which explores identifying the design criteria to answer '*What are the design process requirements?* Section 5.4 takes us from creating a solution to address '*How can the design process requirements be met?* through to assessing the selected concepts against the design process requirements. Section 5.5 evaluates the selected concept to determine *'How well are the design processes requirements met?*' Section 5.6 considers '*What should we do next?*' to manage the concept for the implementation of the system change method. Lastly, the chapter is summarised in Section 5.7.

5.2 Concept selection process

The proposed method assists designers in predicting undesired change propagation effects, especially those which can influence the system life-cycle properties during the introduction of new changes. For a system change process to be successful, a systematic way of guiding the researcher is needed. Therefore, this section suggests a strategic way to develop a concept to set up a change management process in the manufacturing environment. *A concept selection process* has been adapted from the Inclusive Design Toolkit (the University of Cambridge) which supports the selection of the most suitable concepts for implementing a change method in the process of designing an RMS. The process involves four steps: first step is to *explore* the design process requirements, gaps and the success criteria that the design solution should satisfy. In the second step, *create* a possible solution to meet the identified requirements. The third, the *evaluation* step, is about examining the selected concept to determine how well it meets the requirements and, lastly, *manage* is about what should be done next.

5.3 Explore 'What are the design process requirements?'

The motivation of this section is to develop a broad understanding of the design criteria for implementing a system change method. One major theoretical issue that needs to be addressed in designing a resilient system is the design requirements of dealing with *system complexity* and *system changeability*. From the perspective of a Resillient Manufacturing Systems (RMS), the property of resiliency is related to the ability of a system to identify changes that can affect it to know how to identify the occurrence of changes, how to provide better support to reduce the negative impact of the change (Hollnagel and Woods 2006), and how to the change behaves within the system. Therefore, this section explores *the design criteria of resilience-driven systems* to design complex engineered systems. As discussed in Chapter 2 indicates that a system change method in a multi-layered system can be determined by understanding the mechanism of predicting change propagation. The principle of the system change method (SCM) is illustrated in Figure 5.2. Accordingly, in this thesis, the design process requirements of the system change method set up the understanding behind predicting change propagation through modelling and change analysis, dealing with two aspects: complexity through understanding change impact, and changeability through the prediction of change propagation.

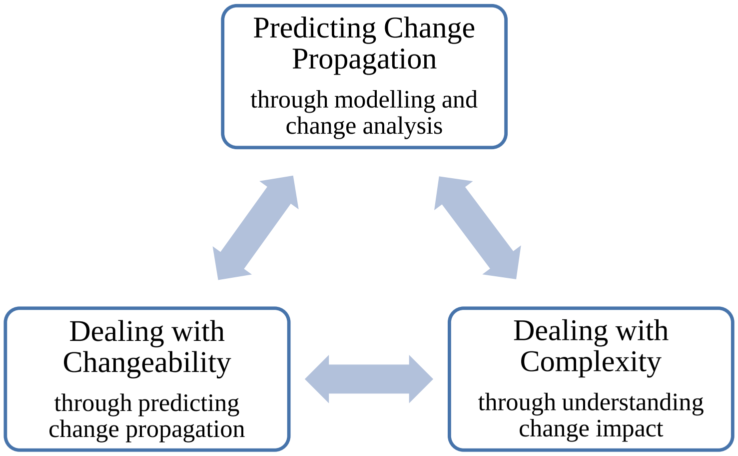


Figure 5.2: The principle of the system change method (SCM)

The following subsections search the design process requirements to deal with complexity, changeability and predicting change propagation. The design process requirements will thus subsequently be assessed using the identified method requirements presented previously in Chapter 4.

5.3.1 Design process requirements for 'Managing Complexity'

As systems continue to grow in size and complexity, they develop increasingly greater risk management challenges (Madni and Jackson 2008). Given this size and complexity, it is also a challenge for the system architecture to embrace the company's business strategies. The need to manage complexity is met by using such a method for the analysis, control, and optimization of complex systems. Managing and controlling complexity in manufacturing businesses involves an understanding of the types and sources of complexity and, accordingly, developing appropriate methodologies. Two types of complexity in the design are described by the authors Simon (1996), Holland (1998), and Eckert *et al*. (2006): (1) *the structural complexity of parts and connections*; and (2) *the dynamic complexity of behaviour*. Below, these two types of complexity are defined separately to better understand and generate the design process requirements.

1. Structural Complexity The complexity of manufacturing systems increases due to constant changes within the system design process. The impact of any engineering change heavily depends on the *system architecture* and its complexity within the design. An *architectural* representation of manufacturing system design (MSD) enables the capture of complex system structure and degree of complexity among the different domains alongside their connectivity (e.g., product, functions, processes, or people and the connectivity between them). A design concept can increase understanding of the architectural system design process at different levels through different domains and, all through the process, can define how change may propagate between them. Thus, representing the manufacturing system design process across different physical and functional perspectives in a diagram is an initial step to visualise complexity (Nedge et al. 2014).

Design Process Requirements-I (DPR-1):
A concept is capable of visualising the design process architecturally to capture the system domains, its elements and connections.

It is desirable to examine the connections, elements and the system life-cycle properties within complex manufacturing systems. As noted in Chapter 2, the structural complexity of a system depends largely on the architectural forms at various levels of system decomposition, and a hierarchal decomposition of the architectural system is a well-known method for understanding structural complexity.

The requirements of hierarchical decomposability of a system help determine the design process of complex systems. The aspect of a concept is to decompose systems into a more manageable level of complexity: for instance, manufacturing systems can be decomposed into three levels: product complexity, process complexity and organisational complexity. The design of a concept for a system involves the relevant elements and their connections within these three levels of manufacturing complexity. Each element can be a sub-system itself and contains hierarchically arranged elements (and connectivity where necessary), which are either tangible or intangible (Koch *et al*. 2016).

Design Process Requirements-II (DPR-1I):
A concept enables the structural decomposition of a system architecture hierarchically into a more manageable level

Clarkson et al. (2004) classify the types of connectives between pairs of elements as being either direct or indirect dependencies. Complexity usually arises from the high quantity of indirect elements and dependencies. In addition, complex systems are frequently characterised by a lack of knowledge concerning the systems' dependencies. Manufacturers need to understand how design issues (or changes) interact with various elements and the interrelation among the elements of a manufacturing system to make a strategic decision. A concept needs to address the identification and analysis of the type of dependencies (e.g. direct) that can exist between two or more system elements. In addition, the concept enables the integration of the core system layers (domains) (e.g. product, process, and organization) into one system to examine the system design process. The high level of connectivity between parts, product, system and subsystems may create complexity because the *time, cost, and resources* that need to be allocated to effect the change are dependent on its potential impact (Eckert *et al*. 2004; Wickel and Lindemann 2015).

Design Process Requirement-III (DPR-III):
A concept capable of capturing *dependencies* between system elements and system layers (domains).

1. **Behavioural Complexity:** The nature of change behaviour increases the complexity of system design by creating additional connectivity among system elements (Eckert *et al*. 2005). It is difficult to predict how a complex system will evolve. The key desirable emerging behaviours of complex manufacturing systems are robustness or adaptability (Chapter 2). Manufacturing systems are designed to satisfy customer demands in a robust or adaptable manner. The demand for robust or adaptable systems is directly related to the control of its *complex interdependency network*. A requirement arises as to how the different element connections can define constraints on behaviour. A novel approach needs to capture the resilient behaviours of a complex manufacturing system by assessing the connections of system elements and its layers.

Design Process Requirement-IV (DPR-IV):
A concept is capable of defining characteristic system behaviours that respond to changes.

5.3.2 Design process requirements for 'Managing Changeability'

Manufacturing systems operate in a constantly changing environment and changeability is desirable in many engineering systems. Changes occur over time in dynamic changing environments (Simon 1996; Holland 1998; Eckert *et al.* 2006*)*. So, in a dynamically changing environment, designing a changeable system supports meeting the company's business strategies and the stakeholders' needs. To this end, the design of a system requires a *continuous evolution of system architecture* (Fricke and Schulz 2005). The evaluation of system architecture through connectivity between the system layers and elements involves analysis and identification of the dependencies (direct or indirect) that can exist between two or more system layers and elements. *A systematic dependency analysis* can increase the understanding of the change patterns through the network of elements allowing insight into connections. The dependencies between the system elements and layers are identified through the knowledge of designers. *A dependency analysis* *method or an effective change prediction analysis method* assists in characterising the relationship between system elements and system layers and translating them into one system.

Design Process Requirement -V (DPR-V):
A concept enables the identification of direct and indirect connected elements with an effective change prediction analysis.

Designing systems for successful changeability can be achieved by understanding the complex system behaviours (Ross and Rhodes 2008). As stated in Chapter 2, robustness or adaptability as a key system behaviour for changeability in designing an RMS. A connectivity modelling concept is capable of quantifying and examining the changeability behaviours to develop a tangible value-added decision. A network-based analysis can be used to quantify and examine system architecture by Understanding the characteristics of changes (Reddi and Moon 2009).

Design Process Requirement-VI (DPR-VI):
A concept enables quantification and examination of the connectivity within the system architecture to define the elements that are to be affected by changes

One significant cause of the problem in managing change originates from a lack of understanding of the possible risk estimation through the connectivity between products, processes and organisation in a manufacturing business. Risk estimation and assessing changeability behaviour requires systematic, analytical support to understand changeability across system architecture. An integrative change approach incorporates the risk assessment of change impacts with a wide range of information while making decisions.

Design Process Requirement-VII (DPR-VII):
A concept enables risk estimation within multi-layered system connectivity.

Measuring the predictability of change propagation paths between the elements is desired to design a robust or adaptable system. Given this, how do changes propagate, and unwanted behaviours emerge into the system architecture? These behaviours can be taken into consideration during change propagation path investigations. A technique needs to be able to identify the most affected elements through change propagation path investigation for further decision making.

Design Process Requirement-VIII (DPR-VIII):

A concept enables propagation path investigation.

The eight design process requirements have thus been developed through an analysis of managing complexity and changeability in system design. A concept can link to the modelling requirements that support the development of change prediction methods (Koh et al. 2012). Table 5.1 presents the link between the design process requirements and the system change method requirements.

Table 5.1: Design process requirements addressee to the method requirements

	No	Design Process Requirements (DPR)	Link to the Method Requirements (MR)
Managing Complexity	**DPR-I**	A concept is capable to visualise the design process architecturally to capture the system domains, its elements and connections.	System Design, System Modelling Competency Architectural Representation, System Elements and Dependency,
	DPR-II	A concept enables to structurally decompose system architecture hierarchically into the more manageable level.	System Design System Modelling Competency, Decomposing Available Data/ Information Architectural Representation, The range of product, process and organisation System Elements and Dependency,
	DPR-III	A concept is capable to capture dependencies between system elements and system layers (domains).	System Design, System Modelling Competency System Elements and Dependency, Architectural Representation, The range of product, process and organisation Available Data/ Information
	DPR-IV	A concept is capable to define characteristic system behaviours that responses to changes.	System Design Model building and application Ease to model building, Model Usability Built Resiliency (Robustness and Adaptability) System Performance and Execution
Managi	**DPR-V**	A concept enables to identify direct and indirect connected elements with an effective change prediction analysis.	Architectural Representation, Available Data/ Information Change Modelling Competency Change Prediction Analysis Competency Resources: Tools, Software,

			Results for solution Numerical Analysis Competency
	DPR-VI	A concept enables to quantify and examine the connectivity on system architecture to define the elements that affected by changes.	Available Data/ Information Change Modelling Competency Change Prediction Analysis Competency Numerical Analysis Competency Resources: Tools, Software, Model Usability
	DPR-VII	A concept enables risk estimation within multi-layered system connectivity.	Change Modelling Competency Change Prediction Analysis Competency Numerical Analysis Competency Resources: Tools, Software, Model Usability Numerical Analysis Competency
	DPR-VIII	A concept enables propagation path investigation.	Change Modelling Competency Built Resiliency (Robustness and Adaptability) Change Prediction Analysis Competency Resources: Tools, Software, Numerical Analysis Competency Model Usability Results for Solution System performance and Execution Benefit-Cost of Model Development

5.4 Create Concept

This section answers the question how can the design process requirements be met? (Create). The design process requirements (DPR) identified in Section 5.3 will be assessed against the potential concepts. The concept is capable of supporting the system change method to assess change risk in multi-levelled system descriptions. In the previous chapter, CPM and MDM met the method requirements in the method selection process and their combination was chosen as a system change method (SCM) for this thesis. On the other hand, *CPM* (Clarkson *et al*. 2004) and *DSM/MDM* (Steward 1981; Maurer and Lindemann 2007) approaches are also used as a prediction methodology in the context of Engineering Change Management. The following briefly reviews these two in the context of design process requirements.

5.4.1 Concepts of change method

CPM approach

CPM developed at the Engineering Design Centre EDC in Cambridge (UK) accompanies the engineering change process in three steps. The approach is structured in three stages: *an initial analysis: a case by case analysis;* and *the actual redesign*. The initial analysis includes the construction of the product model, the completion of the dependency matrices, and the computation of the predictive likelihood and impacts matrices by the CPM algorithm to develop a product risk matrix. In the second step, an analysis of the specific case contributes to identifying the initiating changes and predicting those changes with direct dependencies. The result of the case analysis is the creation of a case risk plot which presents the predicted likelihood and impact of change effects to compare the risk of change to different elements. The last stage represents the redesign of a prototype product based on the predicted change

MDM Approach

The Multi-domain Matrix (MDM) is an extension of DSM modelling in which two or more DSM models in different domains are represented concurrently. DSM-based models have now been extended to two or more domains, which have been termed MDM models by Maurer (2007). The MDM and DSM are often used to examine the structure of a system design process. Though, the DSM cannot handle among the complex system elements in various expectations. MDM provides a system's structure across multiple domains, summarising each s analysis into one DSM that represents multiple domains at a time (Eichinger, Markus & Maurer, Maik & Lindemann, U. 2006, Maurer and Lindemann 2007).

MDM is characterised by the ability to decompose systems and capture functions and parameters; hierarchical decomposition of the approach can only be built by an expert and could be very complicated. The redesign strategies could be useful for decision making and efficient change management. Change propagates only between parameters and functions but not within each of these domains (Clarkson *et.al.* 2005). The solution finding capability of the concept is very good when designing strategies and it supports identifies parameters that need to be changed to meet new requests.
The illustration of DSM / MDM with detailed explanation can be found in the literature - section 2.5.4 Connectivity Model.

5.4.2 Review the concepts with the design process requirements

A concept with well-defined stages guides the designer in implementing methods. The design process requirements were defined according to the specific needs of the suggested method, which describe conditions for method inputs, applications and outputs. The two conceptual ideas (CPM, DSM/MDM) were rated against the eight identified design process requirements as presented in Table 5.2.

The weighted sum scores show the relative gaps between the methods (Table 5.2). The weighted sum scores mean items with lower loadings on the factor have the same weight as the items with higher loadings. So, all items have the same weight when the factor scores are computed. However, items with higher loadings might have a larger effect on the total factor score and vice versa. For this rating, the related publications were reviewed and a colour shade scale is used from poor (1) to excellent (10) to rate these concepts. For each requirement, weighted sum assessment result (Good + Excellent) are stated at last row of Table 5.2. It should be noted that this rating was led only by one person and the assessment is subjective. Nevertheless, for the comparison of two concepts for this thesis, it is adequate. The results of the rating including brief justifications for each concept and were summarised: the weighted sum assessment scores for a CPM approach is (41) and DSM/MDM is (34). The rating results in Table 5.2 show that:

1. DSM/MDM approach is better in managing complexity, on the other hand CPM approach is better in managing complexity (DPR-V, DPR VI; DPR VII, DPR VIII). The both approaches are capable to define characteristic system behaviours that responses to changes (DPRIV)
2. DSM/ MDM, Multi-domain or Multi-layered matrix as a network-based approach has strong capability in design process requirements of managing complexity than the CPM approach concerning visualising the design process and structurally decomposing system architecture hierarchically (DPR I). The techniques also support propagation of properties across levels of hierarchically structured description during the connectivity modelling required (DPR II). DSM/MDM approach is a better capability to capture dependencies between system elements and system domains (DPR III).
3. The CPM approach is more capable of estimating and reducing the risk of changes with connectivity modelling ability and estimation of risk across all hierarchy levels of a system (DPR-V, DPR VI; DPR VII, DPR VIII)

Table 5.2.Rating of the concepts to address the design process requirements

	No	**Design Process Requirements (DPR)**	**Potential concepts for the implementation of the System Change Method**	
			CPM Approach	DSM/ MDM Approach
Managing Complexity	**DPR-I**	A concept is capable to visualise the design process architecturally to capture the system domains, its elements and connections.	●	●
	DPR-II	A concept enables to structurally decompose system architecture hierarchically into a more manageable level.	●	●
	DPR-III	A concept is capable to capture dependencies (direct dependencies) between system elements and system layers (domains).	●	●
	DPR-IV	A concept is capable to define characteristic system behaviours that responses to changes.	●	●

Managing Changeability	**DPR-V**	A concept enables to identify direct and indirect connected elements with an effective change prediction analysis.	●	◔
	DPR-VI	A concept enables to quantify and examine the connectivity on system architecture to define the elements that affected by changes.	◕	◔
	DPR-VII	A concept enables risk estimation within multi-layered system connectivity.	●	○
	DPR-VIII	A concept enables propagation path investigation.	◕	○
The weighted sum assessment result			**41**	**34**

Rating Scale: ○ Poor (1) ◔ Fair (3) ◑ Average (5) ◕ Good (7) ● Excellent (10)

5.5 Evaluate 'How well is the design process requirements met?'

The section evaluates the selected concepts to determine how well the design process requirements are met. The results are presented in Table 5.3.

Table 5.3.The evaluation of design requirements with the selected concepts

	No	**Design Process Requirements (DPR)**	**The selected concepts**	**How the concept ideas met the design process requirements**
Managing Complexity	**DPR-I**	A concept is capable to visualise the design process architecturally to capture the system domains, its elements and connections.	MLN	A Multiple-Layered Network matrix decomposes a system into its key parts (which may include elements, subsystems) and defines how change may propagate between them.
	DPR-II	A concept enables to structurally decompose system architecture hierarchically into a more manageable level.	MLN	Multiple-Layered Network matrix approach combines relevant groundwork for managing complex system structures to allow for a comprehensive, layer analysis, control and optimization of the structural network. The resulting multi-level system elements and the hierarchical system decomposition can be used to simulate manufacturing system property changes and their propagation throughout the system.
	DPR-III	A concept is capable to capture dependencies between system elements and system layers.	MLN CPM	The flow of information captured in the Multi-layered matrix can be used to support the prediction of change propagation effects.
	DPR-IV	A concept is capable to define characteristic system	MLN CPM	Robustness and adaptability are defined by connectivity within manufacturing systems. The demand for robust systems is directly related to the control of its complex interdependency

		behaviours that responses to changes.		network. MLN and CPM enable to define the ability of a manufacturing system to adapt to demand and to demonstrate that different operational policy.
Managing Changeability	**DPR-V**	A concept enables to identify direct and indirect connected elements with an effective change prediction analysis.	CPM	The CPM predicts the likelihood of change propagation between elements by modelling the direct and indirect dependencies between elements in a single layer. MLN expands to view in multiple layers.
	DPR-VI	A concept enables to quantify and examine the connectivity on system architecture to define the elements that affected by changes.	CPM	The data stored in the connectivity model used to predict change propagation consists of quantitative values describing the direct change likelihood and impact of changes propagating directly from one component to another. CPM provides an algorithm that allows the calculation of combined likelihood and combined impact of change propagation based on direct and indirect links. The calculation of combined likelihood and impact is the combination of change propagation paths.
	DPR-VII	A concept enables risk estimation within multi-layered system connectivity.	CPM	The CPM is a numerical method which uses an MDM model of dependencies between elements to visualise the overall risk of change being propagated to other elements when one element is changed. CPM produces the Combined Risk Plot which can identify high-risk element connections at all levels of a system.
	DPR-VIII	A concept enables propagation path investigation.	CPM	CPM tool generates a prioritised list of all affected elements. 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 MLN.

5.6 Manage 'What should we do next?'

The design process requirements have been generated and assessed with the incorporation of the multi-layered network (MLN) and change prediction (CPM) approaches in the sections above. The eight design process requirements provide an outline of the overall concept suggested for the system change method (SCM). Hereafter, the selection rationale for each conceptual stage is discussed according to the correspondingly addressed design process requirements.

1. **Define** stage reflects the design process requirement I (DPR-I) and II (DPR-II). *Decompose the system into its elements and layers* to create a Multi-layered Network (MLN) matrix from these elements and layers. A system can be systematically defined and analysed when broken down hierarchically into its layers and elements, allowing the system to be viewed as a collection of parts whose designs can affect one another. A designer's experience with the original design can help to elicit how a system may be broken down into an appropriate number of sub-systems. Identifying the right level of detail in developing a model is critical; a model with fewer than 50 components is recommended (Clarkson *et al.* 2004);
2. **Identify stage** represents the design process requirements III (DPR-III) and IV (DPR-IV). *Capture dependencies between layers and elements*. The connections are created within the MLN matrix to

mirror these dependencies; the demand for robust or adaptable systems is directly related to the control of its complex interdependency network. MLN and CPM can determine the ability of a manufacturing system to adapt to demand robustly.

3. **Quantify stage** incorporates the design process requirements V (DPR-V) and VI (DPR-VI). *Quantify the Multi-layered connectivity*. The predictive matrix is computed by populating each connection with an estimate for the likelihood and impact of changes between the connected elements. The resulting matrix represents the direct and indirect risk of change propagating between linked elements within the multi-layered system;
4. **Analyse stage** covers design process requirement VII (DPR-VII) *Compute the combined change propagation* by applying the CPM algorithm for a specific number of steps. In this stage, it is important to understand what elements of the system are subject to direct changes and how such changes can propagate to impact elements that have no direct dependencies. The CPM toolbox of CAM is used to analyse how the level of compound risk is correlated with both the level of element interconnectivity and to the likelihood and impact assigned to direct connections between elements;
5. **Use stage** contains the design process requirements VIII (DPR-VIII). *Use the change risk model for decision making* by identifying which elements could have the biggest impact if changed elements are most likely to be impacted by changes to any other element. The model supports the decision-making process by reviewing the effect change effect on each layer in terms of the total combined risk of elements on different likelihood outputs. The CAM modeller is used to identify the riskiest elements and those elements that are most responsive to the problem that arises as a result.

The concept integrates the defined design process requirements into a coherent approach. The fundamental idea of the concept (as illustrated in Figure 5.3) is that the occurrence of most system changes can be modelled by adapting the effort invested in design activities. The concept proposed in this research defines a procedure for the creation of Multi-layer Network (MLN) and CPM matrices based on the five stages below:

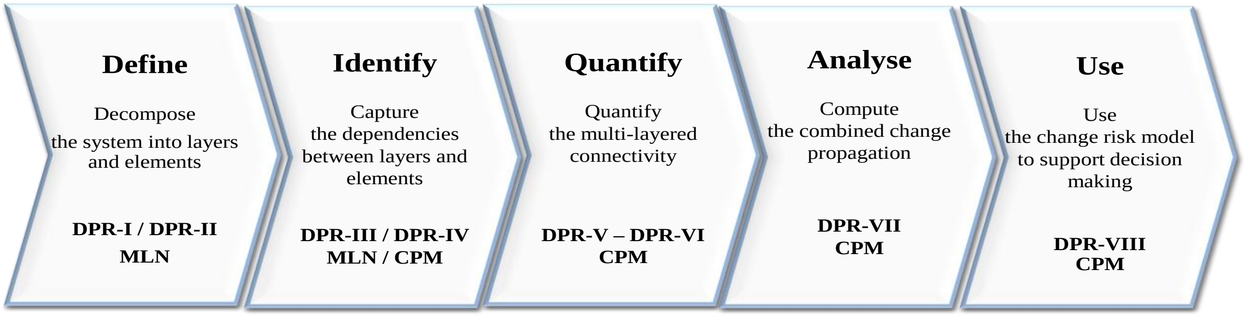


Figure 5.3: The concept for the system change method (SCM)

5.7 Chapter Summary

This chapter has developed the concept for the system change method (SCM). Drawing on the comparative assessment in Chapter 4, the MLN approach was selected as a starting point for the development of the concept after which the CPM was taken. This concept prescribes the integration of the CPM approach with a multi-layered network approach. Thus, this chapter has answered the fourth research question *RQ4: What are the suitable concepts for a change method to support the delivery of Resilient Manufacturing Systems (RMS)?* The following chapter progresses the suggested concept into a change method by presenting the method's detail design for delivering a resilient system.

6 Detail Design

6.1 Chapter Overview

This chapter answers the fifth research question (*RQ5: What are the detailed elements required to deliver the chosen change method concept for Resilient Manufacturing Systems (RMS)?)* by presenting the detail design of the selected concept. Figure 6.1 illustrates the phases of the detail design for the concept development process. The conceptual design proposes *a multi-layered network of change propagation approach* through the combination of two methods: The Multi-layer Network (MLN) and the Change Prediction Method (CPM). This chapter explains how this multi-layered network change propagation approach overcomes the challenges of complexity and changeability in a system.

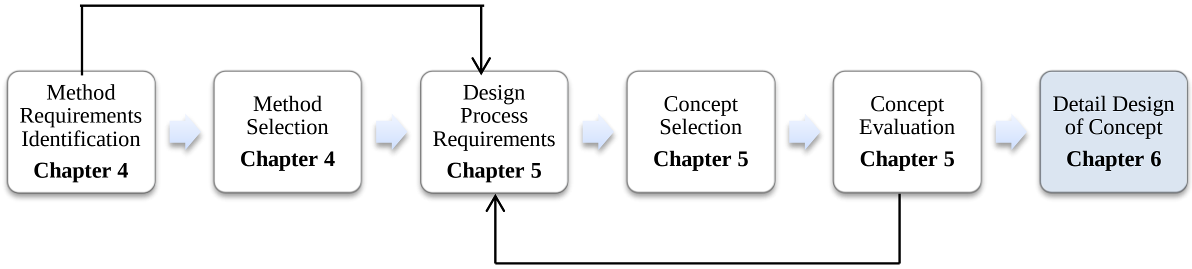


Figure 6.1: The detailed design of the selected concept

The chapter is structured as follows. Section 6.2 discusses how MLN and CPM are combined. Section 6.3 and Section 6.4 describes the detail of design for complexity and changeability Lastly, Section 6.5 summarises this chapter.

6.2 Integration of Multilayer Network Method (MLN) into the Change Prediction Method (CPM)

As explored in Chapter 4, to reduce complexity and to make a system more changeable, it is essential to understand the system complexity and system changeability. Therefore, in Chapter 5, a concept was proposed to examine the potential changes and their effects. The proposed approach will aid to visualise system connectivity and support connectivity analysis of a system for decision-making, for instance, looking at how employees connect to each other and how information flows through networks, or how materials flow within a manufacturing process. Additionally, visualising system connectivity can support identifying where dependencies can be reduced, which can reduce system complexity. A structured representation of changes within a system architecture can be created by the proposed concept, as well as, the connectivity of system networks can be quantified and change propagation can be analysed with a risk model. However, establishing and quantifying system connectivity among its elements, analysing change propagation requires technical knowledge and expertise through established processes for subsystem design and integration.

The multi-layered network change propagation strategy is the foundation of the proposed concept which is defined in two contexts: *designing for complexity* and *designing for changeability*. The concept is the integration of Multi-layered Network (MLN) with Change Prediction Method (CPM) which describes how to predict and analyse change propagation based on the dependencies and connectivity that can exist within the system elements and layers. In this way, the integration enables an examination of the risks of changes impacting a system. The MLN approach represents the structure and connectivity of systems, and the CPM approach to quantify and simulate the connectivity of networks.

Figure 6.2 outlines the stages of the system change method concept to analyse system complexity and system changeability. The first two stages support understanding the system complexity by collecting the change data associated with individual elements and layers. The process starts with the ***Define*** stage which is the hierarchical system decomposition enabling visualisation of the system complexity. MLN representations can increase understanding of the system by providing a holistic view of connectivity and change propagation within the layers and elements. The definition of the dependency between the elements and layers provides information to predict the combined (direct and indirect) change propagation between the elements captured in the ***Identify*** stage. Experts produce the values for the likelihood and impact propagation parameters in the ***Quantify*** stage: the values for the risk parameter is then computed by using the CPM based on the likelihood/impact values of each connection captured from the MLN. In the ***Analyse*** stage, change indices for each system element are computed and plotted on a chart to classify the elements according to their change characteristics by using the information established in the Quantify stage. Once this is done, an assessment of system changeability can be made along with design suggestions for each element in the ***Use*** stage.

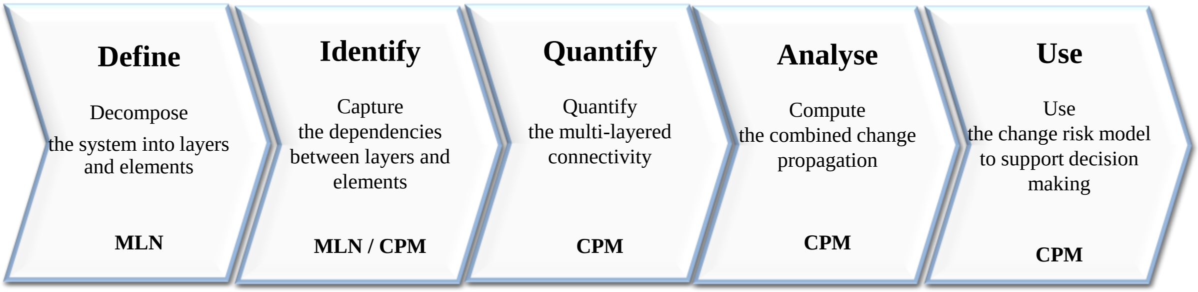


Figure 6.2: Stages of the system change method concept

6.3 Designing for Complexity

This section aims to visualise and understand the system complexity to describe the detail design stages.

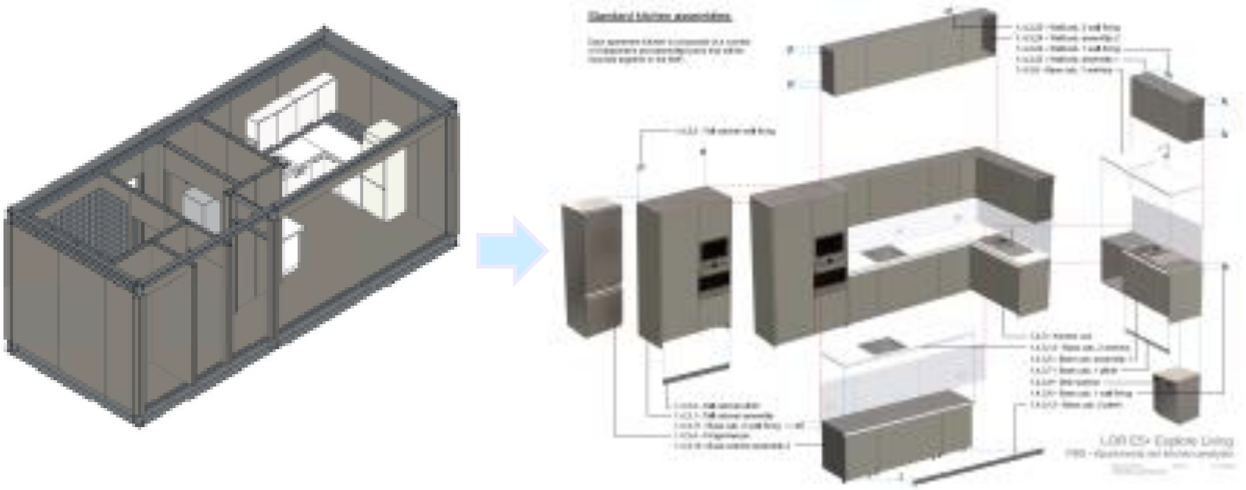
6.3.1 Decompose the system into layers and elements (Define):

The first step of the concept is to decompose the complex system into more manageable parts. If a complex system is NOT decomposed with all of the associated details in one diagram, it would quickly become too large and unmanageable (Oliver et al. 1997). Hence, dividing a system into a hierarchical order provides a method of reducing complexity through an understanding of individual parts of the system and their connectivity (Merdan *et al.* 2011). A hierarchically ordered system addresses *a compositional relationship*, whereby one system is a sub-element of another system (e.g. in the way that a Kitchen can be a part of a Kitchen Assembly System). Manufacturing systems can be decomposed based on different characteristics of the system in response to the requirements, and there is no right or wrong system breakdown (Wiendahl *et al.* 2007).

The use of hierarchies is a means of structuring a system. The structure viewpoint of a complex system can be determined by the architectural system decomposition. A system is broken down into sub-systems that allow the system to be viewed as a collection of parts (Simon 1996). The hierarchical structure of a system depends on how elements are grouped into systems; a multi-layer system representation can have an upright hierarchical structure. Dividing a manufacturing system design (MSD) into hierarchically ordered layers that structure the functional decomposition into subsystems, which can then be easily further decomposed but also integrated and managed in bigger systems as well (Marden et al. 2009).The most common architectural pattern, layered architecture, focuses on the concept of layering for developing systems. An operating system is split into various layers, where each layer has a specific well-defined task to perform. The layered system structure enables functional decomposition into subsystems. Structuring a system into sub-layers means these layers can be logically represented (e.g. product, process and organisation). The limit of layers within a system depends on their role and the design perspective (Merdan *et al.* 2011). An illustration that represents three hierarchical levels in a manufacturing system can be found in Figure 2.10.

The decomposition process can be driven by the aim of building the hierarchical decomposition which must satisfy the system needs. A multi-layered system decomposition and change risk assessments can be interpreted: (1) A practical level of detail must be selected for product or system representation to satisfy mathematical requirements; (2) Each level of the hierarchy should complete the representation of the same individual but at a different degree of complexity; (3) Each element should be assigned to a layer.

Applying the decomposition process in kitchen design is challenging, especially in the hierarchical representation of kitchen design. Figure 6.3 shows an assembled kitchen decomposed to its parts. The assembled kitchen is displayed in a module as shown in Figure 6.3. The description of the kitchen consists mainly of single elements such as *Tall Cabinet* and *Worktop.* This level of decomposition comprising 7 elements is shown in Figure 6.2 (b). Smaller elements such as fixing elements were abstracted at the level of sub-assemblies. The middle level consists mainly of sub-systems and sub-assemblies such as the *Base Cabinet Assembly System.* The highest-level descriptions consist mainly of systems such as the *Electrical or Water Supply System.*



(a) Assembled Kitchen in a Module

(b) Seven Elements of Kitchen

Figure 6.3: Decomposition of Kitchen to its parts

6.3.2 Capturing Dependencies between Layers and Elements (Identify)

The ‘Identify’ stage consists of two processes: (1) how the method captures the interactions within and across the three or more layers; (2) how the method captures change propagation effects. An MLN *visualises the connections* between different layers to identify any change requirements which can be directly mapped to the related elements and tasks. Examining the connections reveals how changes propagate between the elements: a change to one element might impact other elements if they are connected. Connectivity between elements in a layer can be direct or indirect; in addition, connectivity can be one-sided (such as dependency) or two-sided (such as interaction) as shown in Figure 6.6. The modelling of direct and indirect dependencies may be through *intra-layer connectivity*: the connection between elements within the same layer as illustrated in Figure 6.6 (a); or *Inter-layer connectivity*: the connections between the elements of two distinct layers as shown in Figure 6.6 (b).

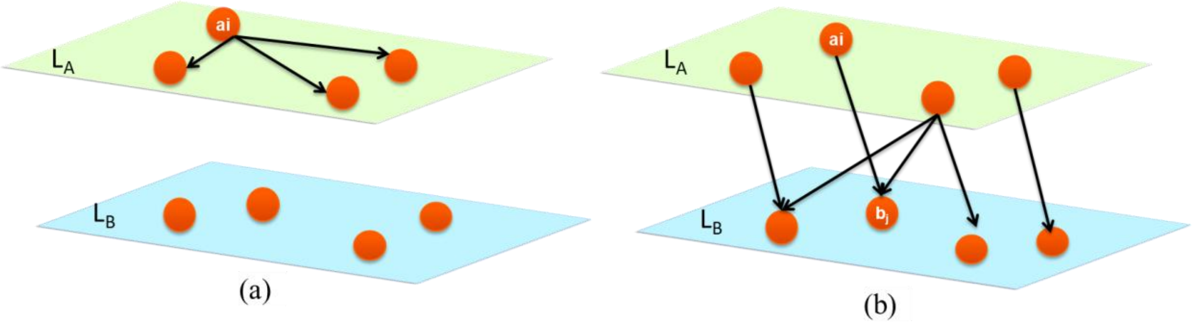


Figure 6.4: (a) Intra-layer connectivity (b) inter-layer connectivity (adapted from Ariyo *et al.* 2007)

The connectivity between layers and elements can be examined with four different connectivity approaches (Figure 6.7) when a change occurs in the design process.

- *Intra-layer direct connectivity*: Examining connectivity is derived from direct intra-layer between the elements of two distinct layers. The single-layer tools allow designers to analyse the individual layer of the MLN. Only direct relations are allowed in a Design Structure Matrix (DSM) to receive information from experts.

- *Intra-layer indirect connectivity:* Indirect relations are defined as connections that are caused by a dependency series that includes one or more elements. Team members that take part in a matrix filling process often are not able to differentiate between direct and indirect relations, as the underlying structure is naturally known (mostly by experience). The designer may only know that two elements are “somehow” related and therefore place the mark in the wrong matrix cell to avoid deviating over the intermitting element. Dependencies between two elements are indirectly linked (without direction) because they work on or access the same layer.

- *Inter-layer direct connectivity:* The connectivity can happen between multiple layers; the concept of direct inter-layer connectivity means the direct connectivity which represents the critical dependencies between the layers. Connectivity can be directed one way (dependency) or be two-sided (interaction). The multi-layer network (MLN) model captures the dependency and interactions within and across the three or more layers of change propagation. MLN analysis of a direct relationship between two elements presents if many other elements are connecting these elements. The algorithm makes it possible to focus on significant elements within the matrix that are connected through multiple other matrix elements. A dependency relation between layers describes how the existence of an element is dependent on another element. This could mean that one element can influence the existence of another.

- *Inter-layer indirect connectivity:* In multiple layers, indirect relations may be caused by relations across different layers of the matrix. These indirect relations are even harder to identify because the designer has to compare different contexts and meanings of elements. Nevertheless, multiple layers provide new possibilities for the analysis of cross-layer relations. Indirect relations between layers are significant in practice for the difference between direct and indirect relations within a layer.

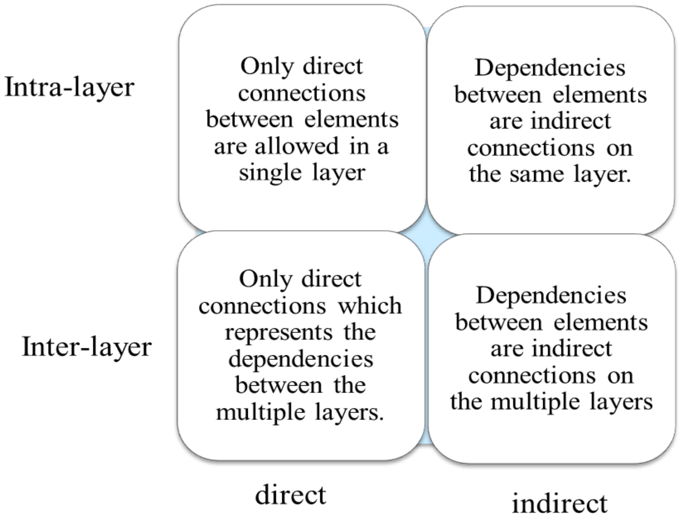


Figure 6.5: Classification of connectivity approaches

Investigating the connectivity of changes through the network of dependency needs a systematic multiple-level dependency analysis. This allows greater insight into connections, which in turn increase the understanding of the system. MLN represents the dependency connections between three and more sets of elements. The aim is to identify the direct dependencies between the elements and create connections within the CPM matrix to reflect these dependencies. The different relations represent the architecture of a system provide for a clarification of many different structures depending on the viewpoint taken (Layer A to Layer B connectivity; Layer A to Layer C connectivity; Layer B to Layer C connectivity) as shown in Table 6.1.

Table 6.1: Intra/Inter-connectivity of Multilayer Network Model (MLN) (adapted from Pasqual 2010)

MLN Matrix	**Layer A**	**Layer B**	**Layer C**
Layer A	Technical interfaces, propagation relationship or hierarchical structure	Layer A affected by Layer B	Layer A affected by Layer C
Layer B	Layer B affected by Layer A	Technical interfaces, propagation relationship or hierarchical structure	Layer B affected by Layer C
Layer C	Layer C affected by Layer A	Layer B affected by Layer C	Technical interfaces, propagation relationship or hierarchical structure

6.4 Designing for Changeability

Resilient system design has been shown to have the characteristic of "changeability", a core concept discussed in Chapter4 Section 2.5.1, which is described by the change requirements and change effects. The change requirements are internal and take into account system resilience. The resilience of the system is embedded in its architectural design; each element of the system employs robust design principles and together the overall system maintains resiliency. Designing resilient, changeable systems makes it possible to maintain value delivery over the system lifecycle, throughout changing contexts. The principle of the key to achieving resilience is the elements of integration into the system life cycle. The aim is to support companies to understand the changeability position for individual elements of their system so that they can be value-added accordingly.

A system is affected by changes within its operational context, and system architectures need to incorporate the ability to adapt to changes within its environment. System architectures which can be changed are more resilient in changing environments (Fricke and Schultz 2005) if the system architecture can be restructured to rearrange the layers and the connectivity of the system (Pimmler and Eppinger 1994; Browning 2001; Frickle and Schulz 2005). The structure of an MLN involves the design of a system, its variety and its changeability across the system life cycle.

6.4.1 Quantify the Multi-layered Network to compute Predictive Matrix (Quantify)

In the ***Quantify*** stage, the CPM described by Clarkson, Simons, and Eckert (2004) is used as a basis to predict the combined (direct and indirect) change propagation between system elements. The prediction is further refined in ***Analyse*** when the influence of planned changes is examined and taken into account. A technique needs to support prediction and quantification of the likelihood, impact and risk values of each connection that is captured from the hierarchy levels of MLN. So, this section explores techniques for finding the essential likelihood and impact estimates vital for risk estimation in a multi-levelled model.

Multi-Layer *Likelihood* Estimation

As a way of estimating likelihoods and risks within a hierarchical model, a context for defining the degree of interaction between systems was developed. This procedure considers that there is a direct dependency between two systems if such a connection occurs between elements. System-level direct dependencies are considered as a combined of three basics: (1) element-level inter-system direct dependencies, (2) element-level intra-system indirect dependencies, and (3) element-level inter-system indirect dependencies.

The first step of the algorithm is to compute the combined likelihoods of changes propagating between two elements across a system boundary (Ariyo *et al.* 2007b). As Figure 6.6 shows, a change initiating in elements $\boldsymbol{a_i}$ in layer $\mathbf{L_A}$ may propagate via a ‘boundary’ element $\boldsymbol{as_k}$**,** which is connected to element $\boldsymbol{b_j}$ in layer $\mathbf{L_B}$**.** The combined intra-layer element-to-boundary-element is calculated with the CPM algorithm described by Clarkson *et al.* (2004). Multiplying this value with the direct likelihood ***(L)*** of changes propagating from boundary elements to elements in layer L_B, yields the likelihood of elements $\boldsymbol{a_i}$ in layer $\mathbf{L_A}$ affecting elements $\boldsymbol{b_j}$ in layer $\mathbf{L_B}$ through a specific boundary element $\boldsymbol{a_k}$ in layer $\mathbf{L_A}$ as in the equation of Figure 6.6:

$$L\ (a_i \rightarrow a_k \rightarrow b_j) = L_c\ (a_i \rightarrow a_k)\ .\ L_d\ (a_k \rightarrow b_j) \qquad \text{Equation 6.1}$$

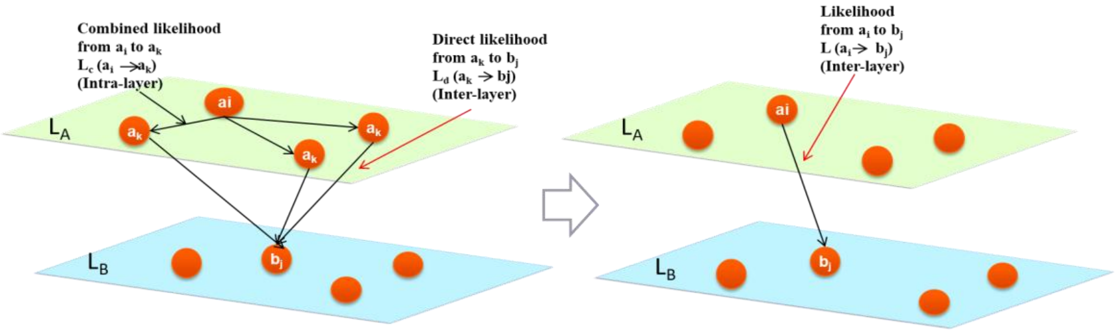


Figure 6.6: Estimating the system level likelihood combination setting (adapted from Ariyo *et al.* 2007b)

Based on this, the likelihood ***(L)*** of a change in a_i affecting b_j via all possible boundary elements a_k can be determined by equation 6.2:

$$L(a_i \rightarrow b_j) = 1 - \prod_{k=1}^{n}\left[1 - L(a_i \rightarrow a_k \rightarrow b_j)\right] \qquad \text{Equation 6.2}$$

In the next section, using a similar approach, equations for estimating elements to layer, layer to elements and layer to layer are described.

I. Element to Layer direct likelihood assessment

This inter-layer elemen to element likelihood $L\ (a_i - b_j)$ is then used to calculate element to layer, layer to element and layer to layer likelihoods (Ariyo *et al.* 2007b). Figure 6.7 illustrates how these likelihoods are estimated. The likelihood of a change propagating from an element a_i to layer L_B is calculated by multiplication.

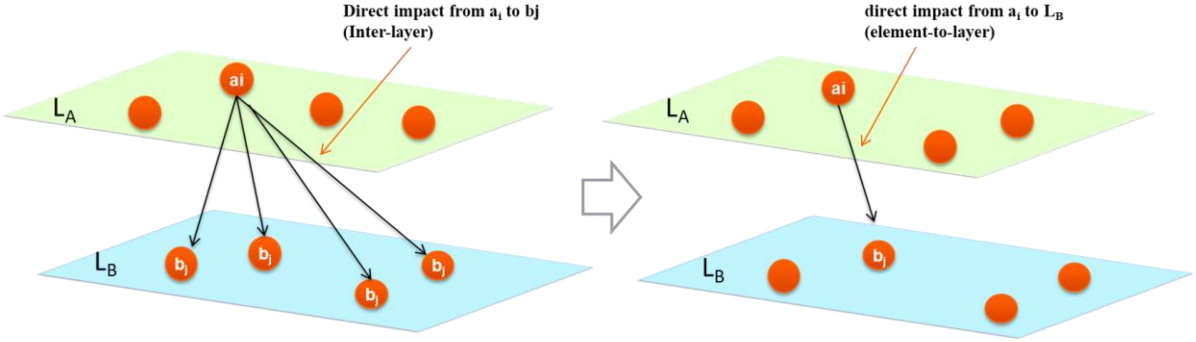


Figure 6.7: Estimating the element-to-layer likelihoods (adapted from Ariyo *et al.* 2007b)

The likelihood of a change propagating from an element ***a_i*** to layer ***L_B*** is calculated by computing a multiplication over ***$L\ (a_i - b_j)$*** obtained from Equation 6.3 for any element in ***L_B***:

$$L(a_i \rightarrow L_B) = 1 - \prod_{j=1}^{n} [1 - L(a_i \rightarrow b_j)]$$

Equation 6.3

II. Layer to Element direct likelihood assessment

Estimating layer-to-elements likelihoods is conceptually more difficult because a change to a layer does not affect all of its elements (Ariyo et al. 2007b) (Figure 6.8). It is thus important to also consider the probability of a change initiating within a system.

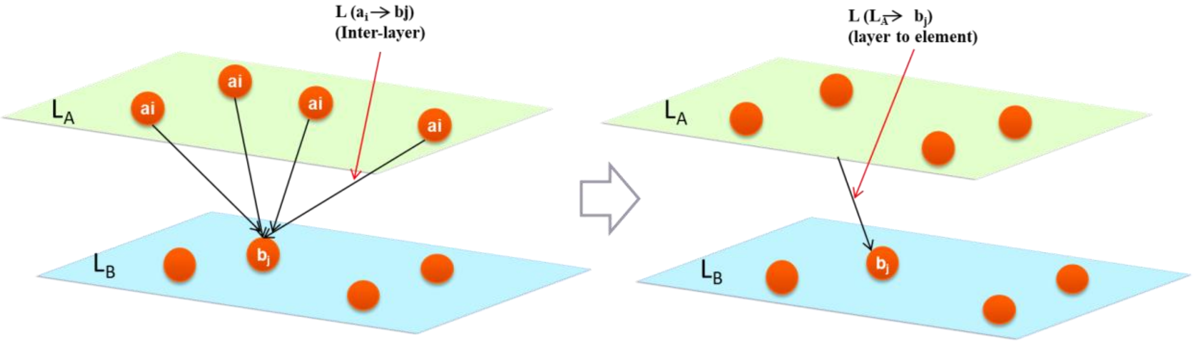


Figure 6.8: Estimating the layer to element likelihoods (adapted from Ariyo *et al.* 2007b)

Ariyo *et al.* (2007b) note that logical problems would result from combining likelihoods as in the two previous equations and suggest using numerical averages to prevent the need for Equation 6.4 below:

$$L(L_A \rightarrow b_j) = \frac{1}{n} \sum_{i=1}^{n} L(a_i \rightarrow b_j)$$

Equation 6.4

III. Layer to Layer direct likelihood estimation

Likewise, the layer-to-layer likelihood is the average of all element-to-layer likelihoods, as calculated in:

$$L(L_A \rightarrow L_B) = \frac{1}{n} \sum_{i=1}^{n} L(a_i \rightarrow L_B)$$

Equation 6.5

Based on these calculations, a layer-level likelihood DSM can be computed, based on an element-level DSM:

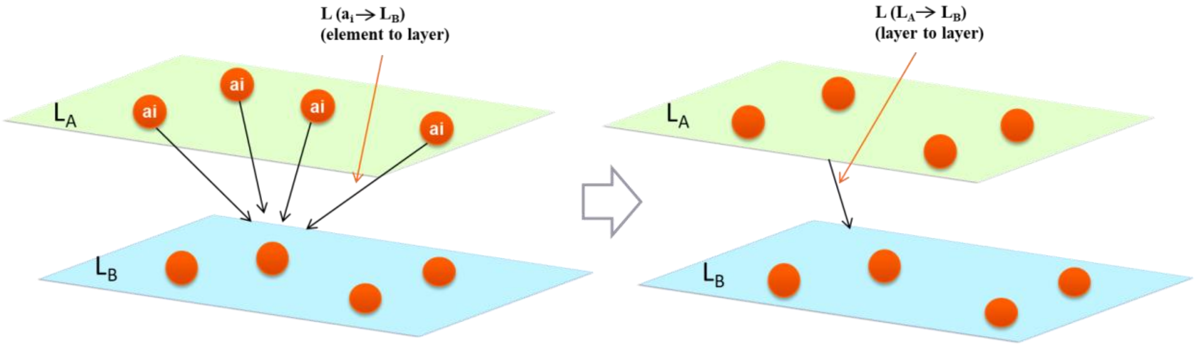


Figure 6.9: Estimating the element to element likelihoods (adapted from Ariyo *et al.* 2007b)

Multi-Layer *Direct Impact* Estimation

System impact is determined by combining the direct impact values of elements ***ai*** on elements ***bj*** of other systems. The assumptions made in cases of element-to-layer and layer-to-element impact estimation are slightly different. Element-to-layer impact estimation is based on a prediction of change, while layer-to-element estimation is based on the occurrence of the change.

I. Element to Layer direct impact estimation

In the estimation of the element-to-layer impact, only the direct interactions between an element and the affected layer are considered, as shown in Figure 6.10. Impact values are calculated from the propensity for elements within a target system to be affected by the change. The element-to-system impact may be derived from the numerical average of the effects of this element on the entire system, using equation 6.6 below:

$$impact(\mathrm{a_j\ to}\ B) = \frac{1}{n}\sum_{j=1}^{n}[impact\ (\mathrm{a_j\ to\ b_j})] \qquad \text{Equation 6.6}$$

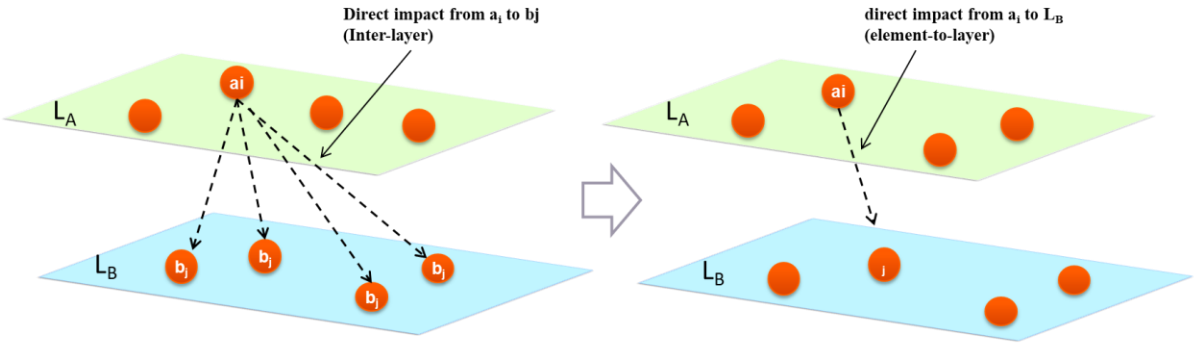


Figure 6.10: Estimating the element-to-element impacts (adapted from Ariyo *et al.* 2007b)

II. Layer to Element direct impact estimation

Theoretically, the layer-to-element impact is more complex to estimate than element-to-layer impact. Depending on the particular "edge" element in a layer, the strength of each element's $\boldsymbol{a_i}$ coupling to element $\boldsymbol{b_j}$ varies. In such situations, the impact value depends on the frequency with which each element within the layer interacts directly with the affected element. As a result, the layer-to-element impact may be estimated by computing a weighted average impact of each element $\boldsymbol{a_i}$ of layer $\boldsymbol{A}$ on element $\boldsymbol{b_j}$. The weight factor is taken to be the probability that an element will cause the change to propagate as shown in the following equation 6.7:

$$impact(\mathrm{a_j} \text{ to } B) = \frac{\sum_{i=1}^{n}[likelihood\ (\mathrm{a_i} \text{ to b})x\ (impact\ (\mathrm{a_k} \text{ to b})]}{\sum_{i=1}^{n}[likelihood\ (\mathrm{a_i} \text{ to b})} \qquad \text{Equation 6.7}$$

III. Layer-to-Layer direct impact estimation

The impact associated with change propagating directly between two layers can be computed by combining the effect of layer $\boldsymbol{A}$ on each element $\boldsymbol{b_j}$ of system $\boldsymbol{B}$ (see Equation 6.8 in Layer-to-element direct impact estimation). The impact of layer $\boldsymbol{A}$ on element $\boldsymbol{b}$ can be calculated using in the following equation:

$$impact(A \text{ to } B) = \frac{1}{n}\sum_{j=1}^{n}[impact\ (\mathrm{A} \text{ to } \mathrm{b_j})] \qquad \text{Equation 6.8}$$

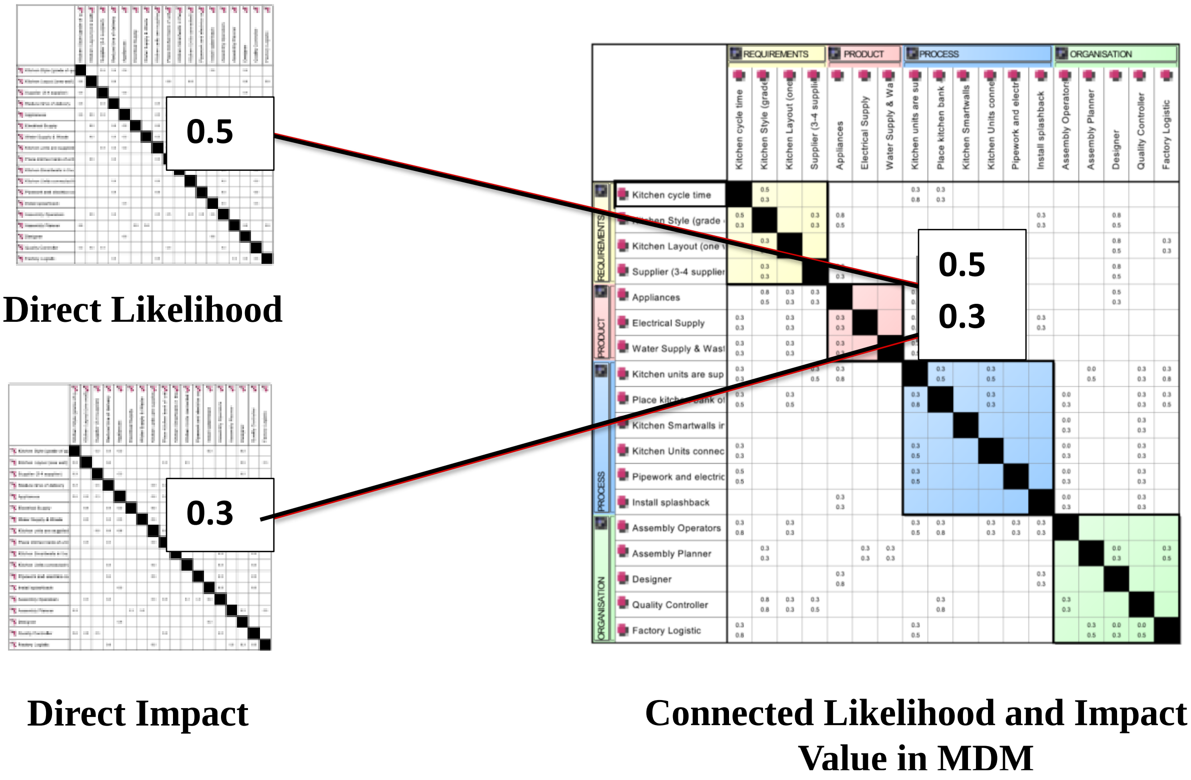
Multi-Layer *Risk* Estimation

This section describes an algorithm which enables risk computation in multi-layered network connectivity. The concept of creating a hypothetical propagation tree is central, not just to likelihood estimation but also to risk computation. The risk is computed using two variables: (1) the likelihood that a change may propagate from an identified source element to an object element; (2) the impact of change propagating from a penultimate element ***u*** in the path. The CPM algorithm computes the risk that changing a component ***a*** may affect another component ***b*** by aggregating each trail in the propagation tree as for likelihood estimation (the Forward CPM algorithm calculates the combined risk of change propagation from element ***a*** to element ***b***, presented in Appendix 6). The risk of change propagating between elements of a multi-layered connectivity model is estimated by applying the following equation 6.9 (i.e. the CPM algorithm) to individual single-layered views of a multi-layered network.

$$risk(a\ to\ b) = 1 - \prod_{i=1}^{n} \left[1 - \left[likelihood(a_i\ to\ b) \times impact(u_i\ to\ b)\right]\right] \quad \text{Equation 6.9}$$

Rating the likelihood and impact connection between pairs of elements

A dependency analysis method or an effective change propagation analysis method requires characterising the relationship between elements and layers and translating it into a system. These dependencies can be characterized qualitatively (Cohen *et al.* 2000; Furtmeier and Tormmelien 2010) and/or quantitatively (Clarkson *et al.* 2004; Hamraz *et al.* 2012b). Qualitative connections indicate approximately how much interaction there can be between two items. However, quantitative connections describe the dependencies that can automatically identify how much the elements are affected (Rutka *et al.* 2006). These quantitative relationships or dependencies can be visualised in the MLN matrix. In Figure 6.11, the quantitative likelihood MLN data and the impact MLN data first separately define, then connected and displayed in MLN.



Direct Likelihood

Direct Impact

Connected Likelihood and Impact Value in MDM

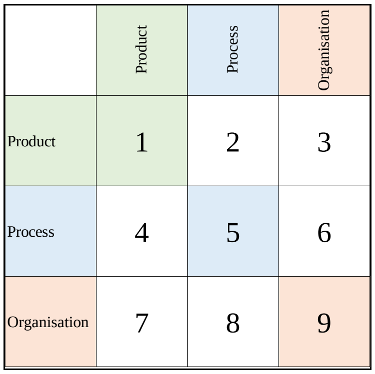
Figure 6.11: Quantitative representation of connected likelihood and impact values.

The change likelihood and change impact of each system element is captured and presented in change matrices. The entries along the diagonal of the change matrices are associated with the planned changes, while the entries in the off-diagonal cells are associated with the propagation of changes between system elements that are directly connected. This information represents the primary *change influences* related to each system element. However, an analysis based on this information can be inadequate as it does not consider the indirect change propagation between system elements. Using the connectivity defined, the direct change propagation likelihood and impact between the elements are rated by the experts. In this thesis, the scale used is ‘Low’, ‘Medium’, and ‘High’, which are then converted into a quantitative {0.3; 0.5; 0.7} scale. The value '0' was assigned when there was no dependency between elements. The choice of input scale was investigated in detail by Koh (2011) concerning the sensitivity of results in a related case study. He found that a moderately-spaced input scale such as {0.25; 0.5; 0.75} or {0.3; 0.5; 0.7} is more appropriate in this respect.

6.4.2 Compute Combined Change Propagation (Analyse Stage)

In the ***Analyse*** stage, the aim is to compute the predictive matrix by populating each connection with an estimate of the likelihood and impact of changes between the connected elements. This captures the elements of the system which are subject to direct changes and how such changes can propagate to impact elements that have no direct dependencies. The CAM toolbox use for risk assessment is associated with the connectivity of elements (the likelihood and impact connections).

The Multiple Layer Matrix (MLN) as shown in Figure 6.14 is used in this work to illustrate the flow of information. The MLN is a combination of DSMs and DMMs. DSMs are square matrices which serve to model the asymmetrical dependencies between objects of a given domain. In contrast, DMMs are non-square matrices which connect associated information across different domains. When these matrices are combined into an MLN as shown in Figure 6.12, the outcome is a square matrix which models the dependencies within and between different domains. The diagonals of the MLN are DSMs while the rest of the fields are DMMs. For instance, Fields 1, 3, and 5 lie on the diagonal of the MLN and thus a DSM which examines the dependencies within the design-features layer. On the other hand, Fields 2, 3, 4, 6, 7 and 8 do not lie on the diagonal of the MLN and hence are a DMM which examines the dependencies between the design-features layers and the required-characteristics layer. More details on a mapping between layers can be found in Danilovic and Browning, 2007.



	Product	Process	Organisation
Product	1	2	3
Process	4	5	6
Organisation	7	8	9

Figure 6.12: The representation of the dependency matrix for the multilayers network

6.4.3 Use the Change Risk Method for Decision Making (Use Stage)

This stage supports decision-making by identifying which elements could have the biggest impact if changed and/or which elements are most likely to be impacted by changes to any other element. The model can be used to assist in the decision-making process by reviewing the effect of the change on each domain in terms of the total combined risk to elements and the combined risk variation across different likelihood outcomes. The CAM modeller can be used to identify the riskiest elements (those which are most likely to initiate problems) and those elements that are most sensitive to issues that arise as a result. The results of such analyses will vary depending on the number of change propagation steps that are applied.

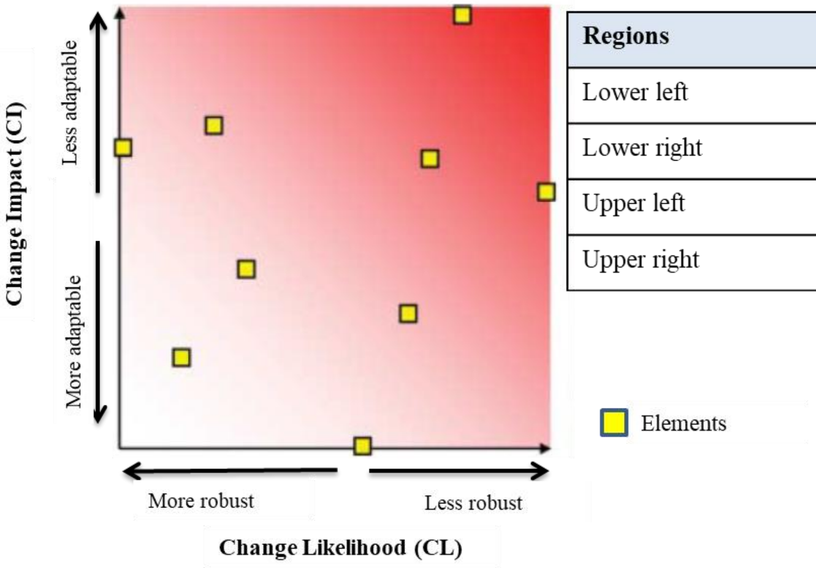
The Risk Assessment of System Changeability and Decision Making

Computing the combined change propagation supports the assessment of system changeability and enables design suggestions to be provided based on this assessment. Figure 6.15 visualise the change indices of each system element computed in a risk plot chart. The horizontal axis represents *the changing likelihood* (CL) axis, while the vertical axis represents *the change impact* (CI) axis. Figure 6.13 illustrates those system elements which fall on the left side of the chart have low CL. This suggests that these system elements are relatively less likely to change when compared with the other system elements. Likewise, system elements that fall on the lower half of the chart have low CI and thus have a lower change impact when compared with other system elements. Based on this, the chart can be further divided into four areas as follows:

1. System elements that fall on *the lower left of the chart* have a comparatively low CI and CL. This means that these system elements are the least critical as they are unlikely to be changed and the impact would be minimal even if a change were required. These elements are categorised as *more robust and more adaptable* to changes when compared with the rest of the elements.
2. System elements that fall on *the lower right of the chart* have comparatively low CI and high CL. This suggests that these system elements are likely to be changed, but will experience low impact if a change

is needed. So, these elements are categorised as *more adaptable but less robust* to changes when compared with the rest of the elements.

3. System elements that fall on *the upper left of the chart* have comparatively high CI and low CL. This indicates that these system elements are unlikely to be changed. But, if a change is needed, the impact of implementing the change will be high. Hence, these elements are categorised as *more robust but less adaptable* to changes when compared with the rest of the elements.
4. System elements that fall on *the upper right of the chart* have comparatively high CI and CL. These system elements are the most critical as both the likelihood of and the impact of change is high. Thus, they are categorised as *less robust and less adaptable* to changes when compared with the rest of the elements.



Regions	**Characteristics**
Lower left	More adaptable, more robust
Lower right	More adaptable, less robust
Upper left	Less adaptable, more robust
Upper right	Less adaptable, less robust

Figure 6.13: Combined risk plot (adapted from Koh 2011)

Based on Figure 6.15 and the classification scheme above, those system elements on the left of the CI versus CL chart are less likely to change and hence are more suitable for standardisation compared with those on the right. Also, as the system elements on the upper left of the chart are harder to change, they should be made even less likely to change. Similarly, it follows that system elements on the lower half of the CI versus CL chart have lesser change impact and thus are comparatively easy to change. However, given that the system elements on the lower right of the chart are more likely to be changed, it is suggested that they should be made even more adaptable to changes to further reduce the impact of future changes.

Suggestions for elements that fall on the upper right of the CI versus CL chart are less obvious as these elements are both likely to be changed and hard to change. The elements falling on this part of the CI versus CL chart in an ideal case should include only adaptable or robust elements. It is therefore vital to make these elements more changeable to improve the overall changeability of the system. However, it is not clear whether they should be made more adaptable or robust to changes based on the incoming change characteristics alone (CI and CL). Therefore, further analysis is essential for these elements. This is carried out by examining the Change Risk (CR) of these elements to evaluate their effect on other parts of the system.

Elements with high CR have a strong effect on other elements and therefore should be made more robust or adaptable to changes to avoid propagating changes to others. Likewise, elements with low CR do not affect other elements as much so should be made as adaptable as possible to future changes. It should be added here that even though any element that falls above or on the right of another element is comparatively less adaptable or robust to changes, and therefore more critical in comparison, it does not necessarily mean that the former would finally be selected for improvement as the cost and potential benefit of making the element more robust or adaptable can vary between elements and is dependent on improvement methods. Hence, further research processes may be essential to be able to make the best decision with the available resources. However, the method described above can be used to facilitate a more focused discussion and support the identification of appropriate elements for improvement from a changeability viewpoint.

6.5 Chapter Summary

This chapter described the detail design of a multi-layered change propagation approach to analysing change impacts within a system design process. The technical contribution of the method in relation to the state-of-the-art are listed in Table 6..2

Table 6.2: The technical contribution of the system change method

Thesis Section	**The design process requirements**	**Implementation of SCM**
6.3.1	Decompose the system into layers and elements	SCM method is better than CPM in a multi-layered system decomposition with level of detail for a system representation to satisfy mathematical requirements: Each level of the hierarchy can complete the representation of the same individual but at a different degree of complexity; Each element can be assigned to a layer.
6.3.2	Capturing Dependencies between Layers and Elements	The method visualises the connections between different layers to identify any change requirements which can be directly mapped to the related elements and tasks. Examining the connections reveals how changes propagate between the elements through the method The method supports investigating the connectivity of changes through the network of dependency with systematic multiple-level

		dependency analysis. This allows greater insight into connections, which in turn increases the understanding of the system.
6.4.1	Quantify the Multi-layered Network to compute Predictive Matrix	The technique supports the prediction and quantification of the likelihood, impact, and risk values of each connection that is captured from the hierarchy levels of MLN. The advantage of this method over CPM is a better understanding of the changeability position for individual elements of a system
6.4.2	Compute Combined Change Propagation	The method computes the predictive multilayer matrix by populating each connection with an estimate of the likelihood and impact of changes between the connected elements. This captures the elements of the system which are subject to direct changes and how such changes can propagate to impact elements that have no direct dependencies. In this way, the model May represent more changes than CPM by considering links between attributes and elements explicitly.
6.4.3	Use the Change Risk Method for Decision Making	The model can be used to assist in the decision-making process by reviewing the effect of the change on each layer in terms of the total combined risk to elements and the combined risk variation across different likelihood outcomes. The technique captures the design concept and thus supports developing solutions to change requests. SCM may be better than CPM in supporting the identification of solution plans and redesign strategies.

Thus, this chapter has answered the fifth research question: “What are the detailed elements required to understand the chosen change method concept for resilient manufacturing systems?”. The next chapter addresses the application of the change method approach to industrial case studies.

7 Applications of the System Change Method in Industry

7.1 Chapter Overview

This chapter addresses the sixth research question (RQ6: How well does the developed system change method perform in real case studies?) by presenting three different case studies and an application of the system change method. The following three sections present three case studies with two different industrial implementations. Sections 7.2, and 7.3 describe the method's implementation at Laing O'Rourke (LOR):

A Kitchen Assembly System, a Kitchen Design Application in an E5+ Module Apartment. Section 7.4 presents a case study in UOP Honeywell: Customer Requirements. Section 7.5 summarises this chapter.

7.2 Case Study 1 – Kitchen Assembly System, Laing O'Rourke

This section presents a case study in a Kitchen Assembly System (KAS) by applying the system change method. The study is part of a broader research programme involving a consortium of 22 associates from research and industry, directed by a UK-based construction company. Laing O'Rourke Corporation Ltd (LOR) is a multinational construction and engineering company, with operations directed through two major geographic centres, Europe and Australia. Laing O'Rourke has operations in engineering expertise, infrastructure construction, building construction, investment and development, modular manufacturing and support services.

This study aims to address the UK's housing capacity gap with the development of a new modular construction system, state-of-the-art off-site manufacturing and intelligent supply chain management. The modules are prefabricated and transported to the construction site where they are assembling. The significant parts-controlled manufacturing setting with purpose managing the constraints of time, cost and quality in project delivery. The complexity of the assembly process of the modules is determined by whether they contain a kitchen, a bathroom, a utility cupboard, or a combination of the three. For instance, modules containing a kitchen require extra work on the finishing line to install the required units and appliances, and to make the necessary electrical and plumbing connections. As a result, the investigation of this project has focused on developing the kitchen assembly system as kitchen assembly is one of the significant factors in the complexity of a module, and as such acts as a bottleneck to the process. Therefore, improvements in the kitchen assembly process will lead to improvements in overall module assembly.

As a part of the plan, the ensuing risks of changes to parts of the system are exploring. The study focuses on the effects of changes to the design; in particular, how their knock-on effects impact the structure of the KAS. Reviewing change propagation behaviour of the system aims to improve the robustness or adaptability of the system design process. Based on the connectivity of system elements, changes can propagate through various paths, which can lead to complex change networks (Eckert et al. 2004). Predicting how the changes will propagate is theoretically an advantage and involves two tasks: (1) the causes of changes have to be predicted for an overview of a change; (2) changes that result from these initiating changes have to be predicted. So, for a series of changes, the initiating change and all the, directly and indirectly, resulting changes have to be considered.

The proposed system change method (SCM) has been used to characterise changes (requested by internal or external customers or stakeholders) in terms of their impact on the assembly time of a module. This characterisation of change type will enable the manufacturer to reduce the operation time on their main assembly line, and increase the volume of modular buildings that can be produced. The case study demonstrates the application of the MLN as both a process-mapping tool and a decision support tool that can improve the understanding of the relationship between product, process, and organisation as a whole system.

Adam Robinson assisted the modelling of the Kitchen Assembly System; he is an expert in Laing O'Rourke (LOR) Corporation Ltd. Mr Robinson has been a Senior Process Engineer for three years in the company. He is specialised in the process of manufacturing module sections in the facility for assembly at a remote building site.

The following sections describe the application of the system change method to the first case study by using the system design concept as shown in Figure 1.

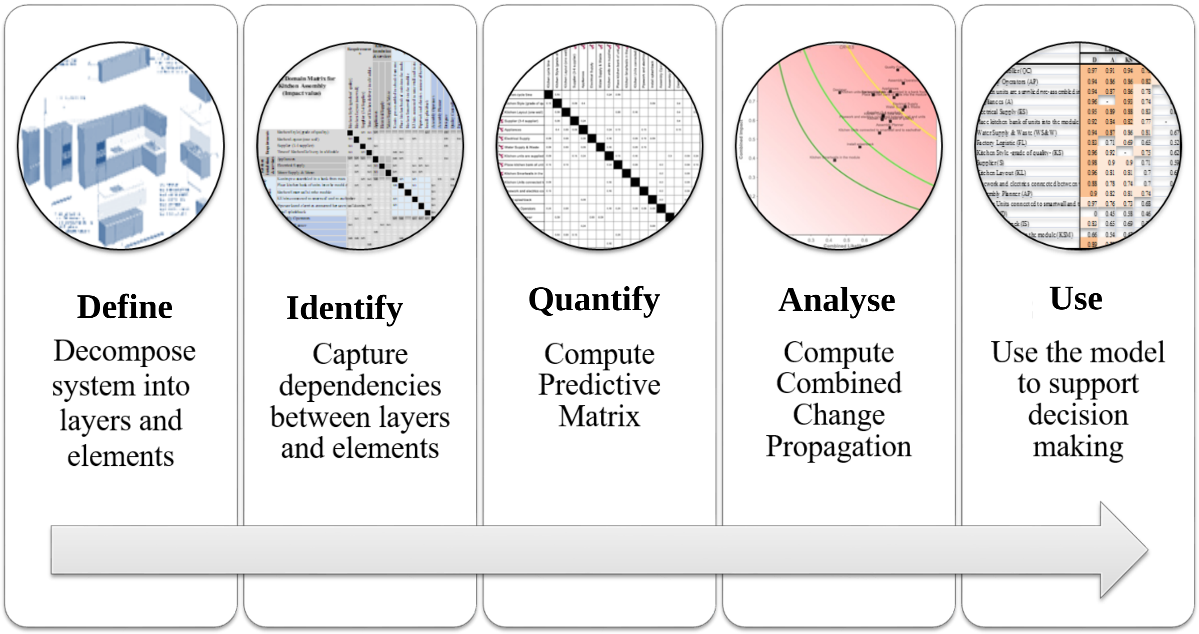


Figure 7.1: The system design concept for case study 1

7.2.1 Decompose the system into layers and elements

The proposed layout for the new advanced manufacturing facility shows in Figure 7.1. The majority of this area is for module assembly, but a proportion is also for Smart Wall assembly. Smart Walls were then used as one of the input materials on the main module assembly line. The kitchen assembly area of the proposed facility with the kitchen as a product displays on the right side at the top of Figure 7.2, which is on the finishing line in the rectangle, immediately before the inspection stations. This thesis focused on the work carried out in the area of the facility.

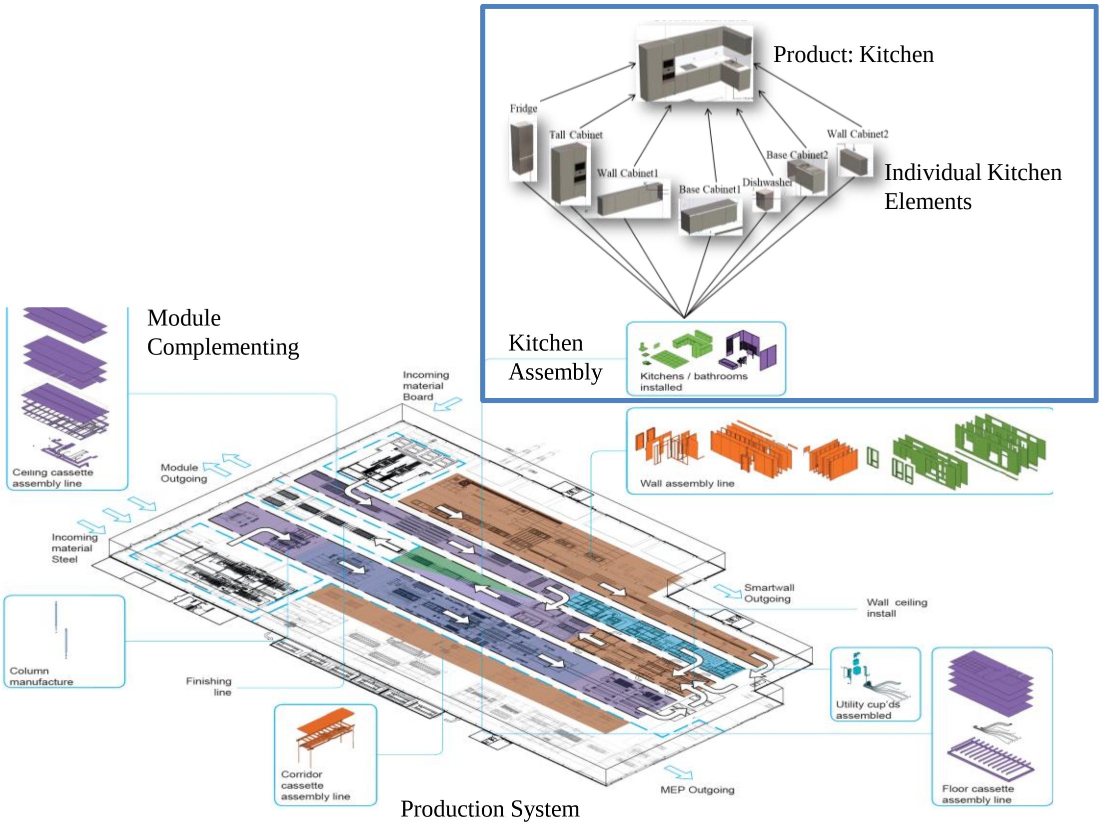


Figure 7.2: Proposed layout of the new advanced manufacturing facility, with the kitchen assembly on the finishing line in the rectangle (adapted from Bryden Wood 2015)

The specific method proposed here is to combine three primary layers: namely, the product layer, the process layer, and the organisational layer with an additional requirement layer also incorporated into the model. Based on several discussions with the expert, *4 layers (Kitchen Requirements, Kitchen Installation, Kitchen Assembly Process and Manufacturing Organisation)* and *18 elements* (listed in Table 7.1) were identified to represent the entire a kitchen assembly system. The identification criteria are a balance between a manageable number of elements and the right level of detail for meaningful analysis.

7.2.2 Capture dependencies between layers and elements

Each system element can be affected by both planned changes and change propagation. The identification of connections between elements and the assessment of their change propagation likelihood and impact is the next step and resulted in *87 direct connections* between the four layers and *18 elements* held in an MLN. Each direct relationship between two elements could be made up of more than one connection, and the expert indicated the likelihood and impact of change propagation on each connection. Table 7.1 shows the dependencies between the elements identified in the case study mapped onto the MLN (Figure 7.3).

Table 7.1: Dependency between the elements of the kitchen assembly system

Element No	Elements	Depends upon elements
1	Kitchen Assembly Cycle Time	2,6,7,8,9,11,12,14,18
2	Kitchen Style (grade of quality)	1,3,4,5,15,17
3	Kitchen Layout	5,6,7,9,15,17
4	Suppliers	2,5,8,17
5	Appliances	2,4,6,7,8,13,16
6	Electrical Supply	15
7	Water Supply & Waste	15
8	Kitchen units are supplied pre-assembled in a bank from the manufacturer	1,5,6,7,9,11,12,14,18
9	Place kitchen bank of units into the module	1,3,5,8,14,17
10	Kitchen smartwalls in the module	None
11	Kitchen units connected to smartwall and each other	3,6,7,8,9,14
12	Pipework and electrics connected between wall and units	5,6,7,14
13	Install splashback	2,6,14,16
14	Assembly Operators	9,10,11,12,13,17
15	Assembly Planner	8,18
16	Designer	2,3,4,5,15,18
17	Quality Controller	8,9,10,11,12,13,18
18	Factory Logistics	3,8,9,14

Figure 7.3 illustrates the complete network for a pilot KAS which presents the direct relationship between the 4 layers and 18 elements. For the qualitative use of the system change approach, an interactive network was developed from the dependency connectivity of the MLN. The qualitative network model supports a

broad view of how the KAS operates, which can also be used for knowledge management and training purposes within an organisation. The designer may have a better assessment of which elements are impacted by the specified change.

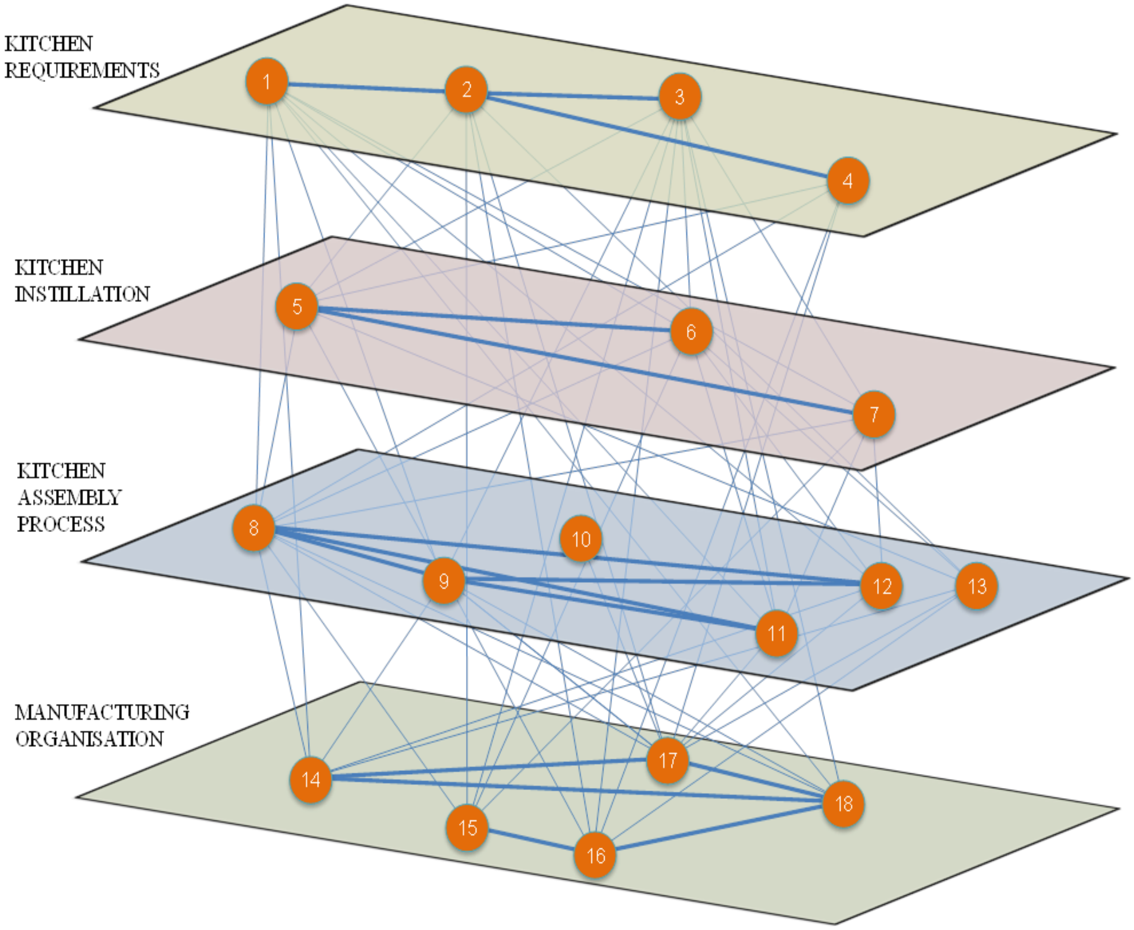
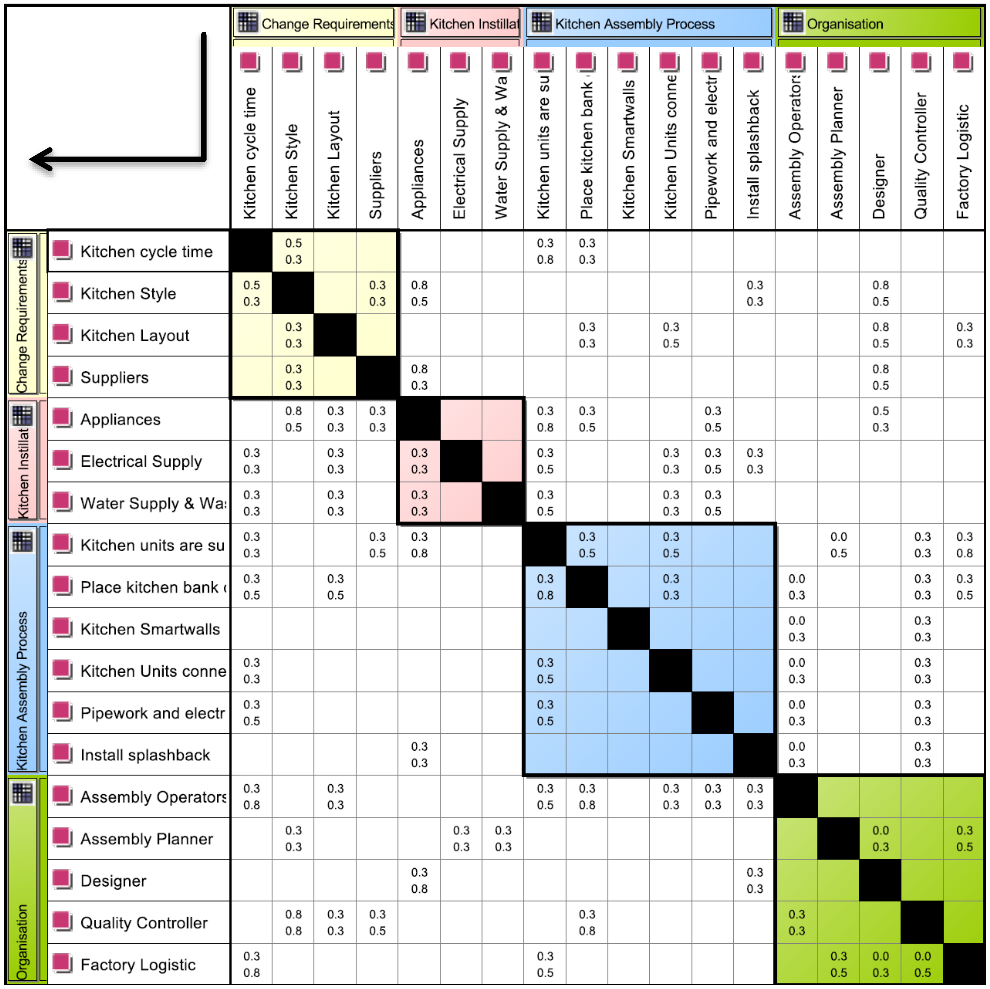


Figure 7.3: Network relationship for the elements of the kitchen assembly system

7.2.3. Quantify the Multilayer Network Method to Change Prediction Method

A detailed understanding of the connections between elements and each connection is characterised by two values – *the likelihood* (frequency) of change and its predicted *impact*. in Figure 7.4, the value on the top is the likelihood, and on the bottom impacts in each cell. To estimate these values, the relations between directly linked characteristics can be investigated for common changes. The network representation is more valuable for this stage. For instance, in the KAS, if the *Suppliers (E4)* changes, it will require likelihood and impact change propagations to *Kitchen Style* (*E2*), *Appliances (E5), Kitchen units are supplied pre-assembled in a bank from the manufacturer (E8)* and *Quality Controller (E17)* following the dependency analysis (Table 7.1 and Figure 7.3). If there is no connection between the elements, no values state in the cells.



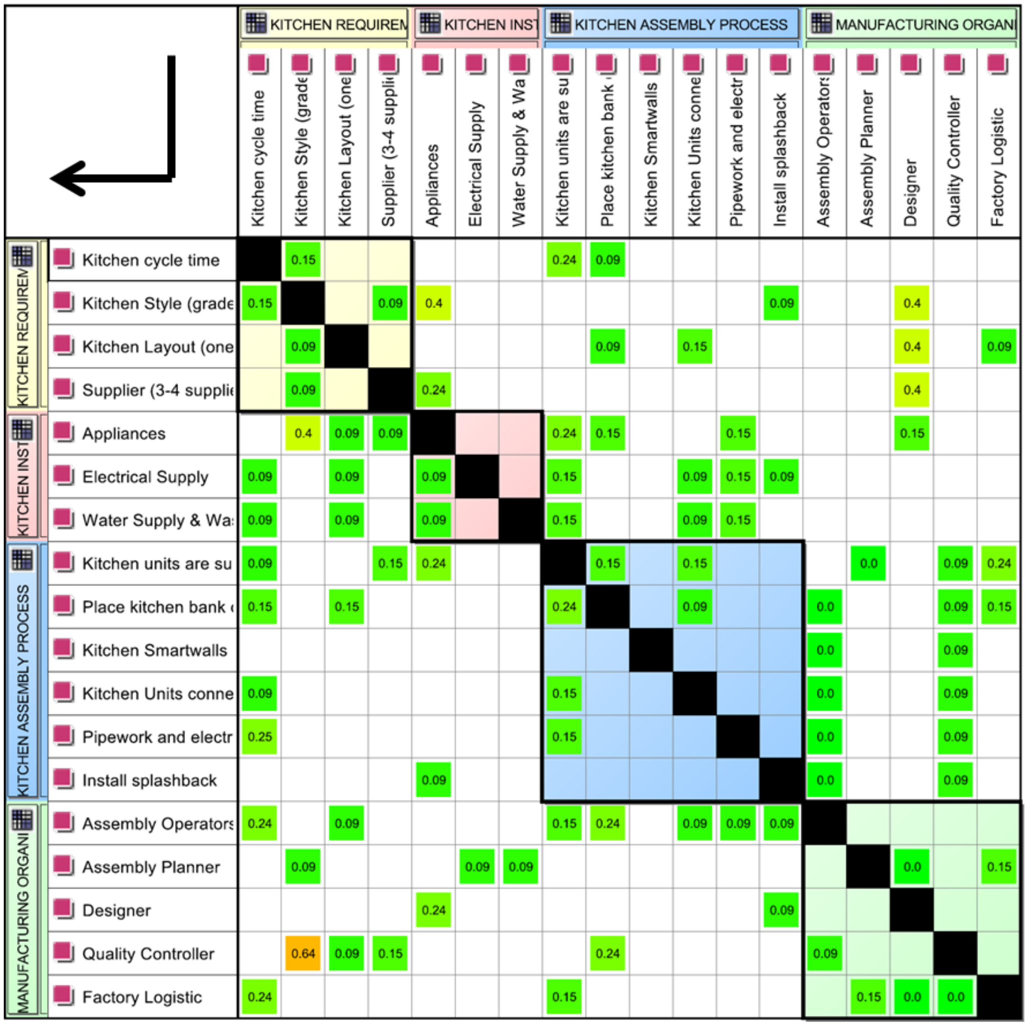
		Change Requirements				Kitchen Instillat			Kitchen Assembly Process						Organisation				
		Kitchen cycle time	Kitchen Style	Kitchen Layout	Suppliers	Appliances	Electrical Supply	Water Supply & Wa	Kitchen units are su	Place kitchen bank	Kitchen Smartwalls	Kitchen Units conne	Pipework and electr	Install splashback	Assembly Operators	Assembly Planner	Designer	Quality Controller	Factory Logistic
Change Requirements	Kitchen cycle time		0.5 0.3						0.3 0.8	0.3 0.3									
	Kitchen Style	0.5 0.3			0.3 0.3	0.8 0.5								0.3 0.3			0.8 0.5		
	Kitchen Layout		0.3 0.3							0.3 0.3		0.3 0.5					0.8 0.5		0.3 0.3
	Suppliers		0.3 0.3			0.8 0.3											0.8 0.5		
Kitchen Instillat	Appliances		0.8 0.5	0.3 0.3	0.3 0.3				0.3 0.8	0.3 0.5			0.3 0.5				0.5 0.3		
	Electrical Supply	0.3 0.3		0.3 0.3		0.3 0.3			0.3 0.5			0.3 0.3	0.3 0.5	0.3 0.3					
	Water Supply & Wa	0.3 0.3		0.3 0.3		0.3 0.3			0.3 0.5			0.3 0.3	0.3 0.5						
Kitchen Assembly Process	Kitchen units are su	0.3 0.3			0.3 0.5	0.3 0.8				0.3 0.5		0.3 0.5				0.0 0.5		0.3 0.3	0.3 0.8
	Place kitchen bank	0.3 0.5		0.3 0.5					0.3 0.8			0.3 0.3			0.0 0.3			0.3 0.3	0.3 0.5
	Kitchen Smartwalls														0.0 0.3			0.3 0.3	
	Kitchen Units conne	0.3 0.3							0.3 0.5						0.0 0.3			0.3 0.3	
	Pipework and electr	0.3 0.5							0.3 0.5						0.0 0.3			0.3 0.3	
	Install splashback					0.3 0.3									0.0 0.3			0.3 0.3	
Organisation	Assembly Operators	0.3 0.8		0.3 0.3					0.3 0.5	0.3 0.8		0.3 0.3	0.3 0.3	0.3 0.3					
	Assembly Planner		0.3 0.3				0.3 0.3	0.3 0.3									0.0 0.3		0.3 0.5
	Designer					0.3 0.8								0.3 0.3					
	Quality Controller		0.8 0.8	0.3 0.3	0.3 0.5					0.3 0.8					0.3 0.3				
	Factory Logistic	0.3 0.8							0.3 0.5							0.3 0.5	0.0 0.3	0.0 0.5	

Figure 7.4: A numerical representation of the connected Likelihood & Impact values in a multilayer network for the kitchen assembly system of Laing O’Rourke Company

Once this information has been extracted from the case study assessment, it is transferred into the MLN using CAM Software. The data are then analysed by the CPM tool. The CPM predicts the likelihood and impact of change propagation between elements by modelling the direct dependencies between them (Figure 7.4).

7.2.4 Compute Combined Change Propagation

This stage determines the combined change propagation likelihood and impact of planned changes for the initiating elements. The tool supports calculating the direct change risks based on the direct likelihood and impact values (Figure 7.5). The shading colour indicates the risk value: the darker the cells, the higher the risk.

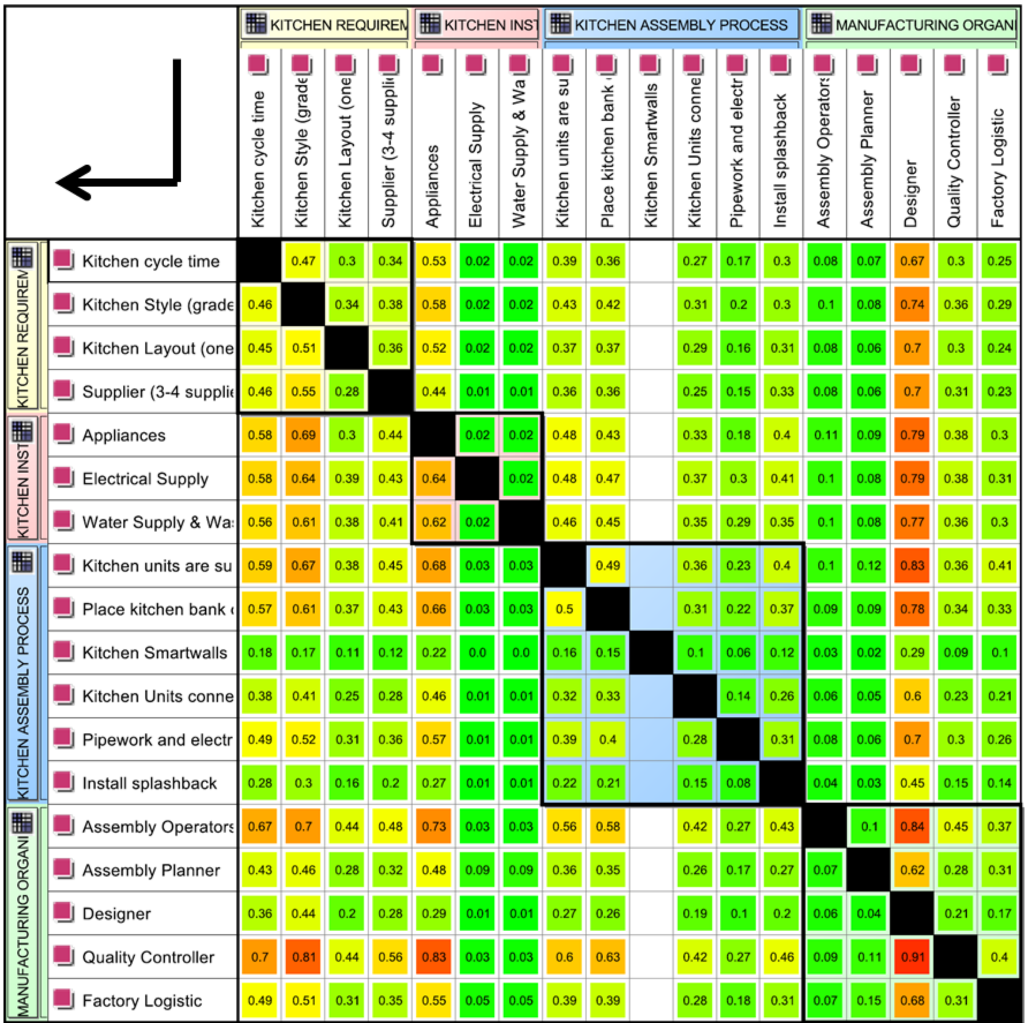


		KITCHEN REQUIREM				KITCHEN INST			KITCHEN ASSEMBLY PROCESS						MANUFACTURING ORGANI				
		Kitchen cycle time	Kitchen Style (grade	Kitchen Layout (one	Supplier (3-4 supplie	Appliances	Electrical Supply	Water Supply & Wa	Kitchen units are su	Place kitchen bank	Kitchen Smartwalls	Kitchen Units conne	Pipework and electr	Install splashback	Assembly Operators	Assembly Planner	Designer	Quality Controller	Factory Logistic
KITCHEN REQUIREM	Kitchen cycle time	■	0.15						0.24	0.09									
	Kitchen Style (grade	0.15	■		0.09	0.4								0.09			0.4		
	Kitchen Layout (one		0.09	■						0.09		0.15					0.4		0.09
	Supplier (3-4 supplie		0.09		■	0.24											0.4		
KITCHEN INST	Appliances		0.4	0.09	0.09	■			0.24	0.15			0.15				0.15		
	Electrical Supply	0.09		0.09		0.09	■		0.15			0.09	0.15	0.09					
	Water Supply & Wa	0.09		0.09		0.09		■	0.15			0.09	0.15						
KITCHEN ASSEMBLY PROCESS	Kitchen units are su	0.09			0.15	0.24			■	0.15		0.15				0.0		0.09	0.24
	Place kitchen bank	0.15		0.15					0.24	■		0.09			0.0			0.09	0.15
	Kitchen Smartwalls										■				0.0			0.09	
	Kitchen Units conne	0.09							0.15			■			0.0			0.09	
	Pipework and electr	0.25							0.15				■		0.0			0.09	
	Install splashback					0.09								■	0.0			0.09	
MANUFACTURING ORGANI	Assembly Operators	0.24		0.09					0.15	0.24		0.09	0.09	0.09	■				
	Assembly Planner		0.09				0.09	0.09								■	0.0		0.15
	Designer					0.24								0.09			■		
	Quality Controller		0.64	0.09	0.15					0.24					0.09			■	
	Factory Logistic	0.24							0.15							0.15	0.0	0.0	■

Key: 🟩 low risk (r<30%) 🟧 medium risk (30%< r<70%) 🟥 high risk (r>70%)

Figure 7.5: The numerical representation of the directly connected risk values in the multilayer network for kitchen assembly system of Laing O'Rourke Company

Applying the CPM algorithm to the case study, the indirect connections between the 18 elements can be generated by using the maximum change propagation steps (*six-step propagation analysis)* to calculate the combined change risks. The detailed results are demonstrated in the risk MLN in Figure 7.6. This MLN includes risk values for all different pairs of elements. This combined matrix contains the maximum combined risk values of 4 square DSMs as well as the 12 DMMs (Domain Mapping Matrix) between them, as illustrated in Figure 7.6. The result represents all elements affected simultaneously while taking the highest risk into account. It can be combined in different ways to generate specific high-level views of change propagation. For example, the blocks within *the kitchen requirements* and *kitchen installation* layers can be combined to generate an element-to-element change risk plot, similar to the result of the CPM (Keller et al. 2009). In Figure 7.5, the colour scale specifies the risk values as follows: the red cells are the higher risk (R>70%), the yellow cells are the medium risk (30% < R<70%) and the green cells are low risks (R< 30%).

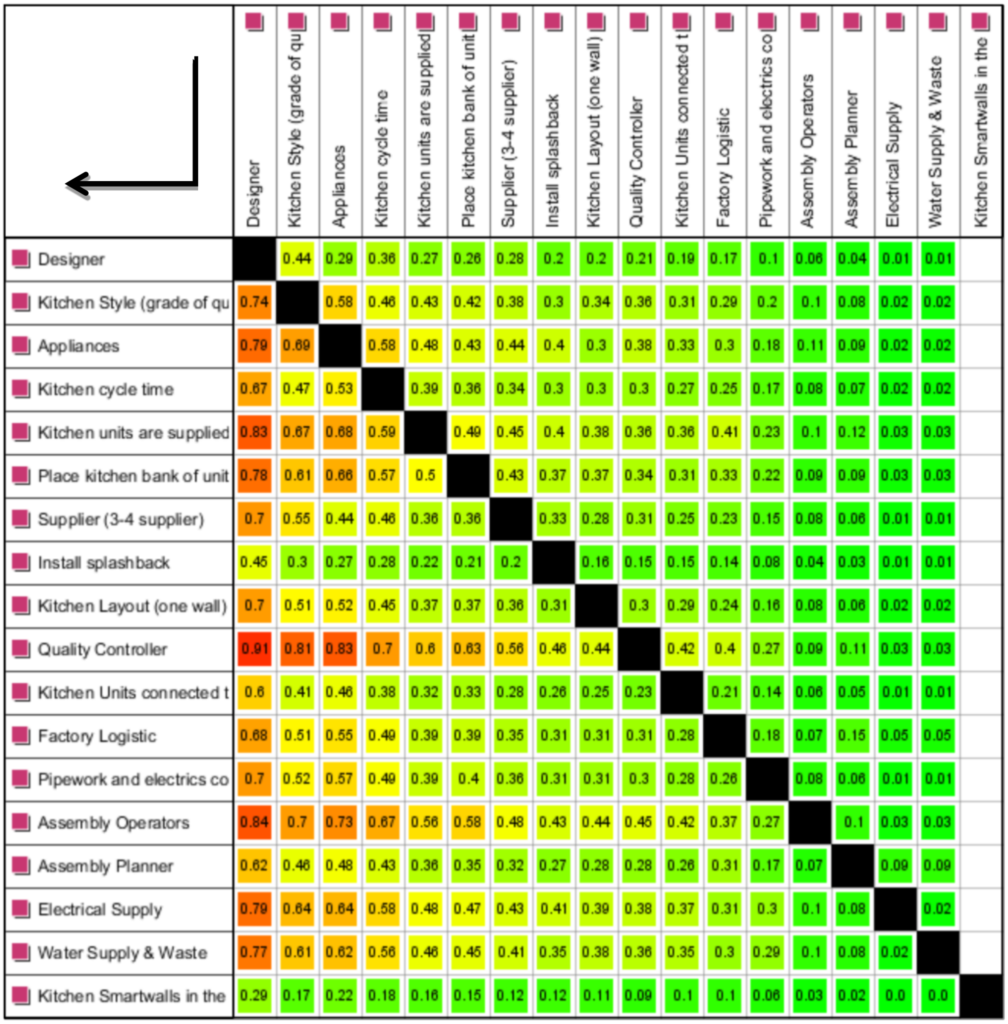


		KITCHEN REQUIREN				KITCHEN INST			KITCHEN ASSEMBLY PROCESS						MANUFACTURING ORGANI				
		Kitchen cycle time	Kitchen Style (grade	Kitchen Layout (one	Supplier (3-4 supplie	Appliances	Electrical Supply	Water Supply & Wa	Kitchen units are su	Place kitchen bank	Kitchen Smartwalls	Kitchen Units conne	Pipework and electr	Install splashback	Assembly Operators	Assembly Planner	Designer	Quality Controller	Factory Logistic
KITCHEN REQUIREM	Kitchen cycle time		0.47	0.3	0.34	0.53	0.02	0.02	0.39	0.36		0.27	0.17	0.3	0.08	0.07	0.67	0.3	0.25
	Kitchen Style (grade	0.46		0.34	0.38	0.58	0.02	0.02	0.43	0.42		0.31	0.2	0.3	0.1	0.08	0.74	0.36	0.29
	Kitchen Layout (one	0.45	0.51		0.36	0.52	0.02	0.02	0.37	0.37		0.29	0.16	0.31	0.08	0.06	0.7	0.3	0.24
	Supplier (3-4 supplie	0.46	0.55	0.28		0.44	0.01	0.01	0.36	0.36		0.25	0.15	0.33	0.08	0.06	0.7	0.31	0.23
KITCHEN INST	Appliances	0.58	0.69	0.3	0.44		0.02	0.02	0.48	0.43		0.33	0.18	0.4	0.11	0.09	0.79	0.38	0.3
	Electrical Supply	0.58	0.64	0.39	0.43	0.64		0.02	0.48	0.47		0.37	0.3	0.41	0.1	0.08	0.79	0.38	0.31
	Water Supply & Wa	0.56	0.61	0.38	0.41	0.62	0.02		0.46	0.45		0.35	0.29	0.35	0.1	0.08	0.77	0.36	0.3
KITCHEN ASSEMBLY PROCESS	Kitchen units are su	0.59	0.67	0.38	0.45	0.68	0.03	0.03		0.49		0.36	0.23	0.4	0.1	0.12	0.83	0.36	0.41
	Place kitchen bank	0.57	0.61	0.37	0.43	0.66	0.03	0.03	0.5			0.31	0.22	0.37	0.09	0.09	0.78	0.34	0.33
	Kitchen Smartwalls	0.18	0.17	0.11	0.12	0.22	0.0	0.0	0.16	0.15		0.1	0.06	0.12	0.03	0.02	0.29	0.09	0.1
	Kitchen Units conne	0.38	0.41	0.25	0.28	0.46	0.01	0.01	0.32	0.33			0.14	0.26	0.06	0.05	0.6	0.23	0.21
	Pipework and electr	0.49	0.52	0.31	0.36	0.57	0.01	0.01	0.39	0.4		0.28		0.31	0.08	0.06	0.7	0.3	0.26
	Install splashback	0.28	0.3	0.16	0.2	0.27	0.01	0.01	0.22	0.21		0.15	0.08		0.04	0.03	0.45	0.15	0.14
MANUFACTURING ORGANI	Assembly Operators	0.67	0.7	0.44	0.48	0.73	0.03	0.03	0.56	0.58		0.42	0.27	0.43		0.1	0.84	0.45	0.37
	Assembly Planner	0.43	0.46	0.28	0.32	0.48	0.09	0.09	0.36	0.35		0.26	0.17	0.27	0.07		0.62	0.28	0.31
	Designer	0.36	0.44	0.2	0.28	0.29	0.01	0.01	0.27	0.26		0.19	0.1	0.2	0.06	0.04		0.21	0.17
	Quality Controller	0.7	0.81	0.44	0.56	0.83	0.03	0.03	0.6	0.63		0.42	0.27	0.46	0.09	0.11	0.91		0.4
	Factory Logistic	0.49	0.51	0.31	0.35	0.55	0.05	0.05	0.39	0.39		0.28	0.18	0.31	0.07	0.15	0.68	0.31	

Key: 🟩 low risk (r<30%) 🟧 medium risk (30%< r<70%) 🟥 high risk (r>70%)

Figure 7.6: Running change prediction method algorithm to represent the indirect risk values for the element of the kitchen assembly system

For high-level analysis, the layers of the combined risk MLN were combined consider the element-element risk DSM (Design Structure Matrix) in Figure 7.7. This DSM helps to compare the risk profiles to each other (Keller *et al.* 2009). The colour scale of Figure 7.7 shows that the core elements are critical about receiving changes from other elements (i.e rows *Kitchen style, to Water supply & Waste*) as well as in initiating changes to other elements (i.e columns *Designer*, *Kitchen Style, Appliances, Kitchen Assembly Cycle Time*) and between each other. The overall average of the risk values is *31%* (risk values range from min 0 to max 91%) with the given conversion of assessed risk to the numerical value. Large parts of the connections contain low-risk values in the matrix. The connectivity between non-core elements is less critical. The matrix provides a view of the KAS that is an entirely combined system with all elements being interconnected to each other. A change to one element may affect virtually any other element.



	Designer	Kitchen Style (grade of qu	Appliances	Kitchen cycle time	Kitchen units are supplied	Place kitchen bank of unit	Supplier (3-4 supplier)	Install splashback	Kitchen Layout (one wall)	Quality Controller	Kitchen Units connected t	Factory Logistic	Pipework and electrics co	Assembly Operators	Assembly Planner	Electrical Supply	Water Supply & Waste	Kitchen Smartwalls in the
Designer	■	0.44	0.29	0.36	0.27	0.26	0.28	0.2	0.2	0.21	0.19	0.17	0.1	0.06	0.04	0.01	0.01	
Kitchen Style (grade of qu	0.74	■	0.58	0.46	0.43	0.42	0.38	0.3	0.34	0.36	0.31	0.29	0.2	0.1	0.08	0.02	0.02	
Appliances	0.79	0.69	■	0.58	0.48	0.43	0.44	0.4	0.3	0.38	0.33	0.3	0.18	0.11	0.09	0.02	0.02	
Kitchen cycle time	0.67	0.47	0.53	■	0.39	0.36	0.34	0.3	0.3	0.3	0.27	0.25	0.17	0.08	0.07	0.02	0.02	
Kitchen units are supplied	0.83	0.67	0.68	0.59	■	0.49	0.45	0.4	0.38	0.36	0.36	0.41	0.23	0.1	0.12	0.03	0.03	
Place kitchen bank of unit	0.78	0.61	0.66	0.57	0.5	■	0.43	0.37	0.37	0.34	0.31	0.33	0.22	0.09	0.09	0.03	0.03	
Supplier (3-4 supplier)	0.7	0.55	0.44	0.46	0.36	0.36	■	0.33	0.28	0.31	0.25	0.23	0.15	0.08	0.06	0.01	0.01	
Install splashback	0.45	0.3	0.27	0.28	0.22	0.21	0.2	■	0.16	0.15	0.15	0.14	0.08	0.04	0.03	0.01	0.01	
Kitchen Layout (one wall)	0.7	0.51	0.52	0.45	0.37	0.37	0.36	0.31	■	0.3	0.29	0.24	0.16	0.08	0.06	0.02	0.02	
Quality Controller	0.91	0.81	0.83	0.7	0.6	0.63	0.56	0.46	0.44	■	0.42	0.4	0.27	0.09	0.11	0.03	0.03	
Kitchen Units connected t	0.6	0.41	0.46	0.38	0.32	0.33	0.28	0.26	0.25	0.23	■	0.21	0.14	0.06	0.05	0.01	0.01	
Factory Logistic	0.68	0.51	0.55	0.49	0.39	0.39	0.35	0.31	0.31	0.31	0.28	■	0.18	0.07	0.15	0.05	0.05	
Pipework and electrics co	0.7	0.52	0.57	0.49	0.39	0.4	0.36	0.31	0.31	0.3	0.28	0.26	■	0.08	0.06	0.01	0.01	
Assembly Operators	0.84	0.7	0.73	0.67	0.56	0.58	0.48	0.43	0.44	0.45	0.42	0.37	0.27	■	0.1	0.03	0.03	
Assembly Planner	0.62	0.46	0.48	0.43	0.36	0.35	0.32	0.27	0.28	0.28	0.26	0.31	0.17	0.07	■	0.09	0.09	
Electrical Supply	0.79	0.64	0.64	0.58	0.48	0.47	0.43	0.41	0.39	0.38	0.37	0.31	0.3	0.1	0.08	■	0.02	
Water Supply & Waste	0.77	0.61	0.62	0.56	0.46	0.45	0.41	0.35	0.38	0.36	0.35	0.3	0.29	0.1	0.08	0.02	■	
Kitchen Smartwalls in the	0.29	0.17	0.22	0.18	0.16	0.15	0.12	0.12	0.11	0.09	0.1	0.1	0.06	0.03	0.02	0.0	0.0	■

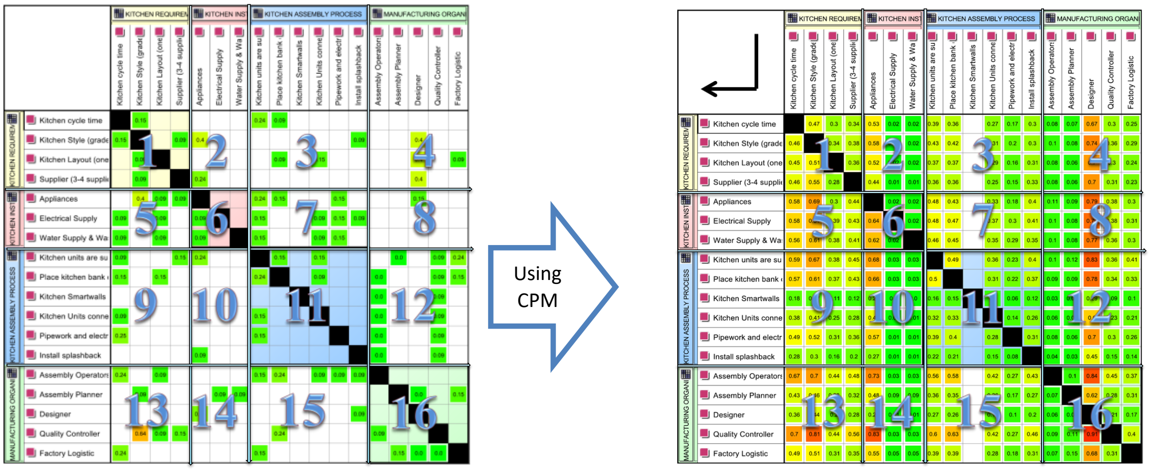
Key: 🟩 low risk (r<30%) 🟧 medium risk (30%< r<70%) 🟥 high risk (r>70%)

Figure 7.7: Reordered combined risk values for the element of the Kitchen Assembly System (in value/ %)

7.2.5 Use of the change risk model for decision making

Comparing direct and indirect risk values with the company expert

This MLN matrix consists of the dependency connectivity of 4 DSMs (1, 6, 11, 16) and 12 DMMs (2 3, 4, 5, 7, 8, 9, 10, 12, 13, 14, 15) (Figure 7.8). Figure 7.8 (a) and (b) present the computed results of the direct and indirect change propagations. Field 1, 6, 11, 16 subsequently show the interaction between *Kitchen Requirements, Kitchen Installation, Kitchen Assembly System and Manufacturing Organisation*. Fields 5, 9, 13 indicate the performance rating of elements that are associated with the kitchen requirements. Fields 2, 10, 14 indicate the performance rating of elements that are connected with the kitchen installation elements. Fields 3, 7, 15 indicate the performance rating of elements which are related to the kitchen assembly process. Fields 4, 8, 12 indicate the performance rating of elements which are attendant on the manufacturing organisation (Figure 7.8).

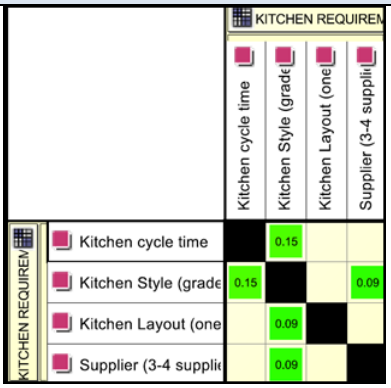
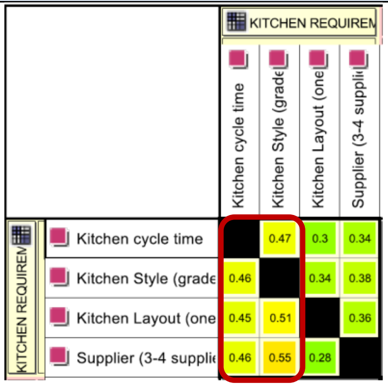


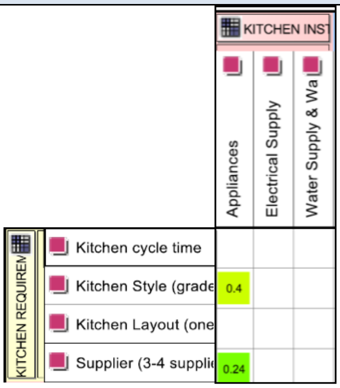
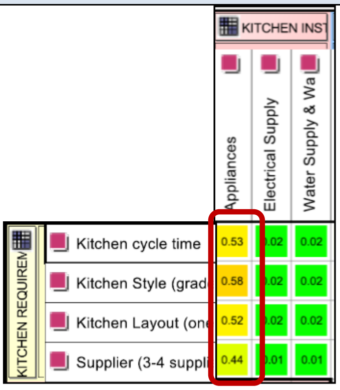
(a) (b)

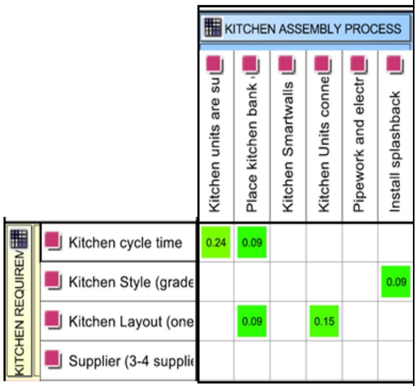
Figure 7.8: Numerical representation of them directly (a) and indirectly (b) connected risk values for the element of the kitchen assembly system

Table 7.2 shows the differences between the original input data and the final results. The comparison was done by the company expert whose comments are stated in the brackets. While comparing the risk values, the yellow and red shades risk values were considered which the highest impacts are on the system

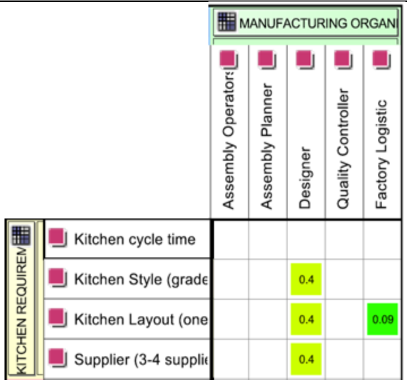
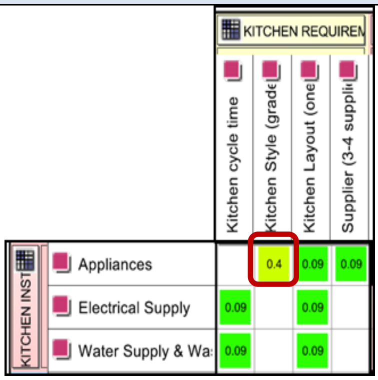
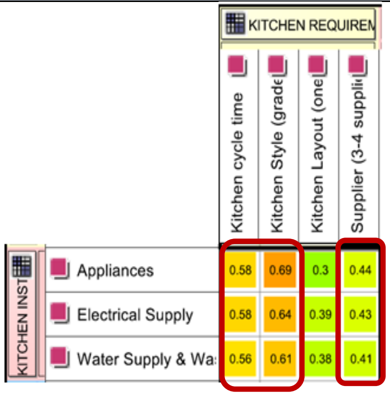
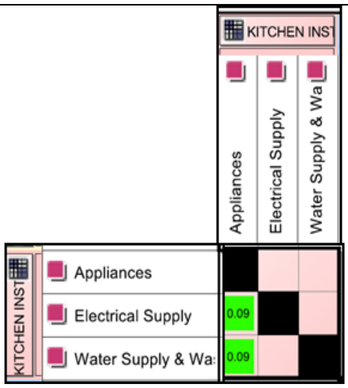
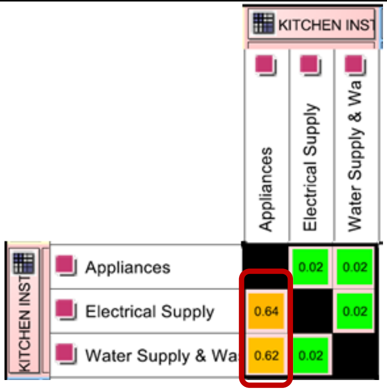
Table 7.2: The comparison of the direct and indirect risk values for the kitchen assembly system

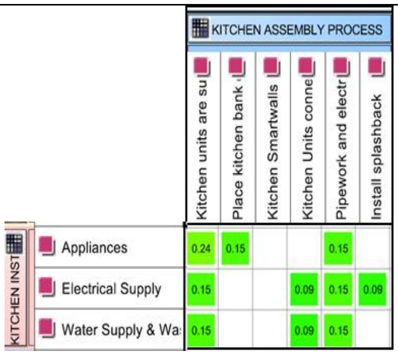
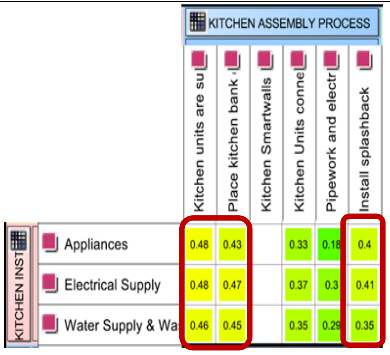
<table>
<tr><th>No</th><th>The input data
(the direct connected Risk=Likelihood x Impact values)</th><th>The CPM Algorithm results
(the indirectly connected risk values)</th><th>Comparison of the input data and final results with Laing O'Rourke</th></tr>
<tr><td>1</td><td>
<table>
<tr><th>KITCHEN REQUIREM</th><th>Kitchen cycle time</th><th>Kitchen Style (grade</th><th>Kitchen Layout (one</th><th>Supplier (3-4 supplie</th></tr>
<tr><td>Kitchen cycle time</td><td></td><td>0.15</td><td></td><td></td></tr>
<tr><td>Kitchen Style (grade</td><td>0.15</td><td></td><td></td><td>0.09</td></tr>
<tr><td>Kitchen Layout (one</td><td></td><td>0.09</td><td></td><td></td></tr>
<tr><td>Supplier (3-4 supplie</td><td></td><td>0.09</td><td></td><td></td></tr>
</table></td><td>
<table>
<tr><th>KITCHEN REQUIREM</th><th>Kitchen cycle time</th><th>Kitchen Style (grade</th><th>Kitchen Layout (one</th><th>Supplier (3-4 supplie</th></tr>
<tr><td>Kitchen cycle time</td><td></td><td>0.47</td><td>0.3</td><td>0.34</td></tr>
<tr><td>Kitchen Style (grade</td><td>0.46</td><td></td><td>0.34</td><td>0.38</td></tr>
<tr><td>Kitchen Layout (one</td><td>0.45</td><td>0.51</td><td></td><td>0.36</td></tr>
<tr><td>Supplier (3-4 supplie</td><td>0.46</td><td>0.55</td><td>0.28</td><td></td></tr>
</table></td><td>Undesirable change propagation towards the *Kitchen Layout and Suppliers* when changes initiated in *Kitchen assembly cycle time* and *Kitchen Style.*

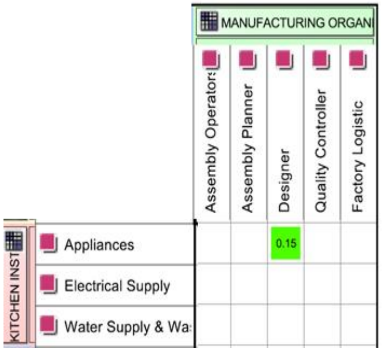
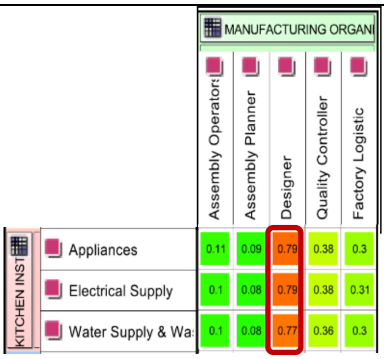
"If we have got the change on the *kitchen assembly cycle time* that the *kitchen layout* and *suppliers* would have got high in the indirect effect. So this shows us if we want to reduce *the assembly cycle time* then it would have big implicated on the *Kitchen Layout* and *Suppliers*"</td></tr>
<tr><th>No</th><th>The input data
(the direct connected Risk=Likelihood x Impact values)</th><th>The CPM Algorithm results
(the indirectly connected risk values)</th><th>Comparison of the input data and final results with Laing O'Rourke</th></tr>
<tr><td>2</td><td>
<table>
<tr><th>KITCHEN INST</th><th>Appliances</th><th>Electrical Supply</th><th>Water Supply & Wa</th></tr>
<tr><td>Kitchen cycle time</td><td></td><td></td><td></td></tr>
<tr><td>Kitchen Style (grade</td><td>0.4</td><td></td><td></td></tr>
<tr><td>Kitchen Layout (one</td><td></td><td></td><td></td></tr>
<tr><td>Supplier (3-4 supplie</td><td>0.24</td><td></td><td></td></tr>
</table></td><td>
<table>
<tr><th>KITCHEN INST</th><th>Appliances</th><th>Electrical Supply</th><th>Water Supply & Wa</th></tr>
<tr><td>Kitchen cycle time</td><td>0.53</td><td>0.02</td><td>0.02</td></tr>
<tr><td>Kitchen Style (grad</td><td>0.58</td><td>0.02</td><td>0.02</td></tr>
<tr><td>Kitchen Layout (one</td><td>0.52</td><td>0.02</td><td>0.02</td></tr>
<tr><td>Supplier (3-4 suppl</td><td>0.44</td><td>0.01</td><td>0.01</td></tr>
</table></td><td>All *Kitchen Requirements* are at risk through changes on *Appliances*.

"The *Appliances* don't have direct connections on the *Kitchen Assembly Cycle Time* and *Kitchen Layout* however indirect connections between them are 53% and 52%; Maybe kitchen cycle time appointed these results. Changing the *Appliances,* for instance, rather put this dishwasher instead of another dishwasher it shouldn't have the direct effect on how the dishwasher probably there are factors taken over it. Changes *Appliances* rather than putting in different dishwasher here it shouldn't have a direct effect on the kitchen delivery time".</td></tr>
<tr><td>3</td><td>
<table>
<tr><th>KITCHEN ASSEMBLY PROCESS</th><th>Kitchen units are su</th><th>Place kitchen bank</th><th>Kitchen Smartwalls</th><th>Kitchen Units conne</th><th>Pipework and electr</th><th>Install splashback</th></tr>
<tr><td>Kitchen cycle time</td><td>0.24</td><td>0.09</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Kitchen Style (grade</td><td></td><td></td><td></td><td></td><td></td><td>0.09</td></tr>
<tr><td>Kitchen Layout (one</td><td></td><td>0.09</td><td></td><td>0.15</td><td></td><td></td></tr>
<tr><td>Supplier (3-4 supplie</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table></td><td>
<table>
<tr><th>KITCHEN ASSEMBLY PROCESS</th><th>Kitchen units are su</th><th>Place kitchen bank</th><th>Kitchen Smartwalls</th><th>Kitchen Units conne</th><th>Pipework and electr</th><th>Install splashback</th></tr>
<tr><td>Kitchen cycle time</td><td>0.39</td><td>0.36</td><td></td><td>0.27</td><td>0.17</td><td>0.3</td></tr>
<tr><td>Kitchen Style (grad</td><td>0.43</td><td>0.42</td><td></td><td>0.31</td><td>0.2</td><td>0.3</td></tr>
<tr><td>Kitchen Layout (on</td><td>0.37</td><td>0.37</td><td></td><td>0.29</td><td>0.16</td><td>0.31</td></tr>
<tr><td>Supplier (3-4 suppl</td><td>0.36</td><td>0.36</td><td></td><td>0.25</td><td>0.15</td><td>0.33</td></tr>
</table></td><td>Changes to the process elements of *Kitchen units are supplied pre-assembly*. *Place kitchen bank of units into the module* cause unexpected change propagation on all elements of *the Kitchen Requirements*

"Probably the indirect connections on *Suppliers* are coming through from the design elements. When you back on the designer, *the bank of a unit* rather being in any kitchen could have an impact on the *Kitchen Style* which will not take from CAM assembly process cause directly doesn't affect us as long as come to *The bank of units*. When you look at the wider picture can understand the supply chain process. We described the direct effects on the assembly process due to suppliers of the</td></tr>
</table>

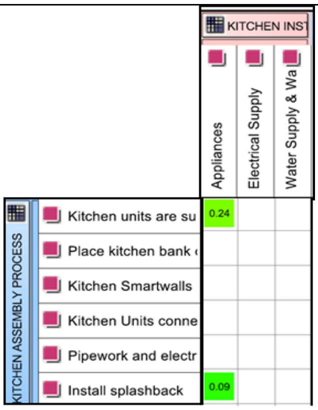
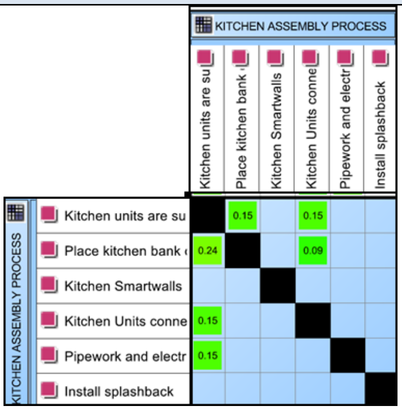
			kitchen in the condition to be assembled”.
4	 MANUFACTURING ORGAN Assembly Operator, Assembly Planner, Designer, Quality Controller, Factory Logistic KITCHEN REQUIREM Kitchen cycle time Kitchen Style (grade: Designer 0.4 Kitchen Layout (one: Designer 0.4, Factory Logistic 0.09 Supplier (3-4 suppli: Designer 0.4	 MANUFACTURING ORGAN Assembly Operator, Assembly Planner, Designer, Quality Controller, Factory Logistic KITCHEN REQUIREM Kitchen cycle time: 0.08, 0.07, 0.67, 0.3, 0.25 Kitchen Style (grade: 0.1, 0.08, 0.74, 0.36, 0.29 Kitchen Layout (one: 0.08, 0.06, 0.7, 0.3, 0.24 Supplier (3-4 suppli: 0.08, 0.06, 0.7, 0.31, 0.23	Extremely undesirable change propagation from *Designer* to the all *Kitchen Requirement* elements. “I would expect that if we change the *Designer* overall impact of the *Kitchen Requirements*. Changing *Designer* means that the designer influences the other elements”.
No	**The input data (the direct connected Risk=Likelihood x Impact values)**	**The CPM Algorithm results (the indirectly connected risk values)**	**Comparison of the input data and final results with Laing O’Rourke**
5	 KITCHEN REQUIREN Kitchen cycle time, Kitchen Style (grade, Kitchen Layout (one, Supplier (3-4 suppli KITCHEN INST Appliances: Kitchen Style 0.4, Kitchen Layout 0.09, Supplier 0.09 Electrical Supply: Kitchen cycle time 0.09, Kitchen Layout 0.09 Water Supply & Wa: Kitchen cycle time 0.09, Kitchen Layout 0.09	 KITCHEN REQUIREN Kitchen cycle time, Kitchen Style (grade, Kitchen Layout (one, Supplier (3-4 suppli KITCHEN INST Appliances: 0.58, 0.69, 0.3, 0.44 Electrical Supply: 0.58, 0.64, 0.39, 0.43 Water Supply & Wa: 0.56, 0.61, 0.38, 0.41	*Kitchen Installation* elements at high risk from changes to *Kitchen Style* and *Kitchen cycle time.* *“*Changing the *Kitchen Style* that has quite an impact on the *Appliances* directly. This gives us a direction, for instance, *Kitchen Style* changes on a low ends council type houses flats may not costly, but we don’t have it change in the high rent private rental then you get a big impact. The direct impact 40% would be right everything else will come along with that results”
6	 KITCHEN INST Appliances, Electrical Supply, Water Supply & Wa KITCHEN INST Appliances Electrical Supply: Appliances 0.09 Water Supply & Wa: Appliances 0.09	 KITCHEN INST Appliances, Electrical Supply, Water Supply & Wa KITCHEN INST Appliances: Electrical Supply 0.02, Water Supply & Wa 0.02 Electrical Supply: Appliances 0.64, Water Supply & Wa 0.02 Water Supply & Wa: Appliances 0.62, Electrical Supply 0.02	Changes to *Appliances* can seriously affect the other *Kitchen Installation* elements “Which is I was expected to see on *Appliances* develop high risks on *Electrical Supply* and *Water supply & Wastewater*”.

<table>
<tr>
<td>7</td>
<td>
<table>
<tr><th></th><th colspan="6">KITCHEN ASSEMBLY PROCESS</th></tr>
<tr><th>KITCHEN INST</th><th>Kitchen units are su</th><th>Place kitchen bank</th><th>Kitchen Smartwalls</th><th>Kitchen Units conne</th><th>Pipework and electr</th><th>Install splashback</th></tr>
<tr><td>Appliances</td><td>0.24</td><td>0.15</td><td></td><td></td><td>0.15</td><td></td></tr>
<tr><td>Electrical Supply</td><td>0.15</td><td></td><td></td><td>0.09</td><td>0.15</td><td>0.09</td></tr>
<tr><td>Water Supply & Wa</td><td>0.15</td><td></td><td></td><td>0.09</td><td>0.15</td><td></td></tr>
</table></td>
<td>
<table>
<tr><th></th><th colspan="6">KITCHEN ASSEMBLY PROCESS</th></tr>
<tr><th>KITCHEN INST</th><th>Kitchen units are su</th><th>Place kitchen bank</th><th>Kitchen Smartwalls</th><th>Kitchen Units conne</th><th>Pipework and electr</th><th>Install splashback</th></tr>
<tr><td>Appliances</td><td>0.48</td><td>0.43</td><td></td><td>0.33</td><td>0.18</td><td>0.4</td></tr>
<tr><td>Electrical Supply</td><td>0.48</td><td>0.47</td><td></td><td>0.37</td><td>0.3</td><td>0.41</td></tr>
<tr><td>Water Supply & Wa</td><td>0.46</td><td>0.45</td><td></td><td>0.35</td><td>0.29</td><td>0.35</td></tr>
</table></td>
<td><i>The Kitchen Installation</i> elements are at high risk especially if changes are made to <i>Kitchen units are supplied pre-assembled in a bank</i>, <i>Place kitchen bank of units into the module</i> and <i>Install splashback.</i>

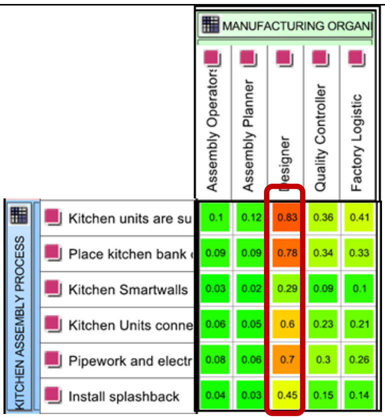
“Its big numbers but I wouldn’t say wrong. If we change what is a unit in effect all the changes are in different degrees it could have effected on target plan to where <i>Electrical Supply</i> and <i>Water Supply</i> & <i>Waste</i> feed, if <i>Kitchen bank of units</i> where are the pluming bank of units if we change that then obviously we don’t have plumbing giving up the bank of units rather than somewhere else. The indirect effects on the other processes to get the water and electric to feed the bank of units. It is a difficult one.”</td>
</tr>
<tr>
<td>8</td>
<td>
<table>
<tr><th></th><th colspan="5">MANUFACTURING ORGANI</th></tr>
<tr><th>KITCHEN INST</th><th>Assembly Operators</th><th>Assembly Planner</th><th>Designer</th><th>Quality Controller</th><th>Factory Logistic</th></tr>
<tr><td>Appliances</td><td></td><td></td><td>0.15</td><td></td><td></td></tr>
<tr><td>Electrical Supply</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Water Supply & Wa</td><td></td><td></td><td></td><td></td><td></td></tr>
</table></td>
<td>
<table>
<tr><th></th><th colspan="5">MANUFACTURING ORGANI</th></tr>
<tr><th>KITCHEN INST</th><th>Assembly Operators</th><th>Assembly Planner</th><th>Designer</th><th>Quality Controller</th><th>Factory Logistic</th></tr>
<tr><td>Appliances</td><td>0.11</td><td>0.09</td><td>0.79</td><td>0.38</td><td>0.3</td></tr>
<tr><td>Electrical Supply</td><td>0.1</td><td>0.08</td><td>0.79</td><td>0.38</td><td>0.31</td></tr>
<tr><td>Water Supply & Wa</td><td>0.1</td><td>0.08</td><td>0.77</td><td>0.36</td><td>0.3</td></tr>
</table></td>
<td>Undesirable change propagation to all <i>Kitchen Installation</i> elements is associated with a change in <i>Designer.</i>

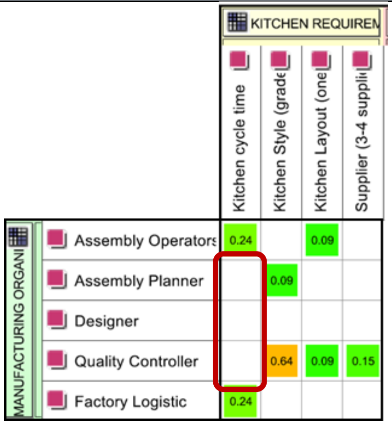
“We know why the <i>Designer</i> behind the risk of <i>Kitchen Installation.</i> Previously the Dishwasher and Washing machine was not in the factory but now it is in the factory. So Appliances effected by the <i>Designer</i>. Then If you change <i>Appliances</i> or the location of appliances, it would affect <i>Electrical Supply</i> and <i>Water Supply</i>. So If you have any change on <i>Quality Control</i> and <i>Factory Logistics</i> person then the kitchen installation can be quite affected indirectly.”</td>
</tr>
<tr>
<td>9</td>
<td>
<table>
<tr><th></th><th colspan="4">KITCHEN REQUIREM</th></tr>
<tr><th>KITCHEN ASSEMBLY PROCESS</th><th>Kitchen cycle time</th><th>Kitchen Style (grade</th><th>Kitchen Layout (one</th><th>Supplier (3-4 supplie</th></tr>
<tr><td>Kitchen units are su</td><td>0.09</td><td></td><td></td><td>0.15</td></tr>
<tr><td>Place kitchen bank</td><td>0.15</td><td></td><td>0.15</td><td></td></tr>
<tr><td>Kitchen Smartwalls</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Kitchen Units conne</td><td>0.09</td><td></td><td></td><td></td></tr>
<tr><td>Pipework and electr</td><td>0.25</td><td></td><td></td><td></td></tr>
<tr><td>Install splashback</td><td></td><td></td><td></td><td></td></tr>
</table></td>
<td>
<table>
<tr><th></th><th colspan="4">KITCHEN REQUIREM</th></tr>
<tr><th>KITCHEN ASSEMBLY PROCESS</th><th>Kitchen cycle time</th><th>Kitchen Style (grade</th><th>Kitchen Layout (one</th><th>Supplier (3-4 supplie</th></tr>
<tr><td>Kitchen units are su</td><td>0.59</td><td>0.67</td><td>0.38</td><td>0.45</td></tr>
<tr><td>Place kitchen bank</td><td>0.57</td><td>0.61</td><td>0.37</td><td>0.43</td></tr>
<tr><td>Kitchen Smartwalls</td><td>0.18</td><td>0.17</td><td>0.11</td><td>0.12</td></tr>
<tr><td>Kitchen Units conne</td><td>0.38</td><td>0.41</td><td>0.25</td><td>0.28</td></tr>
<tr><td>Pipework and elecr</td><td>0.49</td><td>0.52</td><td>0.31</td><td>0.36</td></tr>
<tr><td>Install splashback</td><td>0.28</td><td>0.3</td><td>0.16</td><td>0.2</td></tr>
</table></td>
<td>Any changes to the elements of <i>Kitchen Requirement</i> will impact on the elements of the <i>Kitchen Assembly Process</i> except the <i>Kitchen Smartwall</i>.

“If we change the <i>Kitchen assembly cycle time</i> so we go from probably we don’t need to <i>Suppliers</i> in <i>the bank of units</i> which would have quite an indirect impact. If you change the <i>Kitchen Style</i> to one which didn't suit <i>the bank of units</i> it could have quite impacted on very use of elements. If change a supplier to a new supplier, it could have a direct impact hired kitchen comes in rather being the bank of four units or bank of three units. We also by end up paying extra or maybe extra design worker works on that. <i>Kitchen units</i> connected <i>Kitchen Style</i> that it is drastic changes the style of different connection types so different connection points which means the connections which line</td>
</tr>
</table>

			back of the connections that sort of changes”
10			Changes on *Appliances* affect all elements of the *Kitchen Assembly Process*. “If we change *Appliances*, the kitchen units come in one big bank, if we change dishwasher in the middle of the process then we need to separate banks of space, so direct effect 24%, but indirect effects that would be twice as long it takes units that one. I think that effect the assembly cycle time.”
No	**The input data (the direct connected Risk=Likelihood x Impact values)**	**The CPM Algorithm results (the indirectly connected risk values)**	**Comparison of the input data and final results with Laing O’Rourke**
11			Direct changes to only a few elements of the *Kitchen Assembly* process create an indirect impact on the other process elements. “*Install splashback* not sure where it is come from, potentially part of the designer or supplier type. Genuinely speak last things to do. 49% and 50% connections that on the top left; I was expected. The results in the first two columns (32%, 33%, 39%, 40%): If you get units first line bank of units than you have got more connection make in it. if I don’t get a house of kitchen units, we affect the bank of units, potentially we can get more connections. *Place kitchen bank of the unit* is quite close to *Kitchen units are supplied*. The matrix picked it up where we do not get the connections. The questions are doing it worth if changes the missing direct connections on the second column of *Kitchen units’ connections* and *Pipework and electrical* connections.

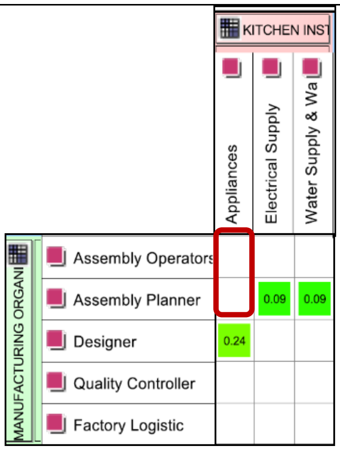
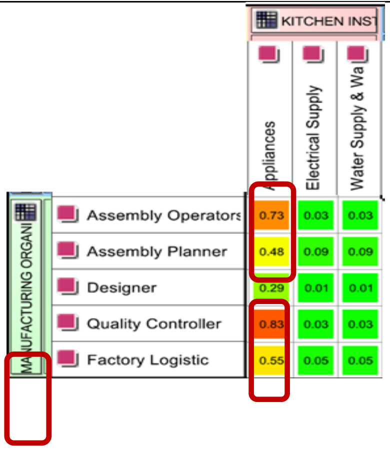
<table>
<tr>
<td>12</td>
<td>

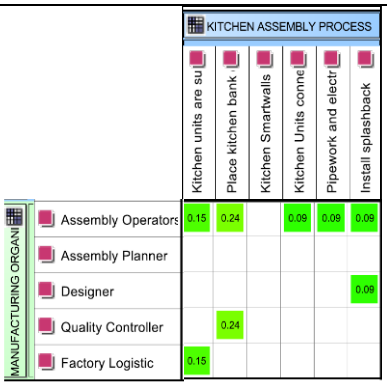
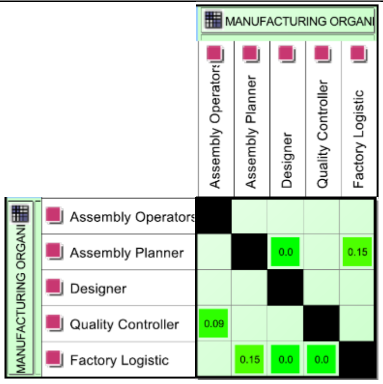
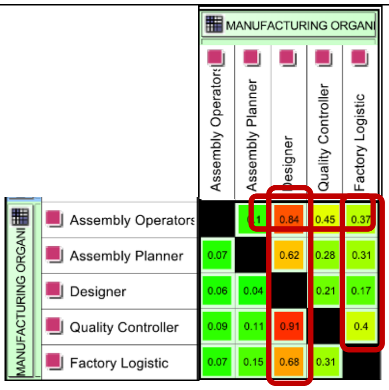
<table>
<tr><th colspan="6">MANUFACTURING ORGANI</th></tr>
<tr><th>KITCHEN ASSEMBLY PROCESS</th><th>Assembly Operators</th><th>Assembly Planner</th><th>Designer</th><th>Quality Controller</th><th>Factory Logistic</th></tr>
<tr><td>Kitchen units are su</td><td></td><td>0.0</td><td></td><td>0.09</td><td>0.24</td></tr>
<tr><td>Place kitchen bank</td><td>0.0</td><td></td><td></td><td>0.09</td><td>0.15</td></tr>
<tr><td>Kitchen Smartwalls</td><td>0.0</td><td></td><td></td><td>0.09</td><td></td></tr>
<tr><td>Kitchen Units conne</td><td>0.0</td><td></td><td></td><td>0.09</td><td></td></tr>
<tr><td>Pipework and electr</td><td>0.0</td><td></td><td></td><td>0.09</td><td></td></tr>
<tr><td>Install splashback</td><td>0.0</td><td></td><td></td><td>0.09</td><td></td></tr>
</table>
</td>
<td>

<table>
<tr><th colspan="6">MANUFACTURING ORGANI</th></tr>
<tr><th>KITCHEN ASSEMBLY PROCESS</th><th>Assembly Operators</th><th>Assembly Planner</th><th>Designer</th><th>Quality Controller</th><th>Factory Logistic</th></tr>
<tr><td>Kitchen units are su</td><td>0.1</td><td>0.12</td><td>0.83</td><td>0.36</td><td>0.41</td></tr>
<tr><td>Place kitchen bank</td><td>0.09</td><td>0.09</td><td>0.78</td><td>0.34</td><td>0.33</td></tr>
<tr><td>Kitchen Smartwalls</td><td>0.03</td><td>0.02</td><td>0.29</td><td>0.09</td><td>0.1</td></tr>
<tr><td>Kitchen Units conne</td><td>0.06</td><td>0.05</td><td>0.6</td><td>0.23</td><td>0.21</td></tr>
<tr><td>Pipework and electr</td><td>0.08</td><td>0.06</td><td>0.7</td><td>0.3</td><td>0.26</td></tr>
<tr><td>Install splashback</td><td>0.04</td><td>0.03</td><td>0.45</td><td>0.15</td><td>0.14</td></tr>
</table>
</td>
<td>Unexpected change propagations occurring on all elements of the <i>Kitchen Assembly Process</i> is associated with change on <i>Designer</i>.

“The indirect impact of the <i>Designer</i> is huge which is probably right, I mean we wouldn’t any direct changes we want the <i>Designer</i> to be able to directly impact on the assembly process. The element of <i>Designer</i> itself changing elements of all over products. For example, we order walls going to modules we always bang on the floor of the internal walls then the long walls, short walls and ceiling. When we change the design sequence would affect what we order. The <i>Assembly Planner</i> in my eyes the person who decide to build production sequences, the direct effects should be zero the order we make module shouldn’t affect how we make modules. It may be good to explain the roles of the organisations.”</td>
</tr>
<tr>
<th>No</th>
<th>The input data
(the direct connected Risk=Likelihood x Impact values)</th>
<th>The CPM Algorithm results
(the indirectly connected risk values)</th>
<th>Comparison of the input data and final results with Laing O’Rourke</th>
</tr>
<tr>
<td>13</td>
<td>

<table>
<tr><th colspan="5">KITCHEN REQUIREN</th></tr>
<tr><th>MANUFACTURING ORGANI</th><th>Kitchen cycle time</th><th>Kitchen Style (grade</th><th>Kitchen Layout (one</th><th>Supplier (3-4 supplie</th></tr>
<tr><td>Assembly Operators</td><td>0.24</td><td></td><td>0.09</td><td></td></tr>
<tr><td>Assembly Planner</td><td></td><td>0.09</td><td></td><td></td></tr>
<tr><td>Designer</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Quality Controller</td><td></td><td>0.64</td><td>0.09</td><td>0.15</td></tr>
<tr><td>Factory Logistic</td><td>0.24</td><td></td><td></td><td></td></tr>
</table>
</td>
<td>

<table>
<tr><th colspan="5">KITCHEN REQUIREN</th></tr>
<tr><th>MANUFACTURING ORGANI</th><th>Kitchen cycle time</th><th>Kitchen Style (grade</th><th>Kitchen Layout (one</th><th>Supplier (3-4 supplie</th></tr>
<tr><td>Assembly Operators</td><td>0.67</td><td>0.7</td><td>0.44</td><td>0.48</td></tr>
<tr><td>Assembly Planner</td><td>0.43</td><td>0.46</td><td>0.28</td><td>0.32</td></tr>
<tr><td>Designer</td><td>0.36</td><td>0.44</td><td>0.2</td><td>0.28</td></tr>
<tr><td>Quality Controller</td><td>0.7</td><td>0.81</td><td>0.44</td><td>0.56</td></tr>
<tr><td>Factory Logistic</td><td>0.49</td><td>0.51</td><td>0.31</td><td>0.35</td></tr>
</table>
</td>
<td>The highest risks are to <i>Assembly Operators</i> and <i>Quality Controller</i> if changes are made on all the elements of <i>Kitchen Requirements.</i> Additionally, changes to <i>Kitchen cycle time</i> and <i>Kitchen Style</i> indirectly have a high impact on all elements of the <i>Manufacturing Organisation.</i>

“On the top of the left: <i>Kitchen cycles time</i> against the <i>Assembly Operators</i>. "The quicker works by the operators may reduce the cycle time". Changes <i>Kitchen cycle time</i> against <i>the Assembly Planner</i>: the direct effect has on that individual doing the job does not link. The indirect effect of having to change of the cycle time to the planning processes is more on the <i>Assembly Planner</i> if we change the cycle time still do the same activities indirectly, we need to do same activities indirect effect of.
<i>Kitchen Requirements</i> always an indirect effect on the <i>Quality Controller</i>. I am not sure we missed or consider the numbers of the <i>Kitchen Cycle Time</i> against the <i>Designer</i> and <i>QC</i> because you should never plan to cycle time</td>
</tr>
</table>

<table>
<tr>
<td></td>
<td></td>
<td></td>
<td>affect the quality. A general principle we all have QC after every operation step because we couldn't afford it. Every operation has cycle time but the factory has takt time 10min. I don't know where the number is 70% coming from between <i>Kitchen Style</i> and <i>Assembly Operators</i>. Changing <i>Kitchen Style</i> shouldn't affect the designer; the Designer should affect the Kitchen Style.
<i>Factory Logistic</i> should expect when the kitchen arriving at the work, the style of the kitchen shouldn't affect directly. I can understand what indirect effect: if say when from solid granule worktop being indirectly the effect of it.
Previously <i>Kitchen Layout</i> did have quite impact on the certain elements which would have a direct impact on the process back on the people. <i>Kitchen bank of units</i> coming from the different <i>Suppliers</i> which could affect the <i>Assembly Operators</i> indirectly."</td>
</tr>
<tr>
<td>14</td>
<td>
<table>
<tr><td>MANUFACTURING ORGANI</td><td>KITCHEN INST
Appliances</td><td>Electrical Supply</td><td>Water Supply & Wa</td></tr>
<tr><td>Assembly Operators</td><td></td><td></td><td></td></tr>
<tr><td>Assembly Planner</td><td></td><td>0.09</td><td>0.09</td></tr>
<tr><td>Designer</td><td>0.24</td><td></td><td></td></tr>
<tr><td>Quality Controller</td><td></td><td></td><td></td></tr>
<tr><td>Factory Logistic</td><td></td><td></td><td></td></tr>
</table></td>
<td>
<table>
<tr><td>MANUFACTURING ORGANI</td><td>KITCHEN INST
Appliances</td><td>Electrical Supply</td><td>Water Supply & Wa</td></tr>
<tr><td>Assembly Operators</td><td>0.73</td><td>0.03</td><td>0.03</td></tr>
<tr><td>Assembly Planner</td><td>0.48</td><td>0.09</td><td>0.09</td></tr>
<tr><td>Designer</td><td>0.29</td><td>0.01</td><td>0.01</td></tr>
<tr><td>Quality Controller</td><td>0.83</td><td>0.03</td><td>0.03</td></tr>
<tr><td>Factory Logistic</td><td>0.55</td><td>0.05</td><td>0.05</td></tr>
</table></td>
<td>Unexpected highest risks are to <i>Assembly Operators</i> and <i>Quality Controller</i> if changes are made to the <i>Appliances</i>.
"This is quite interesting; we missed the direct link but software picked the numbers. We might miss the numbers on the first line on the left-hand side. <i>Appliances</i> on the <i>Quality Controller</i> could be linked back to connections to <i>Water Supply & Waste</i> and <i>Electrical Supply</i>.
<i>Factory Logistics:</i> if not received the appliances than the logistics impact on that. <i>Assembly Operators</i>: you got to more difficult in <i>Appliances</i>. I was expected less on the <i>Assembly Planner</i> but still, know what would it affect. Based on the indirect matrix we cannot say <i>Appliances</i> is more concern but more get to do."The expert suggested that for another trial: to put in a number for AO/ AP/ FL/ QC: 0.3 Likelihood and 0.5 Impact.</td>
</tr>
</table>

<table>
<tr>
<td>15</td>
<td>
<table>
<tr><td></td><td colspan="6">KITCHEN ASSEMBLY PROCESS</td></tr>
<tr><td>MANUFACTURING ORGANI</td><td>Kitchen units are su</td><td>Place kitchen bank</td><td>Kitchen Smartwalls</td><td>Kitchen Units conne</td><td>Pipework and electr</td><td>Install splashback</td></tr>
<tr><td>Assembly Operators</td><td>0.15</td><td>0.24</td><td></td><td>0.09</td><td>0.09</td><td>0.09</td></tr>
<tr><td>Assembly Planner</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Designer</td><td></td><td></td><td></td><td></td><td></td><td>0.09</td></tr>
<tr><td>Quality Controller</td><td></td><td>0.24</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Factory Logistic</td><td>0.15</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>
</td>
<td>
<table>
<tr><td></td><td colspan="6">KITCHEN ASSEMBLY PROCESS</td></tr>
<tr><td>MANUFACTURING ORGANI</td><td>Kitchen units are su</td><td>Place kitchen bank</td><td>Kitchen Smartwalls</td><td>Kitchen Units conne</td><td>Pipework and electr</td><td>Install splashback</td></tr>
<tr><td>Assembly Operators</td><td>0.56</td><td>0.58</td><td></td><td>0.42</td><td>0.27</td><td>0.43</td></tr>
<tr><td>Assembly Planner</td><td>0.36</td><td>0.35</td><td></td><td>0.26</td><td>0.17</td><td>0.27</td></tr>
<tr><td>Designer</td><td>0.27</td><td>0.26</td><td></td><td>0.19</td><td>0.1</td><td>0.2</td></tr>
<tr><td>Quality Controller</td><td>0.6</td><td>0.63</td><td></td><td>0.42</td><td>0.27</td><td>0.46</td></tr>
<tr><td>Factory Logistic</td><td>0.39</td><td>0.39</td><td></td><td>0.28</td><td>0.18</td><td>0.31</td></tr>
</table>
</td>
<td>When changes on all elements of the <i>Kitchen Assembly Process; Assembly Operator</i> and <i>Quality Controller</i> are more affected elements of the <i>Manufacturing Organisation.</i>
“The missing for <i>Quality Controller</i> 0.3/0.7 to all <i>Kitchen Assembly Process</i> elements. Why <i>Kitchen Smartwalls</i> has no numbers at all on the vertical side. I think the column empty that ways: if we change the wall behind the kitchen that might affect the kitchen next to if we change the kitchen against the wall might be effected on highly. It is a difficult one; there is a hard number on the first matrix and the second one almost all elements connected indirectly.”</td>
</tr>
<tr>
<td>16</td>
<td>
<table>
<tr><td></td><td colspan="5">MANUFACTURING ORGANI</td></tr>
<tr><td>MANUFACTURING ORGANI</td><td>Assembly Operators</td><td>Assembly Planner</td><td>Designer</td><td>Quality Controller</td><td>Factory Logistic</td></tr>
<tr><td>Assembly Operators</td><td>■</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Assembly Planner</td><td></td><td>■</td><td>0.0</td><td></td><td>0.15</td></tr>
<tr><td>Designer</td><td></td><td></td><td>■</td><td></td><td></td></tr>
<tr><td>Quality Controller</td><td>0.09</td><td></td><td></td><td>■</td><td></td></tr>
<tr><td>Factory Logistic</td><td></td><td>0.15</td><td>0.0</td><td>0.0</td><td>■</td></tr>
</table>
</td>
<td>
<table>
<tr><td></td><td colspan="5">MANUFACTURING ORGANI</td></tr>
<tr><td>MANUFACTURING ORGANI</td><td>Assembly Operators</td><td>Assembly Planner</td><td>Designer</td><td>Quality Controller</td><td>Factory Logistic</td></tr>
<tr><td>Assembly Operators</td><td>■</td><td>0.1</td><td>0.84</td><td>0.45</td><td>0.37</td></tr>
<tr><td>Assembly Planner</td><td>0.07</td><td>■</td><td>0.62</td><td>0.28</td><td>0.31</td></tr>
<tr><td>Designer</td><td>0.06</td><td>0.04</td><td>■</td><td>0.21</td><td>0.17</td></tr>
<tr><td>Quality Controller</td><td>0.09</td><td>0.11</td><td>0.91</td><td>■</td><td>0.4</td></tr>
<tr><td>Factory Logistic</td><td>0.07</td><td>0.15</td><td>0.68</td><td>0.31</td><td>■</td></tr>
</table>
</td>
<td><i>All elements of the Manufacturing Organisation</i> are extremely affected by changes in <i>Designer</i>. Changes to <i>Quality Controller</i> and <i>Factory Logistic</i> affect <i>Assembly Operators, Assembly Planner</i> and <i>Quality Controller.</i>
Any changes on the <i>Designer</i> might indirectly affect the <i>Manufacturing Organisation</i> in the information level. <i>Factory Logistic:</i> if you change <i>Quality Controller</i>, for instance, when you stop checking the product or process control that might have an impact on the <i>Factory Logistics.</i> However, where material delivered from the supplier to the factory side, there is no link to the <i>Quality Controller. Assembly Operator:</i> If you change <i>Designer</i> activities these not directly affect <i>Operator</i> differently. It may affect when the way of designing the kitchen differently.</td>
</tr>
</table>

The risk model for decision making

In this case study, “*Kitchen assembly cycle time”* (1) is selected as a specific change option and a possible scenario created. After the reduction of the kitchen assembly cycle time how to manage change propagation was discussed. The connections of KAS can be mapped onto a combined risk plot by using CAM software which enables the user to simultaneously change the characteristics of the direct relationships between elements and evaluate the impact of these changes on the indirect relationships. that fall within the top-left region of the *Combined Risk Plot* (Figure 7.9) have a low likelihood of change propagation but will incur a high amount of redesign effort if a change is required. Therefore, elements that fall within this region should be standardised. If a change is required, the connectivity between these elements and the rest of the elements should be reduced to further decrease the likelihood of changes through propagation. The elements that fall within the bottom-right region of the risk plot (Figure 7.9) have a high likelihood of change propagation but require a low amount of effort if a change is required. Therefore, if a change is required, these components can be redesigned as flexible elements. This is to reduce the impact of future changes, as these elements are very likely to be changed. The elements that fall within the bottom-left region have low likelihood and impact of change propagation. These are the least critical elements and platform strategies are optional. The elements with the number are listed in Table 7.3.

Table 7.3: Elements of the Kitchen Assembly Cycle Time

Element No	Elements
1	Kitchen Assembly Cycle Time
2	Kitchen Style (grade of quality)
3	Kitchen Layout
4	Suppliers
5	Appliances
6	Electrical Supply
7	Water Supply & Waste
8	Kitchen units are supplied pre-assembled in a bank from the manufacturer
9	Place kitchen bank of units into the module
10	Kitchen smartwalls in the module
11	Kitchen units connected to smartwall and each other
12	Pipework and electrics connected between wall and units
13	Install splashback
14	Assembly Operators
15	Assembly Planner
16	Designer
17	Quality Controller
18	Factory Logistics

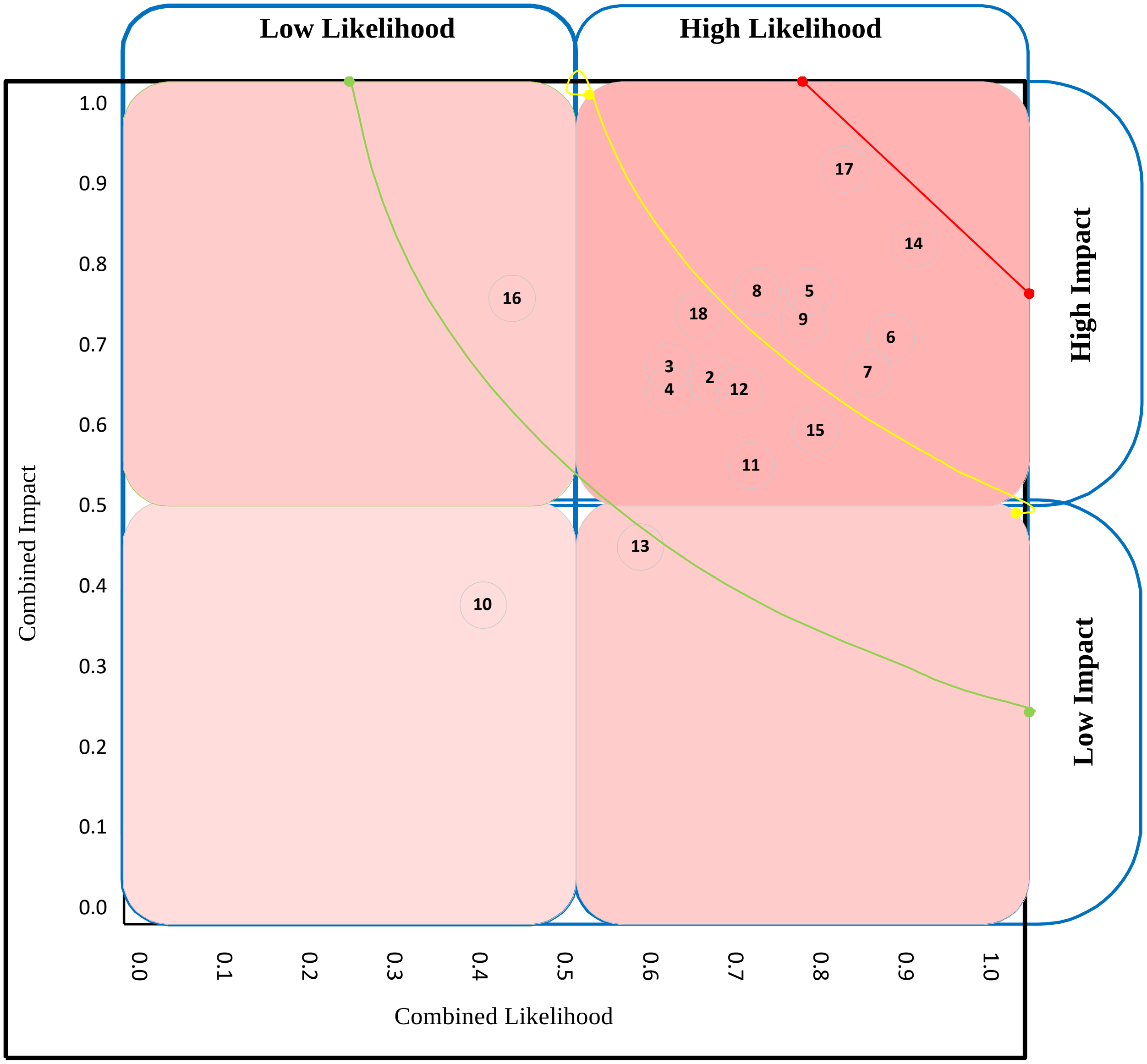


Figure 7.9: The combined risk plot to the kitchen cycle time (Element 1)

In this plot, any elements are placed above or to the right of other system elements have a relatively higher change impact or likelihood and are, therefore, more subject to change. System elements with high axis plot have a high impact on other system elements and so should be made more resistant to change to avoid propagating further changes to others. System elements lower down do not affect other system elements as much and therefore changes to them are easier to accommodate. Overall, the proposed approach reflected an acceptable outcome in addressing change propagation prediction in the kitchen assembly system. Providing reliable MLN (avoiding unnecessary connectivity) data and the collected data associated with likelihoods and impacts in CPM can affect the performance of the model.

The CPM approach presented in this section enables a designer to explore a scenario for how changes on *"Kitchen Assembly Cycle Time*" (1) element can affect the other elements and overall system performance. The key relationships in a large system are often over multiple levels across different layers. It can be seen from the Figure 7.9, the "Combined impacts (CI) versus combined likelihood (CL)" chart, that those system elements such as "*Kitchen smartwall in the module*"(10) and "*Install Splashback*"(13) have low CI and CL, suggesting that these elements have less change impact compared with the rest of system elements. Therefore, this could suggest that these two elements are suitable for standardization. On the other hand, "*Designer*"(16) has high CI and low CL value which suggests that although they are not very likely to change if the change is required it should be considered with caution. Approaches to reduce the impact of changing the Designer can also be considered; however, the benefit of doing this would be minimal as the likelihood of change is quite small. Possible suggestions for system elements with moderate CI and CL are less clear.

The system elements in the upper right quadrant of the risk plot (Figure 7.9) such as "*Quality Controller" (17), "Assembly Operator"(14), and "Kitchen units are supplied pre-assembled in a bank from the manufacturer" (8)* are most likely to be changed and have a high change impact if a change is required. The expert's comment makes sense with regard to why Quality Controller (17) has a high change impact if a change is required: effects of reducing cycle time on the quality can be missed during the planning stage. As a general principle, every operation has QC steps and may not be affordable. In addition that, the expert's review explains in a high change impact of *Assembly Operators (14*) when a change initiative on the Kitchen cycle time with the quicker works by the operators may reduce the cycle time. However, the expert commented that changes on the *Kitchen Assembly Cycle Time (1)* would have the most impact on the the *Kitchen Layout (3)* and *Suppliers (4)* indirectly than the other elements. On the other hand, E3 and E4 are still in the upper right quadrant of the risk plot (Figure 7.9) and they are likely to be affected.

The combined risk method can be used for the change propagation investigation. For every element, a prioritised list of all affected elements can be prepared based on the DSM direct connectivity. For example, Table 7.3 shows such a prioritised change risk list for "Kitchen assembly cycle time". The prioritised list may help to avoid oversight of change impacts on the high-risk elements. The list states that "*Quality Controller"(17), "Assembly Operator"(14). "Kitchen units are supplied pre-assembled in a bank from the manufacturer" (8), "Electrical Supply"(6), Appliances" (5) and "Water Supply & Waste"(7)* are at over 50% of the highest risk if the "Kitchen assembly cycle time"(1) changes. However, the connections to the elements in the mid-array of the risk values are not always clear because these elements are usually only indirectly connected.

Table 7.4: Prioritised change risk list for the change initiator: kitchen assembly cycle time (Element 1)

Priority No	Affected Elements		Risk value %
	Name	**Element No**	
1	**Quality Controller**	**17**	**70**
2	**Assembly Operator**	**14**	**66**
3	Kitchen units are supplied pre-assembled in a bank from the manufacturer	8	59
4	Electrical Supply	6	58
5	Appliances	5	58
6	Place kitchen bank of units into the module	9	57
7	Water supply & Waste	7	56
8	Pipework and electrics connected between wall and units	12	49
9	Factory Logistic	18	49
10	Kitchen Style	2	46
11	Supplier	4	46
12	Kitchen Layout	3	45
13	Assembly Planner	15	43
14	Kitchen Units connected to smartwall and each other	11	38
15	Designer	16	36
16	Install splashback	13	28
17	Kitchen smartwalls in the module	10	18

Figure 7.10 presents small, abstract system connectivity between "Kitchen assembly cycle time" and "Kitchen style" that consists of nine elements and eleven change propagation paths. This propagation path examination delivers the risk value of how initiating a change. It is important to understand that more connection exists. This figure does not contain direct impact values, and the method allows for a comparison of only the combined likelihood values computed by the CPM Algorithm. The shortest path length between E1 and E2 is shown with the green line, which indicates that the two elements are directly connected. The other coloured line shows the indirect connectivity between E1 and E2. The detail of the propagation paths analysis is stated in Chapter 8.

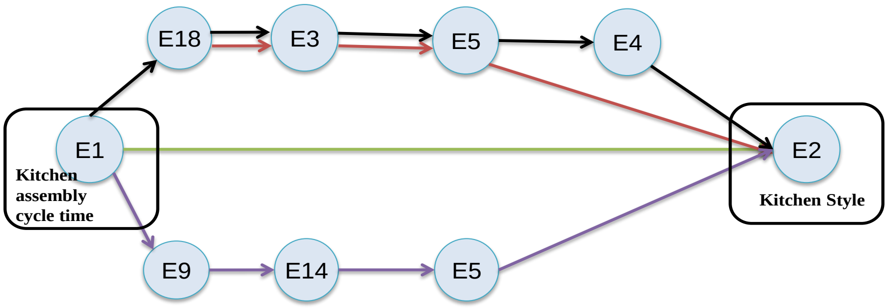


Figure 7.10: selected change propagation paths from kitchen assembly cycle time (E1) to kitchen style (E2)

7.3 *CS 2–Kitchen Design System in an E5+ Module Apartment,* LOR

The second case study focuses on the installation of kitchen design in an E5+ module apartment. Installing a kitchen in a module means that several individual kitchen units will be supplied to the assembly line and grouped in one assembly. There is, therefore, the potential to reduce the kitchen installation process by redesigning the individual units into a module apartment. Figure 7.11 shows the supply chain mapping for kitchen design system suppliers within the AMSCI (Advanced Manufacturing Supply Chain Initiative) partnership. Close collaboration is required with suppliers for the redesign of kitchen units, to take advantage of the increased factory installation. Such redesign has the potential to benefit the supplier, through reduced installation costs, and also Laing O'Rourke (LOR), through reduced installation time. It is therefore in the interests of both parties to work closely together in the development of such changes and a partnership helps to achieve this. The suggested supply chain for kitchen units is based on the capabilities of AMSCI partner Saint-Gobain, which owns both Jewson and Internal Decorating Services.

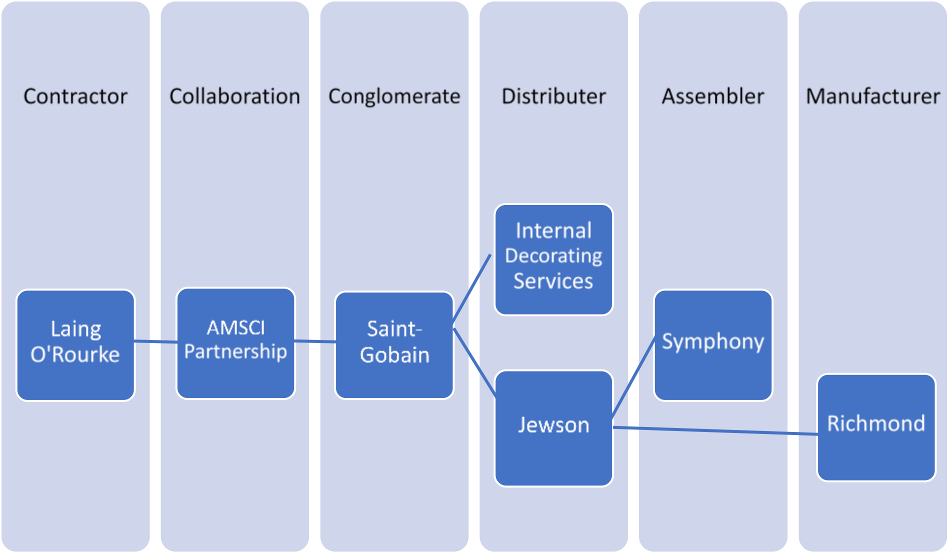


Figure 7.11: Kitchen design supply chain map (Bryden Wood 2015)

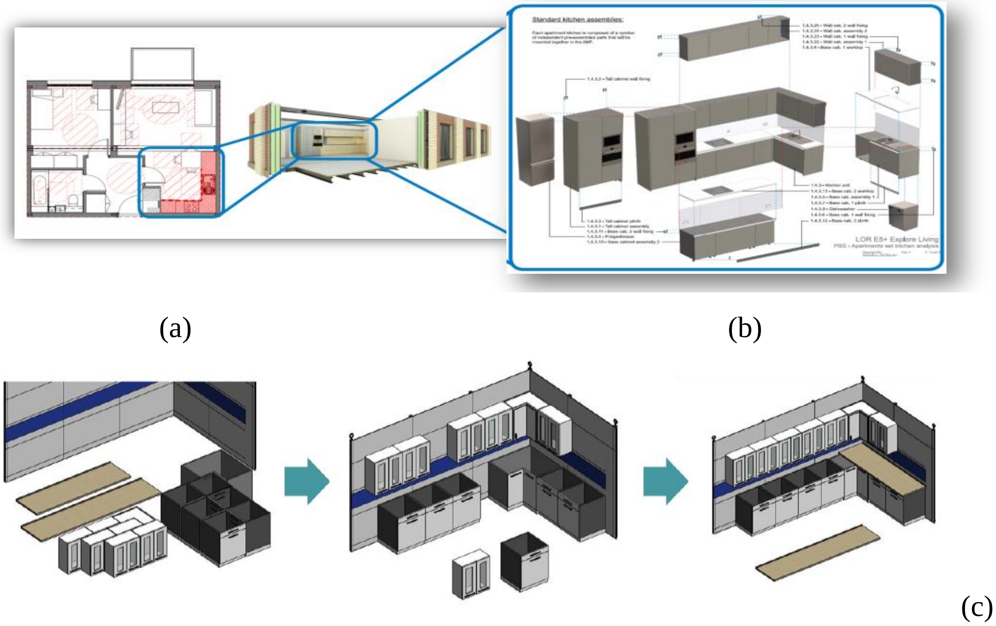
In this case study, there is a need for knowledge of and expertise in the kitchen design process to capture the constraints in the model by setting up a conceptual experiment to make an assumption. The challenge is to conceptually exercise flexibility before LOR fix the kitchen in their module apartments. The proposed model helps to visualise the impact of variation on the overall architecture of kitchen design. Basically, in the kitchen design experiment, the aim is to understand how the kitchen dimension is impacted by following different customer's design choices.

Discussions for this case study were held with representatives from Jewson and Internal Decorating Services to determine their ability to work in partnership for the E5+ project. The case study was assisted by Brian East who is a kitchen design expert at Jewson Ltd. Mr East is a Sector Director with 30 years of experience in kitchen design. The expert knowledge enabled constraints in the proposed model to be captured by setting up the conceptual experiment with reasonable starting assumptions.

During the beginning of the detail design phase of the system change method (SCM), a kitchen design project was developed to explore issues of feasibility as well as to uncover challenges and opportunities relating to employing the kitchen design system in practice. The proposed SCM can be applied in the design stage of a kitchen to take into account the implications of aspects such as kitchen installation, kitchen assembly process, and the manufacturing organisation. To investigate this, kitchen design and a solution for a kitchen design system scenario were modelled. The design of the 'E5+' building is based on an existing building that was constructed in a modular way (i.e. in a non-traditional way).

7.3.1 Decompose the system into layers and elements

The kitchen design architectures form a varying number of sub-systems, which make up the core structure and are customised features like the kitchen as a product, kitchen design process, and stakeholders. Building the model by defining the kitchen design sub-systems and elements helps to visualise the impact on the overall architecture of the kitchen design system. To aid in understanding the case study, Figure 7.12 (a) illustrates the E5+ module apartment plan with a fitted kitchen, Figure 7.12 (b) portrays the decomposition of an L-shaped kitchen into individual parts, and Figure 7.12 (c) illustrates the L-shaped kitchen installation steps (Bryden Wood 2015).



(a) (b)

(c)

Figure 7.12: Kitchen design system decomposition and integration on L-shape kitchen layout (Bryden Wood 2015)

The decomposition strategies provide customer preference options regarding different kitchen appliances or units. In terms of the variation that arises when fitting the kitchen units, what is the impact when a customer chooses a different type or size of fridge freezer, or if change the supplier is changed, what constraints may appear? The architecture of kitchen design decomposition criteria was a balance between a manageable number of elements and the right level of detail for meaningful analysis. Based on the discussion with the kitchen design expert, the case model was verified with 3 layers and 24 elements. The 3 layers are Kitchen, Kitchen Design Process, and Stakeholders and their elements are listed in Table 7.4.

7.3.2 Capture dependencies between layers and elements

In the second stage, the connection between elements and layers of the KDS was defined. The design changes and their knock-on effects onto the L-shape kitchen layout were reviewed with the kitchen design expert. 122 direct connections were developed by assessing the relations between 24 elements. Table 7.4 placed the identified direct connections between the elements for further specified indirect connections. Each direct connection between two elements could be made up of more than one connection and the expert indicated the likelihood and impact of change propagation on each connection as he analysed each connection. All layers, elements and connections were transferred into DSMs/DMMs to generate a multilayer network matrix (MLN).

Table 7.5: Dependency between the elements of the kitchen design system

No	**Elements (E)**	**Depends upon**
1	Tall cabinet assembly	16,17,18,20,21
2	Free standing (FF) USA	1,5,6,7,8,10,11,16
3	Free standing (FF) EU	1,5,6,7,8,10,11,16
4	Plinth	None
5	Base cabinet	1,4,6,7,8,11,16,17,18,20,21
6	Sink cabinet	1,4,5,7,8,11,16,17,18,20,21
7	Oven cabinet	1,4,5,6,8, 11,16,17,18,20,21
8	Draw unit (pac)	1,4,5,6,7,11,16,17,18,20,21
9	Worktop	19
10	Appliances	None
11	Wall cabinets	1,4,5,6,7,8,16,17,18,20,21
12	Cornice - pelmet	None
13	Electrical supply	2,3,7,10
14	Gas supply	2,3,7,10
15	Water supply & Waste	2,3,6,10
16	Fitting and Assembling a kitchen corner posts	24
17	Assembling kitchen cabinet	24
18	Fixing kitchen units to the wall	24
19	Cutting the worktops	24
20	Attaching kitchen doors and drawers	24
21	Fitting coordinated end panels	24
22	Suppliers	1,5,6,7,8,11,16,17,18,19,20,21
23	Customers	1,2,3,5,6,7,8,9,10,11,12,13,14,15,22
24	Installers	16,17,18,19,20,21

Figure 7.13 illustrates the complete interactive network for the developed kitchen design experiment, which represents the direct dependencies between the elements based on Table 7.4. A broad view of complex network relations supports understanding the architecture of kitchen design elements and how they are connected.

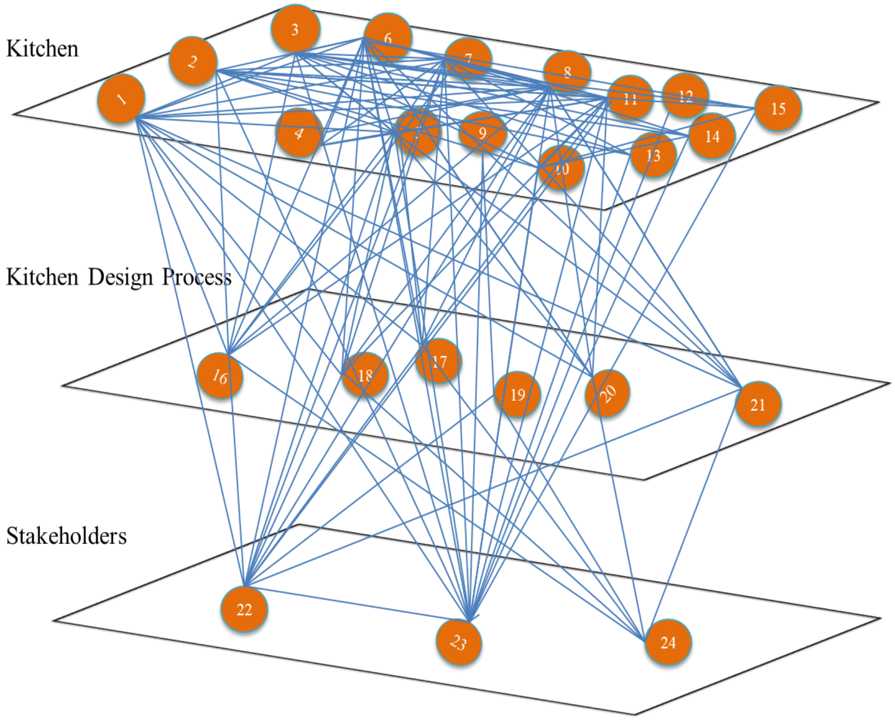
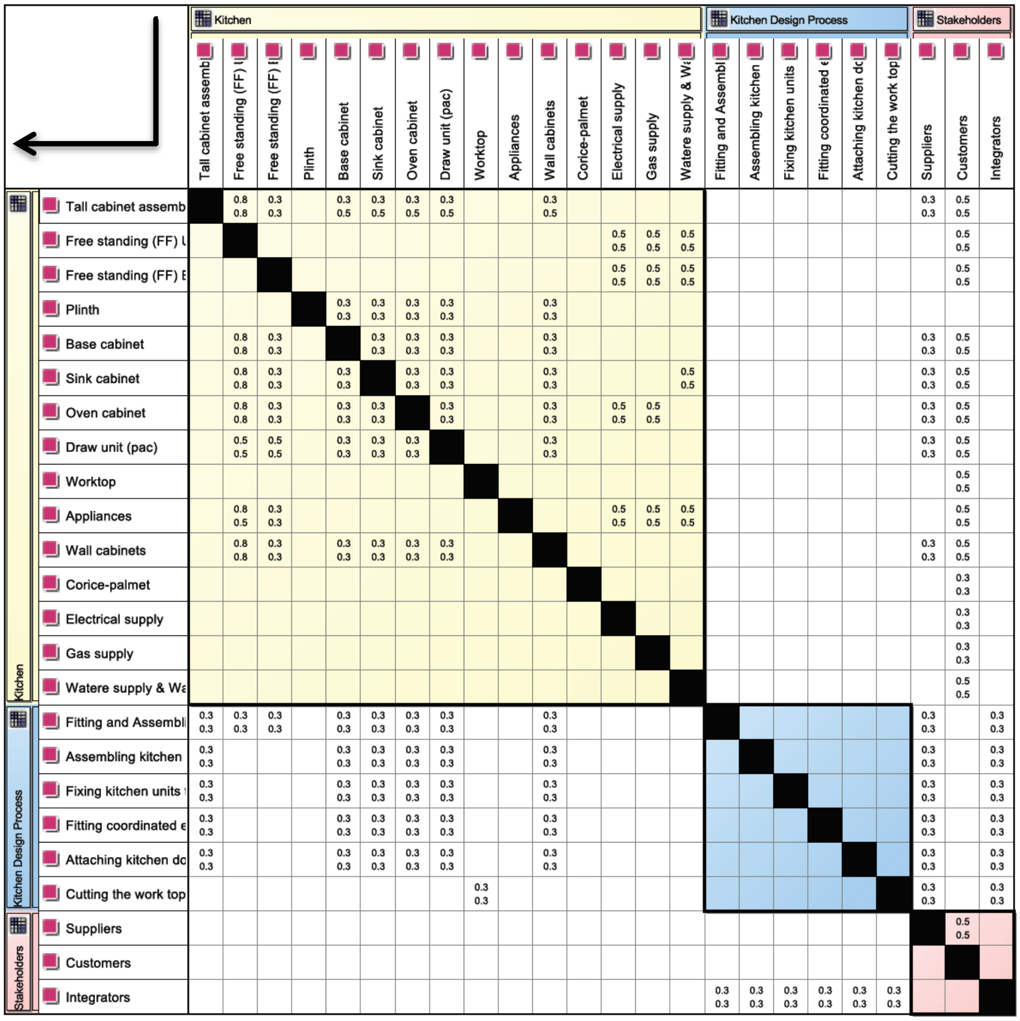


Figure 7.13: Network relationship for the elements of the kitchen design system

7.3.3 Quantify the Multilayer Network Method to Change Prediction Method

The system elements in Table 7.4 served as the basis for a preliminary kitchen design model, capturing dependencies between the elements including the kitchen design. Each connection was assessed and the total 122 likelihood and 122 impact values were determined. In general, each connection between two elements was quantified separately as described in the previous case study (Section 7.2). The relations between directly linked characteristics can be investigated for common changes. For instance, if the *Free Standing (FF) USA* (E2) element changed, it will require likelihood and impact change propagations to *Tall cabinet assembly (E1), Base cabinet (E5), Sink cabinet (E6), Oven cabinet (E7), Drawer Unit (8), Appliances (E10), Wall cabinet (E11), Fitting and Assembling a kitchen corner posts (E16)* stemming from the dependency analysis (Table 7.4; Figure 7.14). If there is no connection between the elements, the cell remains empty.

Once this information has been extracted from the case study assessment, it is transferred into the MLN using CAM Software. Then the data are analysed by the CPM tool. The CPM predicts the likelihood and impact of change propagation between elements by modelling the direct dependencies between them (Figure 7.14).

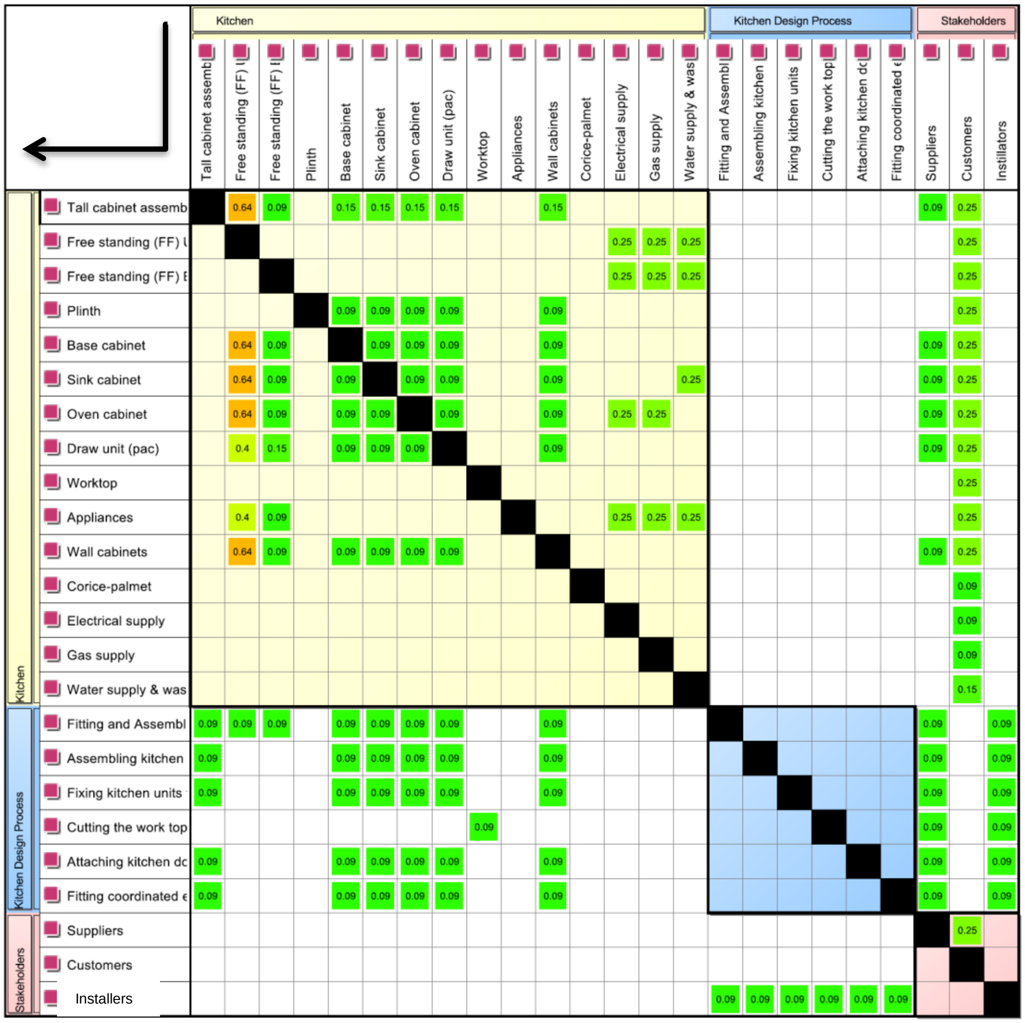


		Kitchen															Kitchen Design Process						Stakeholders		
		Tall cabinet assembl	Free standing (FF) l	Free standing (FF) I	Plinth	Base cabinet	Sink cabinet	Oven cabinet	Draw unit (pac)	Worktop	Appliances	Wall cabinets	Corice-palmet	Electrical supply	Gas supply	Watere supply & Wa	Fitting and Assembl	Assembling kitchen	Fixing kitchen units	Fitting coordinated e	Attaching kitchen dc	Cutting the work top	Suppliers	Customers	Integrators
Kitchen	Tall cabinet assemb	■	0.8 0.8	0.3 0.3		0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5			0.3 0.5											0.3 0.3	0.5 0.5	
	Free standing (FF) l		■											0.5 0.5	0.5 0.5	0.5 0.5								0.5 0.5	
	Free standing (FF) E			■										0.5 0.5	0.5 0.5	0.5 0.5								0.5 0.5	
	Plinth				■	0.3 0.3	0.3 0.3	0.3 0.3	0.3 0.3			0.3 0.3													
	Base cabinet		0.8 0.8	0.3 0.3		■	0.3 0.3	0.3 0.3	0.3 0.3			0.3 0.3											0.3 0.3	0.5 0.5	
	Sink cabinet		0.8 0.8	0.3 0.3		0.3 0.3	■	0.3 0.3	0.3 0.3			0.3 0.3				0.5 0.5							0.3 0.3	0.5 0.5	
	Oven cabinet		0.8 0.8	0.3 0.3		0.3 0.3	0.3 0.3	■	0.3 0.3			0.3 0.3		0.5 0.5	0.5 0.5								0.3 0.3	0.5 0.5	
	Draw unit (pac)		0.5 0.5	0.5 0.5		0.3 0.3	0.3 0.3	0.3 0.3	■			0.3 0.3											0.3 0.3	0.5 0.5	
	Worktop									■														0.5 0.5	
	Appliances		0.8 0.5	0.3 0.3							■			0.5 0.5	0.5 0.5	0.5 0.5								0.5 0.5	
	Wall cabinets		0.8 0.8	0.3 0.3		0.3 0.3	0.3 0.3	0.3 0.3	0.3 0.3			■											0.3 0.3	0.5 0.5	
	Corice-palmet												■											0.3 0.3	
	Electrical supply													■										0.3 0.3	
	Gas supply														■									0.3 0.3	
	Watere supply & Wa															■								0.5 0.5	
Kitchen Design Process	Fitting and Assembl	0.3 0.3	0.3 0.3	0.3 0.3		0.3 0.3	0.3 0.3	0.3 0.3	0.3 0.3			0.3 0.3					■						0.3 0.3		0.3 0.3
	Assembling kitchen	0.3 0.3				0.3 0.3	0.3 0.3	0.3 0.3	0.3 0.3			0.3 0.3						■					0.3 0.3		0.3 0.3
	Fixing kitchen units	0.3 0.3				0.3 0.3	0.3 0.3	0.3 0.3	0.3 0.3			0.3 0.3							■				0.3 0.3		0.3 0.3
	Fitting coordinated e	0.3 0.3				0.3 0.3	0.3 0.3	0.3 0.3	0.3 0.3			0.3 0.3								■			0.3 0.3		0.3 0.3
	Attaching kitchen dc	0.3 0.3				0.3 0.3	0.3 0.3	0.3 0.3	0.3 0.3			0.3 0.3									■		0.3 0.3		0.3 0.3
	Cutting the work top									0.3 0.3												■	0.3 0.3		0.3 0.3
Stakeholders	Suppliers																						■	0.5 0.5	
	Customers																							■	
	Integrators																0.3 0.3	0.3 0.3	0.3 0.3	0.3 0.3	0.3 0.3	0.3 0.3			■

Figure 7.14: A numerical representation of the combined likelihood &impact values for the elements of the kitchen design system

7.3.4 Compute Combined Change Propagation

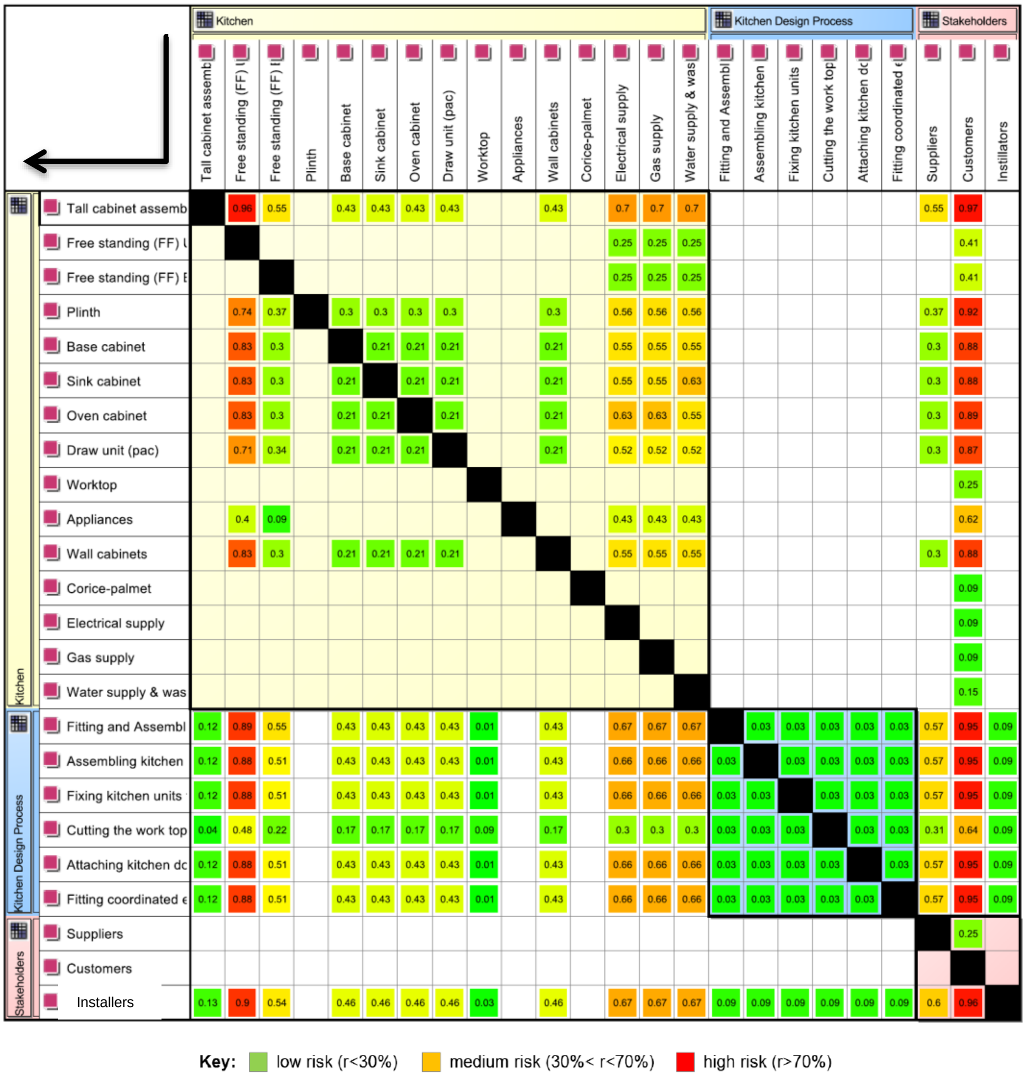
As described in Case 1, understanding the change propagation through the Change Prediction Method (CPM) algorithm (Clarkson et al. 2004) six-step propagation analysis is applied to generate combined change risks. The model explicitly contains detail on the intra-layer level and includes the expert input. Figure 7.15 and 7.16 shows the resulting matrix before and after the CPM analysis was performed, respectively. The rectangles in the cells of the matrix indicate impact (height) and likelihood (width) of change propagation. The size of the rectangles indicates the direct risk of change propagation. Two effects should be noted: firstly, the size of the rectangles increases, i.e. the risk of change propagation between elements is higher than the original matrix; and secondly, the matrix is more populated, i.e. there is a risk of change propagation even between elements which were not previously thought to be dependent on each other. This preliminary example illustrates that the resulting change propagation network is more complex than initially assumed and that changes to one part of the design can potentially weave through the whole design, requiring extensive rework.



		Kitchen															Kitchen Design Process						Stakeholders		
		Tall cabinet assemb	Free standing (FF)	Free standing (FF)	Plinth	Base cabinet	Sink cabinet	Oven cabinet	Draw unit (pac)	Worktop	Appliances	Wall cabinets	Corice-palmet	Electrical supply	Gas supply	Water supply & was	Fitting and Assembl	Assembling kitchen	Fixing kitchen units	Cutting the work top	Attaching kitchen dc	Fitting coordinated	Suppliers	Customers	Instillators
Kitchen	Tall cabinet assemb	■	0.64	0.09		0.15	0.15	0.15	0.15			0.15											0.09	0.25	
	Free standing (FF)		■											0.25	0.25	0.25								0.25	
	Free standing (FF)			■										0.25	0.25	0.25								0.25	
	Plinth				■	0.09	0.09	0.09	0.09			0.09												0.25	
	Base cabinet		0.64	0.09		■	0.09	0.09	0.09			0.09											0.09	0.25	
	Sink cabinet		0.64	0.09		0.09	■	0.09	0.09			0.09				0.25							0.09	0.25	
	Oven cabinet		0.64	0.09		0.09	0.09	■	0.09			0.09		0.25	0.25								0.09	0.25	
	Draw unit (pac)		0.4	0.15		0.09	0.09	0.09	■			0.09											0.09	0.25	
	Worktop									■														0.25	
	Appliances		0.4	0.09							■			0.25	0.25	0.25								0.25	
	Wall cabinets		0.64	0.09		0.09	0.09	0.09	0.09			■											0.09	0.25	
	Corice-palmet												■											0.09	
	Electrical supply													■										0.09	
	Gas supply														■									0.09	
	Water supply & was															■								0.15	
Kitchen Design Process	Fitting and Assembl	0.09	0.09	0.09		0.09	0.09	0.09	0.09			0.09					■						0.09		0.09
	Assembling kitchen	0.09				0.09	0.09	0.09	0.09			0.09						■					0.09		0.09
	Fixing kitchen units	0.09				0.09	0.09	0.09	0.09			0.09							■				0.09		0.09
	Cutting the work top									0.09										■			0.09		0.09
	Attaching kitchen dc	0.09				0.09	0.09	0.09	0.09			0.09									■		0.09		0.09
	Fitting coordinated	0.09				0.09	0.09	0.09	0.09			0.09										■	0.09		0.09
Stakeholders	Suppliers																						■	0.25	
	Customers																							■	
	Installers																0.09	0.09	0.09	0.09	0.09	0.09			■

Figure 7.15: The numerical representation of the directly connected risk values for the elements of the kitchen design system

Applying the CPM algorithm to the case study, the indirect connections between the 18 elements can be generated by using the maximum change propagation steps (*six-step propagation analysis)* to calculate the combined change risks. The detailed results are given in the risk MLN presented in Figure 7.15. This MLN includes risk values for all the different element pairs. It can be combined in different ways to generate specific high-level views of change propagation. For example, the blocks within *The Kitchen, Kitchen Design Process* and *Stakeholders* layers can be combined to generate an element-element change risk plot, similar to the result of CPM. In Figure 7.16, the colour scale specifies the risk values as follows: the red cells are the higher risk (R>70%), the yellow cells are the medium risk (30% < R<70%) and the green cells are low risks (R< 30%).

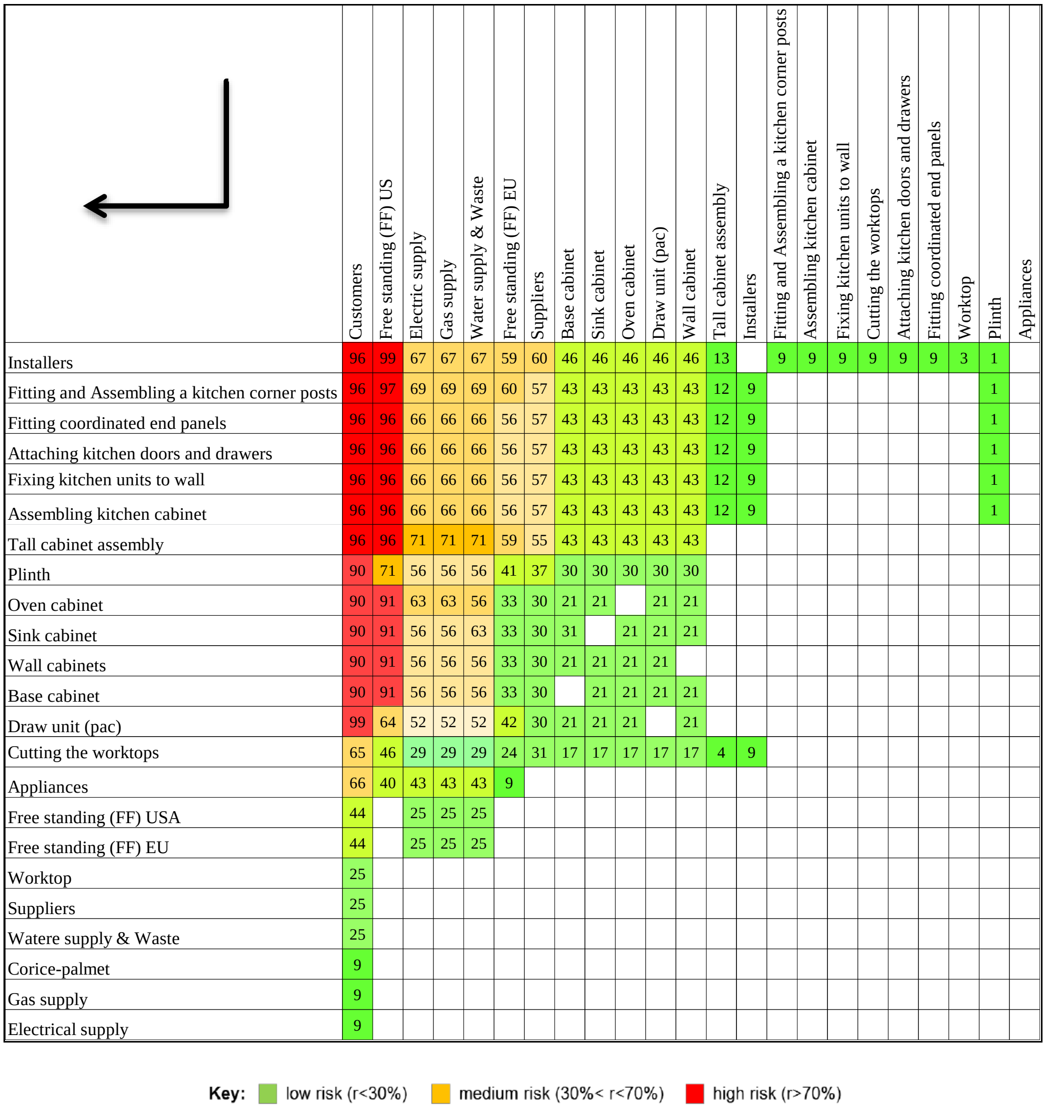


		Kitchen															Kitchen Design Process						Stakeholders		
		Tall cabinet assembl	Free standing (FF) U	Free standing (FF) I	Plinth	Base cabinet	Sink cabinet	Oven cabinet	Draw unit (pac)	Worktop	Appliances	Wall cabinets	Corice-palmet	Electrical supply	Gas supply	Water supply & was	Fitting and Assembl	Assembling kitchen	Fixing kitchen units	Cutting the work top	Attaching kitchen dc	Fitting coordinated e	Suppliers	Customers	Instillators
Kitchen	Tall cabinet assemb		0.96	0.55		0.43	0.43	0.43	0.43			0.43		0.7	0.7	0.7							0.55	0.97	
	Free standing (FF) U													0.25	0.25	0.25								0.41	
	Free standing (FF) I													0.25	0.25	0.25								0.41	
	Plinth		0.74	0.37		0.3	0.3	0.3	0.3			0.3		0.56	0.56	0.56							0.37	0.92	
	Base cabinet		0.83	0.3			0.21	0.21	0.21			0.21		0.55	0.55	0.55							0.3	0.88	
	Sink cabinet		0.83	0.3		0.21		0.21	0.21			0.21		0.55	0.55	0.63							0.3	0.88	
	Oven cabinet		0.83	0.3		0.21	0.21		0.21			0.21		0.63	0.63	0.55							0.3	0.89	
	Draw unit (pac)		0.71	0.34		0.21	0.21	0.21				0.21		0.52	0.52	0.52							0.3	0.87	
	Worktop																							0.25	
	Appliances		0.4	0.09										0.43	0.43	0.43								0.62	
	Wall cabinets		0.83	0.3		0.21	0.21	0.21	0.21					0.55	0.55	0.55							0.3	0.88	
	Corice-palmet																							0.09	
	Electrical supply																							0.09	
	Gas supply																							0.09	
	Water supply & was																							0.15	
Kitchen Design Process	Fitting and Assembl	0.12	0.89	0.55		0.43	0.43	0.43	0.43	0.01		0.43		0.67	0.67	0.67		0.03	0.03	0.03	0.03	0.03	0.57	0.95	0.09
	Assembling kitchen	0.12	0.88	0.51		0.43	0.43	0.43	0.43	0.01		0.43		0.66	0.66	0.66	0.03		0.03	0.03	0.03	0.03	0.57	0.95	0.09
	Fixing kitchen units	0.12	0.88	0.51		0.43	0.43	0.43	0.43	0.01		0.43		0.66	0.66	0.66	0.03	0.03		0.03	0.03	0.03	0.57	0.95	0.09
	Cutting the work top	0.04	0.48	0.22		0.17	0.17	0.17	0.17	0.09		0.17		0.3	0.3	0.3	0.03	0.03	0.03		0.03	0.03	0.31	0.64	0.09
	Attaching kitchen dc	0.12	0.88	0.51		0.43	0.43	0.43	0.43	0.01		0.43		0.66	0.66	0.66	0.03	0.03	0.03	0.03		0.03	0.57	0.95	0.09
	Fitting coordinated e	0.12	0.88	0.51		0.43	0.43	0.43	0.43	0.01		0.43		0.66	0.66	0.66	0.03	0.03	0.03	0.03	0.03		0.57	0.95	0.09
Stakeholders	Suppliers																							0.25	
	Customers																								
	Installers	0.13	0.9	0.54		0.46	0.46	0.46	0.46	0.03		0.46		0.67	0.67	0.67	0.09	0.09	0.09	0.09	0.09	0.09	0.6	0.96	

Key: 🟩 low risk (r<30%) 🟨 medium risk (30%< r<70%) 🟥 high risk (r>70%)

Figure 7.16: After change prediction method algorithm (six-step propagation) to represent direct and indirect connected likelihood & impact values for the elements of the kitchen design system

For high-level analysis, Figure 7.17 is generated by using CPM analysis tools in the highest row first and highest columns of the risk values. This results in 209 risk values with all elements being affected simultaneously when taking the highest risk into account. The colour scale shows that the core elements are critical in terms of receiving changes from other elements (i.e rows *Integrators, Fitting and Assembling a kitchen corner posts, Fitting coordinated end panels, Attaching kitchen doors and drawers)* as well as in initiating changes to other elements (i.e columns *Customers*, *Free Standing (FF) the US*, *Electrical supply*, *Gas supply*, *Water supply & Waste*) and between each other. The overall average of the risk values is 29.7% in the range from min 0% to max 99% (include the distribution of low 0.3; medium 0.5; high 0.8). The majority of connections in the matrix are low-risk values. The connectivity between non-core elements is less critical. The matrix provides a view of the kitchen design system as an entirely combined system, with all elements being interconnected to each other. A change to one element may affect virtually any other element.



	Customers	Free standing (FF) US	Electric supply	Gas supply	Water supply & Waste	Free standing (FF) EU	Suppliers	Base cabinet	Sink cabinet	Oven cabinet	Draw unit (pac)	Wall cabinet	Tall cabinet assembly	Installers	Fitting and Assembling a kitchen corner posts	Assembling kitchen cabinet	Fixing kitchen units to wall	Cutting the worktops	Attaching kitchen doors and drawers	Fitting coordinated end panels	Worktop	Plinth	Appliances
Installers	96	99	67	67	67	59	60	46	46	46	46	46	13		9	9	9	9	9	9	3	1	
Fitting and Assembling a kitchen corner posts	96	97	69	69	69	60	57	43	43	43	43	43	12	9								1	
Fitting coordinated end panels	96	96	66	66	66	56	57	43	43	43	43	43	12	9								1	
Attaching kitchen doors and drawers	96	96	66	66	66	56	57	43	43	43	43	43	12	9								1	
Fixing kitchen units to wall	96	96	66	66	66	56	57	43	43	43	43	43	12	9								1	
Assembling kitchen cabinet	96	96	66	66	66	56	57	43	43	43	43	43	12	9								1	
Tall cabinet assembly	96	96	71	71	71	59	55	43	43	43	43	43											
Plinth	90	71	56	56	56	41	37	30	30	30	30	30											
Oven cabinet	90	91	63	63	56	33	30	21	21		21	21											
Sink cabinet	90	91	56	56	63	33	30	31		21	21	21											
Wall cabinets	90	91	56	56	56	33	30	21	21	21	21												
Base cabinet	90	91	56	56	56	33	30		21	21	21	21											
Draw unit (pac)	99	64	52	52	52	42	30	21	21	21		21											
Cutting the worktops	65	46	29	29	29	24	31	17	17	17	17	17	4	9									
Appliances	66	40	43	43	43	9																	
Free standing (FF) USA	44		25	25	25																		
Free standing (FF) EU	44		25	25	25																		
Worktop	25																						
Suppliers	25																						
Watere supply & Waste	25																						
Corice-palmet	9																						
Gas supply	9																						
Electrical supply	9																						

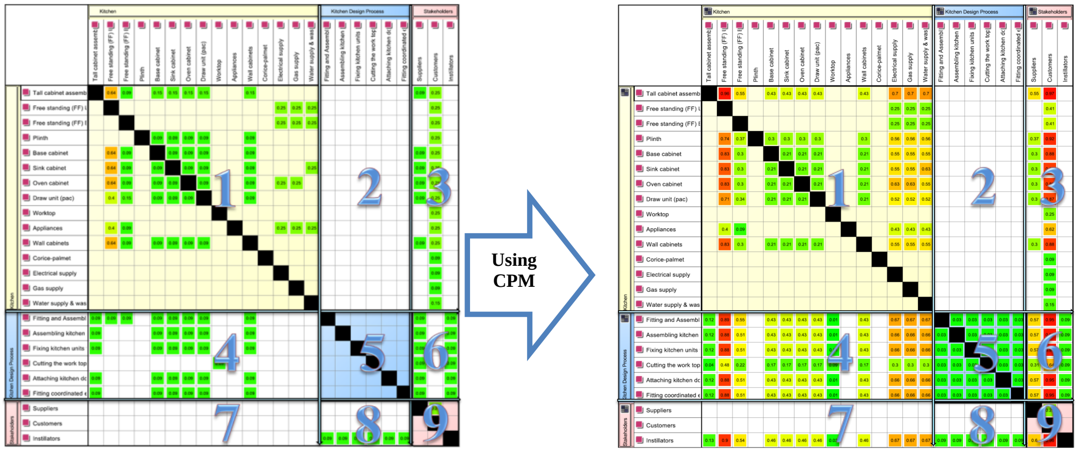
Key: 🟩 low risk (r<30%) 🟨 medium risk (30%< r<70%) 🟥 high risk (r>70%)

Figure 7.17: Combined risk design structure matrix for the elements of the kitchen design system (in value / %)

7.3.5. Use of the Change Risk Model for Decision Making

Comparing direct and indirect risk values with the company expert

For high-level analysis, the layers of the combined risk MLN were combined to gain the element-to-element risk. This combined matrix contains the maximum combined risk values of 3 square DSMs (1, 5, and 9) as well as the 6 DMMs (2, 3, 4, 6, 7, and 8) between them, as illustrated in Figure 7.18. In Figure (a) and (b), the computed results of the direct and indirect change propagations are illustrated. Fields 1, 5, and 9 subsequently show the interaction between *Kitchen, Kitchen Design Process and Stakeholders.* Fields 4 and 7 indicate the performance rating of elements that are connected with the kitchen. Fields 2, 8 and 15 indicate the performance rating of elements related to the kitchen design process. Fields 3 and 6 indicate the performance ratings of elements which are attendant on the stakeholders.

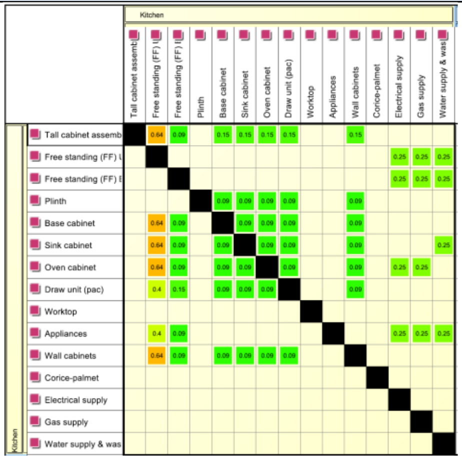
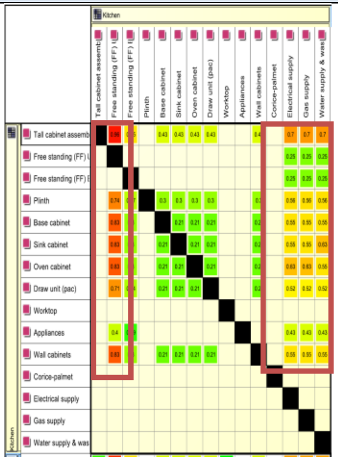
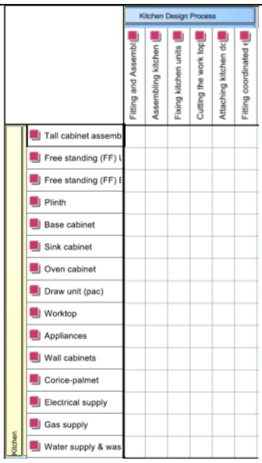
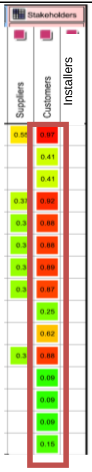


(a) (b)

Figure 7.18: The numerical representation of the directly (a) and indirectly (b) connected risk values for the elements of the kitchen design system

Figure 7.18 (a) and (b) carried out by the use of Table 7.5 illustrate the differences between the original input data and the final results. The comparison was done by the company expert whose comments are quoted in speech marks. In comparing the risk values, the yellow and red risk values were considered which the highest impacts are on the system.

Table 7.6: Comparison of the direct and indirect risk values for the kitchen design system

No	The input data (the direct connected Risk=Likelihood x Impact values)	The CPM Algorithm results (the indirectly connected risk values)	Comparison of the input data and final results With Jewson Ltd.
1			*"The Free Standing (FF) the US* that changes the dimension, because it is much bigger than change any kitchen base cabinets. If you change the position of this tall cabinet that would be expected to highly affect indirectly by the *Electrical, Gas and Water supply &Waste.*"
2			Any changes in the *Kitchen Design Process* do not affect any of the *Kitchen* elements. The software also did not get any indirect connections.
3			*"Customer* gives high risks which makes sense. For instance, change the tall cabinet by a customer and the choice impacts on the installation process and individual Kitchen Units."

1, input data:

Kitchen

Kitchen	Tall cabinet assemb	Free standing (FF) U	Free standing (FF) E	Plinth	Base cabinet	Sink cabinet	Oven cabinet	Draw unit (pac)	Worktop	Appliances	Wall cabinets	Corice-palmet	Electrical supply	Gas supply	Water supply & was
Tall cabinet assemb	■	0.64	0.09		0.15	0.15	0.15	0.15			0.15				
Free standing (FF) U		■											0.25	0.25	0.25
Free standing (FF) E			■										0.25	0.25	0.25
Plinth				■	0.09	0.09	0.09	0.09			0.09				
Base cabinet		0.64	0.09		■	0.09	0.09	0.09			0.09				
Sink cabinet		0.64	0.09		0.09	■	0.09	0.09			0.09				0.25
Oven cabinet		0.64	0.09		0.09	0.09	■	0.09			0.09		0.25	0.25	
Draw unit (pac)		0.4	0.15		0.09	0.09	0.09	■			0.09				
Worktop									■						
Appliances		0.4	0.09							■			0.25	0.25	0.25
Wall cabinets		0.64	0.09		0.09	0.09	0.09	0.09			■				
Corice-palmet												■			
Electrical supply													■		
Gas supply														■	
Water supply & was															■

1, CPM Algorithm results:

Kitchen

Kitchen	Tall cabinet assemb	Free standing (FF) U	Free standing (FF) E	Plinth	Base cabinet	Sink cabinet	Oven cabinet	Draw unit (pac)	Worktop	Appliances	Wall cabinets	Corice-palmet	Electrical supply	Gas supply	Water supply & was
Tall cabinet assemb	■	0.96	[illegible]		0.43	0.43	0.43	0.43			0.4		0.7	0.7	0.7
Free standing (FF) U		■											0.25	0.25	0.25
Free standing (FF) E			■										0.25	0.25	0.25
Plinth		0.74	[illegible]	■	0.3	0.3	0.3	0.3			[illegible]		0.56	0.56	0.56
Base cabinet		0.83	[illegible]		■	0.21	0.21	0.21			0.2		0.55	0.55	0.55
Sink cabinet		0.83	[illegible]		0.21	■	0.21	0.21			0.2		0.55	0.55	0.63
Oven cabinet		0.83	[illegible]		0.21	0.21	■	0.21			0.2		0.63	0.63	0.55
Draw unit (pac)		0.71	[illegible]		0.21	0.21	0.21	■			0.2		0.52	0.52	0.52
Worktop									■						
Appliances		0.4	[illegible]							■			0.43	0.43	0.43
Wall cabinets		0.83	[illegible]		0.21	0.21	0.21	0.21			■		0.55	0.55	0.55
Corice-palmet												■			
Electrical supply													■		
Gas supply														■	
Water supply & was															■

2, input data and CPM Algorithm results:

Kitchen Design Process

Kitchen	Fitting and Assembl	Assembling kitchen	Fixing kitchen units	Cutting the work top	Attaching kitchen dc	Fitting coordinated
Tall cabinet assemb						
Free standing (FF) U						
Free standing (FF) E						
Plinth						
Base cabinet						
Sink cabinet						
Oven cabinet						
Draw unit (pac)						
Worktop						
Appliances						
Wall cabinets						
Corice-palmet						
Electrical supply						
Gas supply						
Water supply & was						

3, input data:

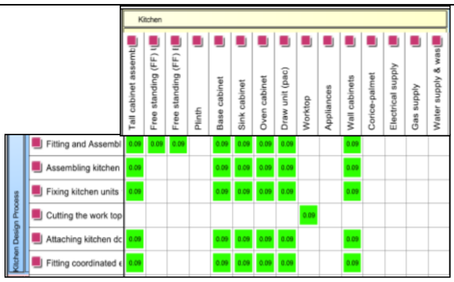
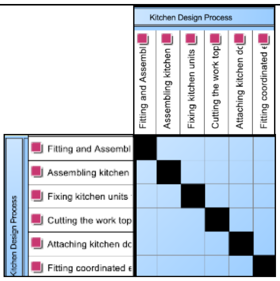
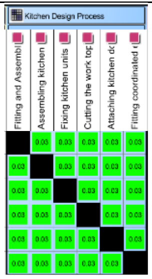
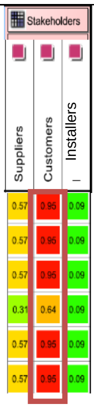
Stakeholders

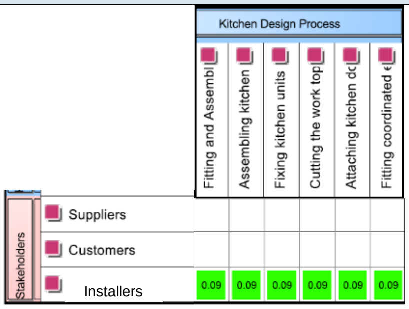
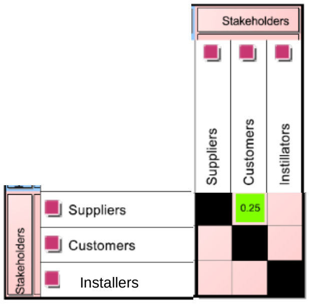
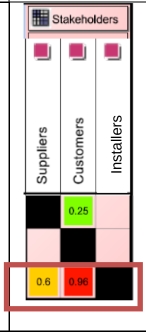
Kitchen	Suppliers	Customers	Installers
Tall cabinet assemb	0.09	0.25	
Free standing (FF) U		0.25	
Free standing (FF) E		0.25	
Plinth		0.25	
Base cabinet	0.09	0.25	
Sink cabinet	0.09	0.25	
Oven cabinet	0.09	0.25	
Draw unit (pac)	0.09	0.25	
Worktop		0.25	
Appliances		0.25	
Wall cabinets	0.09	0.25	
Corice-palmet		0.09	
Electrical supply		0.09	
Gas supply		0.09	
Water supply & was		0.15	

3, CPM Algorithm results:

Stakeholders

Suppliers	Customers	Installers
0.56	0.97	
	0.41	
	0.41	
0.37	0.92	
0.3	0.88	
0.3	0.88	
0.3	0.89	
0.3	0.87	
	0.25	
	0.62	
0.3	0.88	
	0.09	
	0.09	
	0.09	
	0.15	

4			“It is surprising to me! Because how changes *Free Standing Fridge (FF) the US* will affect for instance the attaching kitchen doors and cabinet. *“Electrical, Gas, Water supply and Waste* medium risks on *the Kitchen Design Process*: talking about the position rather than the nature of them. If the position of changes yes that may affect the kitchen design process. If *Electrical, Gas and Water supply* & *Waste* moved after the design that has been done: yes it will affect the design process.”
5			*“Kitchen Design Process* does not affect each other. The indirect connections are quite low and can be eliminated.”
No	**The input data** **(the direct connected Risk=Likelihood x Impact values)**	**The CPM Algorithm results** **(the indirectly connected risk values)**	**Comparison of the input data and final results** **With Jewson Ltd.**
6			“I am wondering how a *Customer* would effect on *Kitchen Design Process* does not make sense. I assume *Customers* affect *Fitting and Assembling* kitchen corner posts. Two corners or one corner might affect *the Corner unit*, *Customer* not affecting materials. Might be customers choice on the kitchen style can impact indirectly. Fitting units and the walls: different supplier has different types, for instance, hanging rackets or some suppliers attached the doors of units some not that hugely effect of the design process.”
7			*“Free Standing (FF) the US* to *Installers* may affect but I don't think so it is a major effect. I don't see any threatening or risk.” “If *Electrical, Gas and Water supply & Waste* are done in an early stage that cannot affect the *Installer* but after the design stage that may affect the *Installer*.”

No	The input data (the direct connected Risk=Likelihood x Impact values)	The CPM Algorithm results (the indirectly connected risk values)	Comparison of the input data and final results With Jewson Ltd.
8			"Installers have been low affected in changes in the *Kitchen Design Process.* The indirect connections are quite low and can be eliminated*"*
9			"When a Change come from *Customers, Installers* is under the 98% high risk on it can be expected; *Customers* would affect the designer of the kitchen. *Suppliers* can affect the *Installer* because of the type of units, which the CAM software found the risk value as 60%. However, I don't think there is a high risk of Installers through *Customers."*

The risk model for decision making

The simulation results for a kitchen design change were run and a prioritised change risk list was developed which enables the user to assess the characteristics of the direct relationships between elements and the impact of the changes on the indirect relationships. Table 7.6 indicates such a prioritised change risk list for a *Customer (23)* preference for the *Freestanding US Fridge Freezer (15)* . When a customer chose the US fridge instead of the EU one, the kitchen design elements in the bold red colour are at a high risk of impact (such as "*Tall cabinet assembly"(1), "Installers"(24),* "*Fitting and assembling a kitchen corner post (18) and "Assembling kitchen cabinet"(17)* are most likely to be changed.). However, the expert did not agree with the change effects of Customers on the Kitchen Design Process directly. On the other hand, his reviews on some elements of the design process support the results of the risk plot. For instance, a chosen tall cabinet by *Customer (23)* gives high risks, and the choice may impact the installation process and individual Kitchen Units. Similarly Customers Choise of two corners or one corner kitchen might affect *Fitting and Assembling Kitchen Corner Posts* (16). Customers' choice of the kitchen style can impact some elements of the kitchen design processes indirectly. In addition, despite the risk plot, the expert mentioned the impossibility of high risk in *Installers (E24)* through *Customers (23).*

Table 7.7: Prioritised change risk list for Customers
Initiating change: Customers (E23)

Priority No	**Affected Elements**		**Risk value %**
	Name	**Element No**	
1	**Tall cabinet assembly**	**E1**	**98**
2	**Installers**	**E24**	**96**
3	**Fitting and Assembling a kitchen corner posts**	**E16**	**96**
4	**Assembling kitchen cabinet**	**E17**	**96**
5	**Fixing kitchen units to the wall**	**E18**	**96**
6	**Attaching kitchen doors and drawers**	**E20**	**96**
7	**Fitting coordinated end panels**	**E21**	**96**
8	Oven cabinet	E7	90
9	Sink cabinet	E6	90
10	Plinth	E4	90
11	Base cabinet	E5	90
12	Wall cabinet	E11	88
13	Draw unit (PAC)	E8	66
14	Appliances	E10	65
15	Freestanding (FF) US	E2	44
16	Freestanding (FF) EU	E3	44
17	Worktop	E9	25
18	Water supply & Waste	E15	25
19	Suppliers	E22	25
20	Cornice - pelmet	E12	9
21	Electric supply	E13	9
22	Gas supply	E14	9

Figure 7.19 indicates the possible paths between E23 (Customers) and E2 (Free Syanding Fridge US), which incorporates five elements and seven links. This figure includes direct and indirect combined likelihood values. The green direct line (E23-E2) is the shortest path (0.5) between the two elements and indicates the two elements directly connected. The figure also indicates the number of common neighbours (E13, E14 and E15) between the elements that share links with these two elements (E23 and E2). The more neighbours in common that two elements have, the more likely it is that a change will propagate between them. The higher the changing likelihood is given, the more likely that change will propagate along this route. In the figure, the most likely path line between two elements is E23-E15-E2 (0.5-0.5). Specific challenges of the method when applied to the case study will be detailed as part of the method evaluation in Chapter 8.

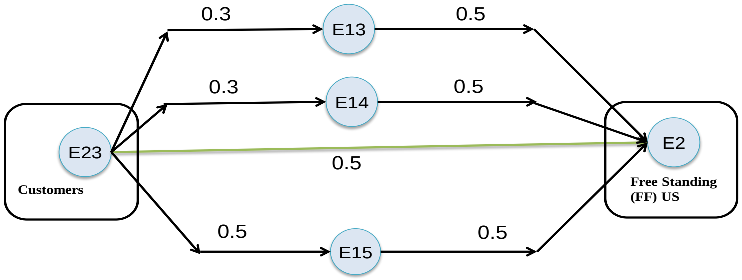


Figure 7.19: Selected change propagation paths from kitchen customers (E23) to freestanding (FF) US (E2)

7 Case Study 3 – Change Requirements, UOP Honeywell

This case study explores the application of the proposed system change method to the production system in the refining and petrochemical plant of *UOP Honeywell*, which is UK-based. The petrochemical industry is more global, competitive and complex than ever before and sometimes quick solutions are needed to meet changing requirements or regulations. Demands on the Honeywell UOP manufacturing plant are to produce high performing catalysts and absorbents for the customer's refinery processes. The company wants to create a more efficient manufacturing change process to avoid possible change propagations to meet the expectation of change requirements coming from customers. The opportunity of the project as a whole also includes manufacturing and supply chain management. The case study considers the design stages of a manufacturing system with a characteristically decomposed hierarchical architecture. In particular, how changes to one part of the design would propagate to other parts was investigated. The challenge was to select an opportunity and level of detail applicable for this type of analysis and to continually model hierarchical systems decomposition while keeping the modelling work sensible.

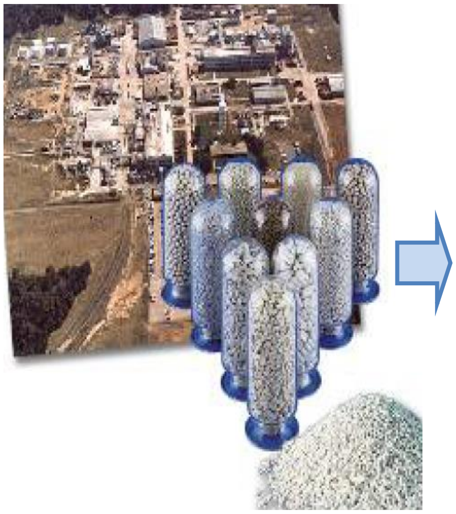
The production system architecture consists of many sub-systems and elements. The method was initially generated with data estimated based on documentation and then a workshop was run for model building by engaging production experts who had a good experience of the complex environment (Table 7.7). Each was aware of the perception of risk assessment and had an experience of giving subjective estimates of risks based on their professional decisions. Each person had different degrees of participation in the exercise dependent on the nature of the task being executed during the model development process. Change, change propagation and associated risks were investigated in a range of modelling development activities, mostly based on a Multi-layered Network (MLN), which captures the dependencies between parts of the design on different levels. The Change Prediction Method (CPM) provides insights into the company's production plant to investigate the implications of multilayer hierarchical system decomposition as well as to undertake analyses at varying levels of detail.

Table 7.8: The participants in the study to model development

Person	Job Function	Experience
I.	Production Planner	30 years at various departments at UOP Honeywell Brimsdown Plant, UK
II.	Process Engineer	4 years' experience in the operational process.
III.	Production Supervisor	15 years' experience in various process sections
IV.	Warehouse Operator	19 years' experience in the warehouse department.

7.4.1 Decompose the system into layers and elements

The multilayered production system architecture decomposes into 19 system elements. The criteria are having a more manageable number of elements and staying at the right level of the detail to satisfy the risk analysis. Based on the change requirements from the past experiences, the catalyst or absorbent production system was divided into four layers: *Requirements, Product Specifications, Production Process and Personnel*, which consist of 19 elements as shown Figure 7.20.



Layer 1: Change Requirements
- Recipie
- Materials
- Equipment
- Instructions

Layer 2: Product Specifications
- Activation
- Metal content
- Hardness
- Surface Area
- Impurity Content

Layer 3: Production Process
- Production Planning
- Product Development
- Impegration
- Oxidation / Drying
- Drumming
- Reduction

Layer 4: Personnel
- Product Designer
- Supply Chain Planner
- Production Staff
- Warehouse Staff

No	Components
1	Recipie
2	Materials
3	Equipment
4	Instructions
5	Activation
6	Metal content
7	Hardness
8	Impurity Content
9	Surface Area
10	Production Planning
11	Product Development
12	Impegration
13	Oxidation / Drying
14	Drumming
15	Reduction
16	Product Designer
17	Supply Chain Planner
18	Production Staff
19	Warehouse Staff

Figure 7.20: Decomposition of the Production System of UOP Honeywell Brimsdown Plant

7.4.2 Capture dependencies between layers and elements

The second stage of the design concept was to capture the connectivity between the 19 elements in a multi-layer network matrix. The information was collected from current documents and through interviews with the manufacturing staff. A production system is subject to potential changes associated with subsystems and system elements. Each system element can be affected by both planned changes and change propagation. The identification of connections between elements and the assessment of their change propagation likelihood and impact, the next step, resulted in 164 direct connections between the 4 layers and 19 elements held in a Multilayer Network (MLN) matrix. Each direct connection between two elements could be made up of more than one connection and the manufacturing personnel indicated the likelihood and impact of change propagation on each connection. Table 7.8 shows the connectivity between the elements resulting from the dependency analysis.

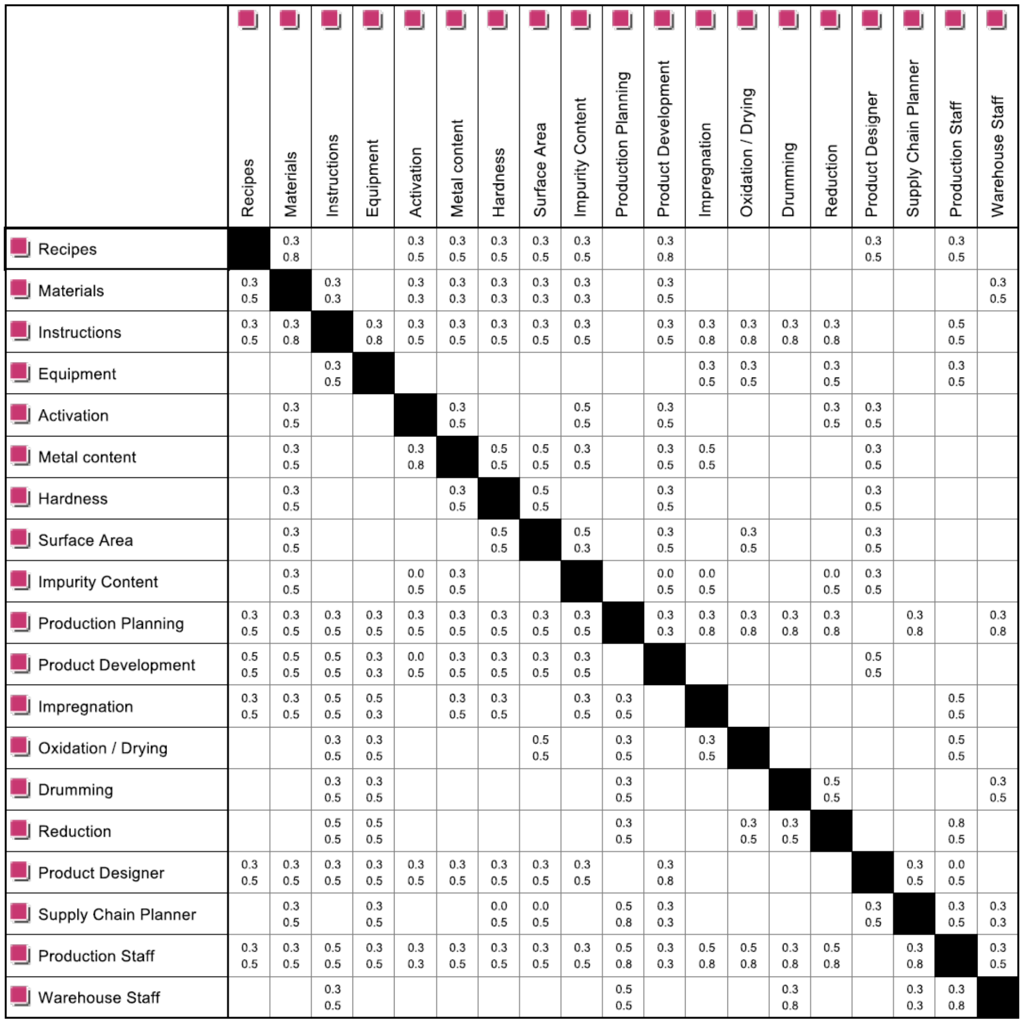
Table 7.9: Connectivity between the elements for the change requirements of the production system

Element No	Elements Name	Depends upon elements
1	Recipes	2,4,10,11,12,16,18
2	Materials	1,4,5,6,7,8,9,10,11,12,16,17,18
3	Equipment	4,10,11,12,13,14,15,16,17,18
4	Instructions	2,3, 10,11,12,13,14,15,16,18,19
5	Activation	1,2,4,6,10,16,18
6	Metal content	1,2,4,5,7,8,10,11,12,13,16,18
7	Hardness	1,2,4,6,8,9,10,12,16,18
8	Impurity content	1,2,4,5,6,9,10,11,12,16,18
9	Surface Area	1,2,4,6,7,10,11,13,16,19
10	Production Planning	12,13,14,15,17,18,19
11	Product Development	1,2,4,5,6,7,9,10,16,17,18
12	Impregnation	3,4,6,10,13,18
13	Oxidation & Drying	3,4,9,10,15,18
14	Drumming	4,10,15,18,19
15	Reduction	3,4,5,10,14,18
16	Product Designer	1,5,6,7,8,9,11,17
17	Supply Chain Planner	10,16,18,19
18	Production Staff	1,3,4,12,13,15,17,19
19	Warehouse Staff	2,10,14,17,18

7.4.3. Quantify the Multilayer Network Method to Change Prediction Method

The information gained from Table 7.8 was complemented by estimates of the likelihood and impact of change propagating through connectivity between two system elements. In this research study, the likelihood estimation strategy is based on *the frequency* with which the element is changed. Some elements are less frequently changed than others regardless of their dependency properties.

In general, each link between two elements can be quantified individually and separately for each direction as in the previous case studies. The values for each connection initially were linked then quantified by likelihood and impact values on a case-by-case basis analysis. The connections are quantified using three different thresholds, namely 0.3 for low, 0.5 for medium, and 0.8 for high impact. To estimate these values, the relations between directly linked attributes were investigated for common changes. The computations were carried out using the CAM software and quantifications are illustrated in Figure 21.

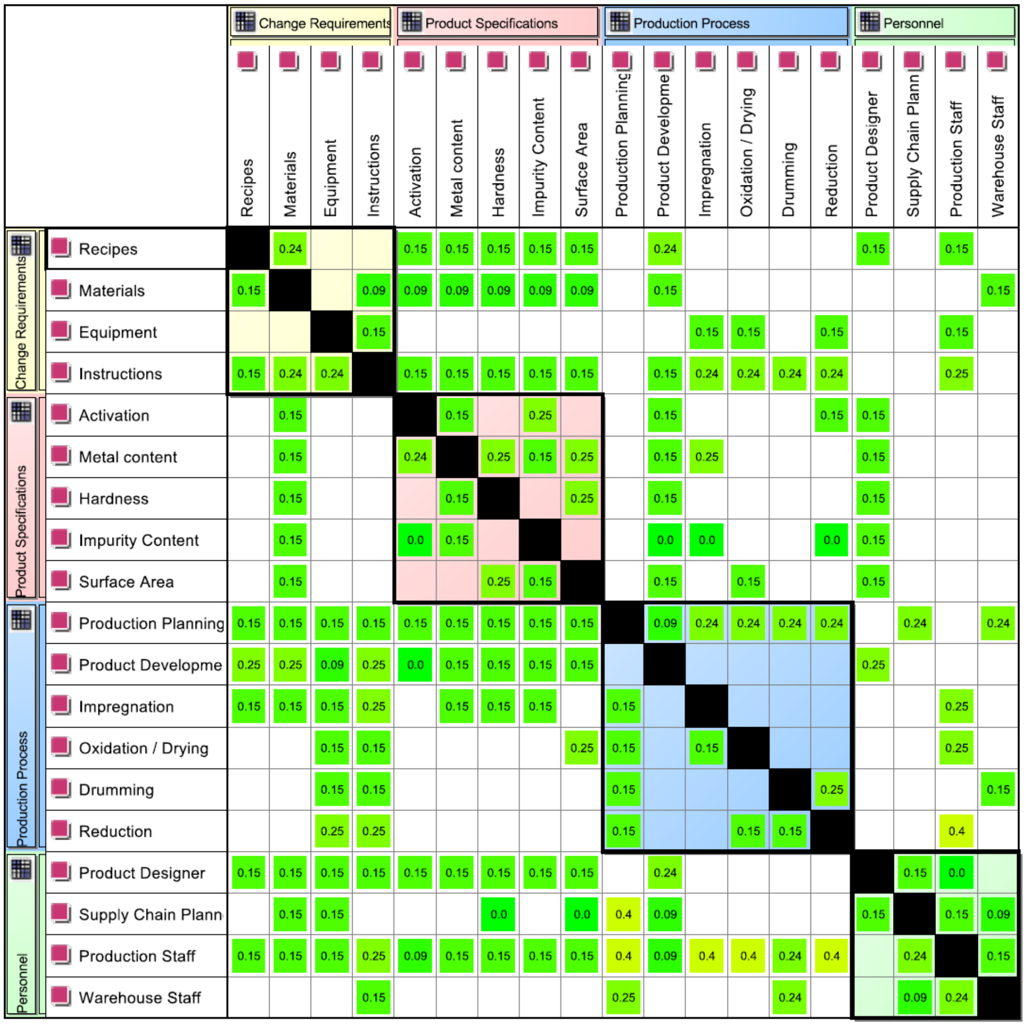


	Recipes	Materials	Instructions	Equipment	Activation	Metal content	Hardness	Surface Area	Impurity Content	Production Planning	Product Development	Impregnation	Oxidation / Drying	Drumming	Reduction	Product Designer	Supply Chain Planner	Production Staff	Warehouse Staff
Recipes	■	0.3 0.8			0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5		0.3 0.8					0.3 0.5		0.3 0.5	
Materials	0.3 0.5	■	0.3 0.3		0.3 0.3	0.3 0.3	0.3 0.3	0.3 0.3	0.3 0.3		0.3 0.5								0.3 0.5
Instructions	0.3 0.5	0.3 0.8	■	0.3 0.8	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5		0.3 0.5	0.3 0.8	0.3 0.8	0.3 0.8	0.3 0.8			0.5 0.5	
Equipment			0.3 0.5	■								0.3 0.5	0.3 0.5		0.3 0.5			0.3 0.5	
Activation		0.3 0.5			■	0.3 0.5			0.5 0.5		0.3 0.5				0.3 0.5	0.3 0.5			
Metal content		0.3 0.5			0.3 0.8	■	0.5 0.5	0.5 0.5	0.3 0.5		0.3 0.5	0.5 0.5				0.3 0.5			
Hardness		0.3 0.5				0.3 0.5	■	0.5 0.5			0.3 0.5					0.3 0.5			
Surface Area		0.3 0.5					0.5 0.5	■	0.5 0.3		0.3 0.5		0.3 0.5			0.3 0.5			
Impurity Content		0.3 0.5			0.0 0.5	0.3 0.5			■		0.0 0.5	0.0 0.5			0.0 0.5	0.3 0.5			
Production Planning	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5	■	0.3 0.3	0.3 0.8	0.3 0.8	0.3 0.8	0.3 0.8		0.3 0.8		0.3 0.8
Product Development	0.5 0.5	0.5 0.5	0.5 0.5	0.3 0.3	0.0 0.5	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5		■					0.5 0.5			
Impregnation	0.3 0.5	0.3 0.5	0.5 0.5	0.5 0.3		0.3 0.5	0.3 0.5		0.3 0.5	0.3 0.5		■						0.5 0.5	
Oxidation / Drying			0.3 0.5	0.3 0.5				0.5 0.5		0.3 0.5		0.3 0.5	■					0.5 0.5	
Drumming			0.3 0.5	0.3 0.5						0.3 0.5				■	0.5 0.5				0.3 0.5
Reduction			0.5 0.5	0.5 0.5						0.3 0.5			0.3 0.5	0.3 0.5	■			0.8 0.5	
Product Designer	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5		0.3 0.8					■	0.3 0.5	0.0 0.5	
Supply Chain Planner		0.3 0.5		0.3 0.5			0.0 0.5	0.0 0.5		0.5 0.8	0.3 0.3					0.3 0.5	■	0.3 0.5	0.3 0.3
Production Staff	0.3 0.5	0.3 0.5	0.5 0.5	0.3 0.5	0.3 0.3	0.3 0.5	0.3 0.5	0.3 0.5	0.3 0.5	0.5 0.8	0.3 0.3	0.5 0.8	0.5 0.8	0.3 0.8	0.5 0.8		0.3 0.8	■	0.3 0.5
Warehouse Staff			0.3 0.5							0.5 0.5				0.3 0.8			0.3 0.3	0.3 0.8	■

Figure 7.21: The numerical representation of the directly connected change risk values in a multilayer network for the production system of UOP Honeywell

7.4.4 Compute Combined Change Propagation

The Change Propagation Method (CPM) is used to estimate the 'combined risk matrix'. This matrix indicates the total risk of change initiated in one element (in the column) propagating to any other element in the system (in the row), either directly or through a chain of intermediate connections. The risk is calculated as *Risk=Likelihood x Impact*. The likelihood and impact values were drawn and quantified as a combined risk value using CPM software (Figure 7.22). The shading colours from dark green to yellowish indicate the lower to highest risk values. Figure 7.22 also indicates each layer (domain) of the system and their network relations, for instance, '*Change Requirements*' has relations with '*Product Specifications'* or '*Production Process'*.

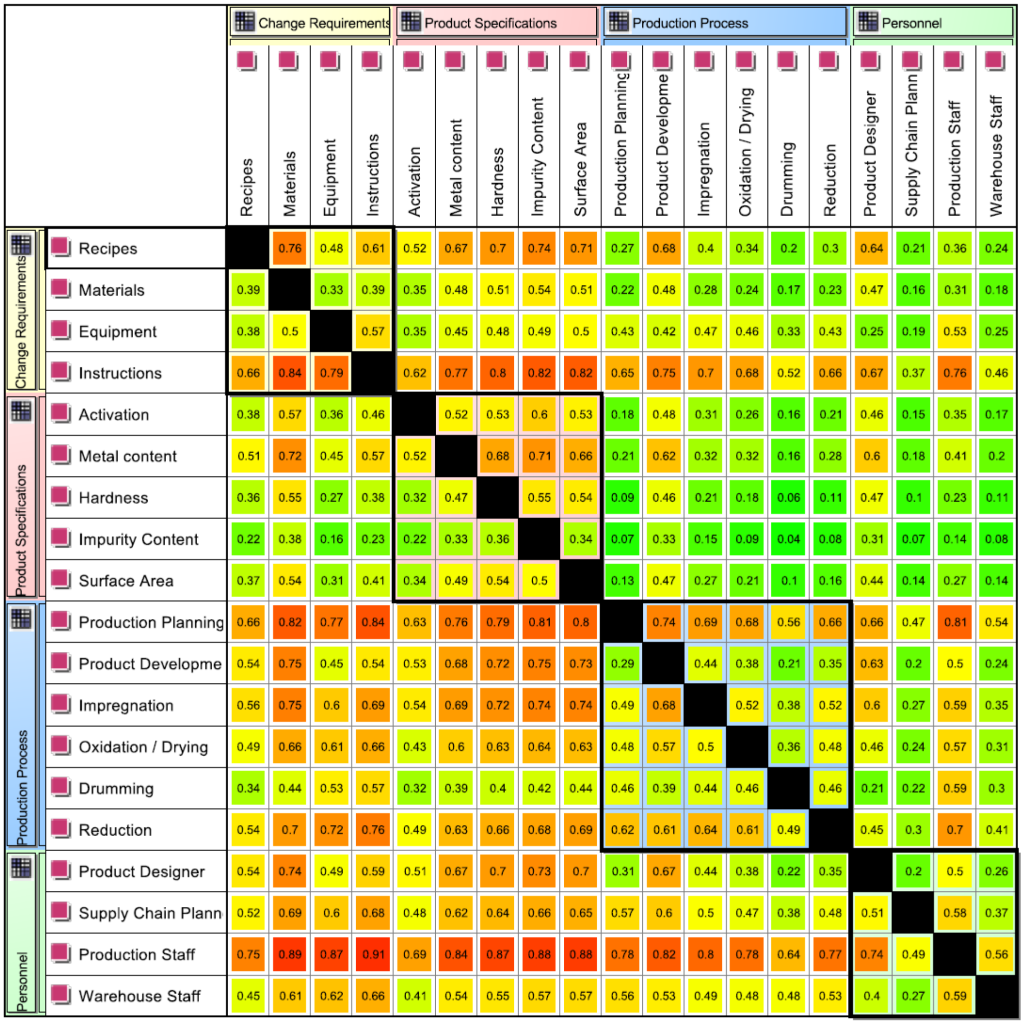


		Change Requirements				Product Specifications					Production Process						Personnel			
		Recipes	Materials	Equipment	Instructions	Activation	Metal content	Hardness	Impurity Content	Surface Area	Production Planning	Product Developme	Impregnation	Oxidation / Drying	Drumming	Reduction	Product Designer	Supply Chain Plann	Production Staff	Warehouse Staff
Change Requirements	Recipes	■	0.24			0.15	0.15	0.15	0.15	0.15		0.24					0.15		0.15	
	Materials	0.15	■		0.09	0.09	0.09	0.09	0.09	0.09		0.15								0.15
	Equipment			■	0.15								0.15	0.15		0.15			0.15	
	Instructions	0.15	0.24	0.24	■	0.15	0.15	0.15	0.15	0.15		0.15	0.24	0.24	0.24	0.24			0.25	
Product Specifications	Activation		0.15			■	0.15		0.25			0.15				0.15	0.15			
	Metal content		0.15			0.24	■	0.25	0.15	0.25		0.15	0.25				0.15			
	Hardness		0.15				0.15	■		0.25		0.15					0.15			
	Impurity Content		0.15			0.0	0.15		■			0.0	0.0			0.0	0.15			
	Surface Area		0.15					0.25	0.15	■		0.15		0.15			0.15			
Production Process	Production Planning	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	■	0.09	0.24	0.24	0.24	0.24		0.24		0.24
	Product Developme	0.25	0.25	0.09	0.25	0.0	0.15	0.15	0.15	0.15		■					0.25			
	Impregnation	0.15	0.15	0.15	0.25		0.15	0.15	0.15		0.15		■						0.25	
	Oxidation / Drying			0.15	0.15					0.25	0.15		0.15	■					0.25	
	Drumming			0.15	0.15						0.15				■	0.25				0.15
	Reduction			0.25	0.25						0.15			0.15	0.15	■			0.4	
Personnel	Product Designer	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15		0.24					■	0.15	0.0	
	Supply Chain Plann		0.15	0.15				0.0		0.0	0.4	0.09					0.15	■	0.15	0.09
	Production Staff	0.15	0.15	0.15	0.25	0.09	0.15	0.15	0.15	0.15	0.4	0.09	0.4	0.4	0.24	0.4		0.24	■	0.15
	Warehouse Staff				0.15						0.25				0.24			0.09	0.24	■

Key: 🟩 low risk (r<30%) 🟧 medium risk (30%< r<70%) 🟥 high risk (r>70%)

Figure 7.22: Numerical representation of the directly connected change risk values in a multilayer network for the elements of a production system

Applying the CPM algorithm to the case study, the indirect connections between the 19 elements can be generated by using *the three-step propagation analysis* to calculate the combined change risks. The risk values are given for different pairs of elements within MLN in Figure 7.23. The results reveal that all elements are affected simultaneously when taking the highest risk into account. The colour scale specifies the risk values as follows: the red cells are the higher risk (R>70%), the yellow cells are the medium risk (30% < R<70%) and the green cells are low risks (R< 30%). This combined matrix contains the maximum combined risk values within the 4 square DSM (Design Structure Matrix) and the 12 DMMs (Domain Mapping Matrix) (Figure 7.23). A different view of the combined risk can be generated. For instance, the blocks within *the change requirements* and *product specifications* can be combined to generate an element-to-element change risk plot, similar to the result of CPM (Keller *et al.* 2009). This will be discussed in the model evaluation section 8.



		Change Requirements				Product Specifications					Production Process						Personnel			
		Recipes	Materials	Equipment	Instructions	Activation	Metal content	Hardness	Impurity Content	Surface Area	Production Planning	Product Developme	Impregnation	Oxidation / Drying	Drumming	Reduction	Product Designer	Supply Chain Plann	Production Staff	Warehouse Staff
Change Requirements	Recipes		0.76	0.48	0.61	0.52	0.67	0.7	0.74	0.71	0.27	0.68	0.4	0.34	0.2	0.3	0.64	0.21	0.36	0.24
	Materials	0.39		0.33	0.39	0.35	0.48	0.51	0.54	0.51	0.22	0.48	0.28	0.24	0.17	0.23	0.47	0.16	0.31	0.18
	Equipment	0.38	0.5		0.57	0.35	0.45	0.48	0.49	0.5	0.43	0.42	0.47	0.46	0.33	0.43	0.25	0.19	0.53	0.25
	Instructions	0.66	0.84	0.79		0.62	0.77	0.8	0.82	0.82	0.65	0.75	0.7	0.68	0.52	0.66	0.67	0.37	0.76	0.46
Product Specifications	Activation	0.38	0.57	0.36	0.46		0.52	0.53	0.6	0.53	0.18	0.48	0.31	0.26	0.16	0.21	0.46	0.15	0.35	0.17
	Metal content	0.51	0.72	0.45	0.57	0.52		0.68	0.71	0.66	0.21	0.62	0.32	0.32	0.16	0.28	0.6	0.18	0.41	0.2
	Hardness	0.36	0.55	0.27	0.38	0.32	0.47		0.55	0.54	0.09	0.46	0.21	0.18	0.06	0.11	0.47	0.1	0.23	0.11
	Impurity Content	0.22	0.38	0.16	0.23	0.22	0.33	0.36		0.34	0.07	0.33	0.15	0.09	0.04	0.08	0.31	0.07	0.14	0.08
	Surface Area	0.37	0.54	0.31	0.41	0.34	0.49	0.54	0.5		0.13	0.47	0.27	0.21	0.1	0.16	0.44	0.14	0.27	0.14
Production Process	Production Planning	0.66	0.82	0.77	0.84	0.63	0.76	0.79	0.81	0.8		0.74	0.69	0.68	0.56	0.66	0.66	0.47	0.81	0.54
	Product Developme	0.54	0.75	0.45	0.54	0.53	0.68	0.72	0.75	0.73	0.29		0.44	0.38	0.21	0.35	0.63	0.2	0.5	0.24
	Impregnation	0.56	0.75	0.6	0.69	0.54	0.69	0.72	0.74	0.74	0.49	0.68		0.52	0.38	0.52	0.6	0.27	0.59	0.35
	Oxidation / Drying	0.49	0.66	0.61	0.66	0.43	0.6	0.63	0.64	0.63	0.48	0.57	0.5		0.36	0.48	0.46	0.24	0.57	0.31
	Drumming	0.34	0.44	0.53	0.57	0.32	0.39	0.4	0.42	0.44	0.46	0.39	0.44	0.46		0.46	0.21	0.22	0.59	0.3
	Reduction	0.54	0.7	0.72	0.76	0.49	0.63	0.66	0.68	0.69	0.62	0.61	0.64	0.61	0.49		0.45	0.3	0.7	0.41
Personnel	Product Designer	0.54	0.74	0.49	0.59	0.51	0.67	0.7	0.73	0.7	0.31	0.67	0.44	0.38	0.22	0.35		0.2	0.5	0.26
	Supply Chain Plann	0.52	0.69	0.6	0.68	0.48	0.62	0.64	0.66	0.65	0.57	0.6	0.5	0.47	0.38	0.48	0.51		0.58	0.37
	Production Staff	0.75	0.89	0.87	0.91	0.69	0.84	0.87	0.88	0.88	0.78	0.82	0.8	0.78	0.64	0.77	0.74	0.49		0.56
	Warehouse Staff	0.45	0.61	0.62	0.66	0.41	0.54	0.55	0.57	0.57	0.56	0.53	0.49	0.48	0.48	0.53	0.4	0.27	0.59	

Figure 7.23: Results of running the change prediction method algorithm to represent the indirectly connected risk values in a multilayer network for the elements of the production system

7.4.5. Use of the Change Risk Model for Decision Making

Comparing direct and indirect risk values by the author

This MLN matrix consists of the dependency connectivity of 4 DSMs (1, 6, 11, 16) and 12 DMMs (2 3, 4, 5, 7, 8, 9, 10, 12, 13, 14, 15) (Figure 7.24). Figure 7.24 (a) and (b) provide the computed results of the direct and indirect change propagations. Fields 1, 6, 11, and 16 subsequently show the interaction between Change Requirements, Product Specifications, Production Process and Personnel. Fields 5, 9, and 13 indicate the performance rating of elements that are associated with the elements of change requirements. Fields 2, 10, and 14 indicate the performance rating of elements that are connected with the elements of product specifications. Fields 3, 7, and 15 indicate the performance rating elements which are related to the elements of the production process. Finally, fields 4, 8, and 12 indicate the performance rating of elements which are attendant on the elements of the manufacturing personnel (Figure 7.24).

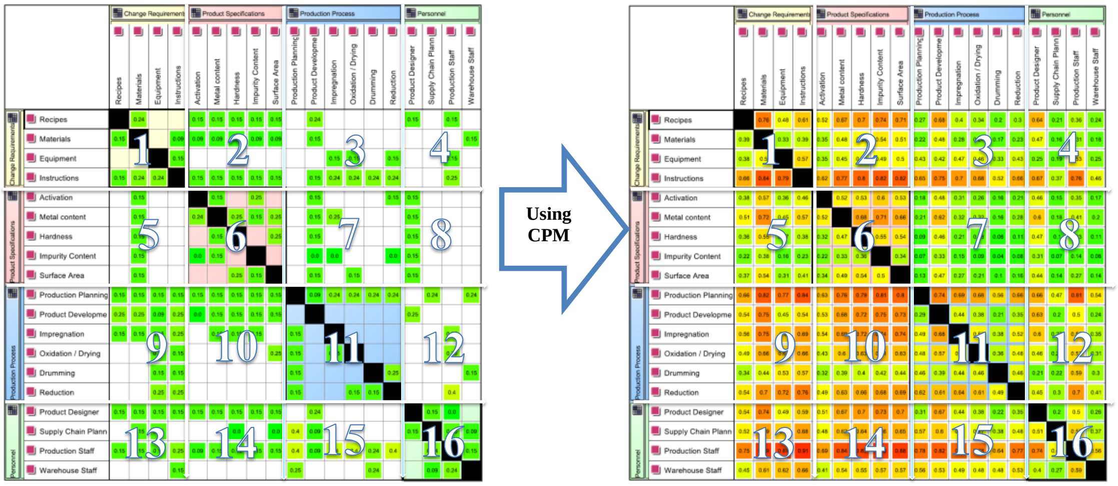
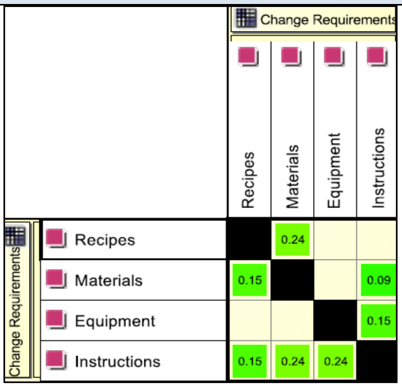
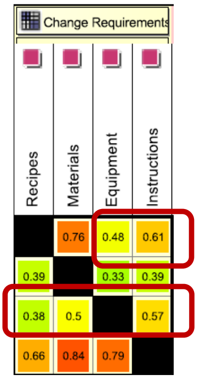
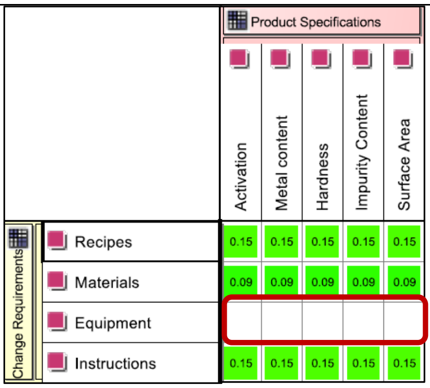
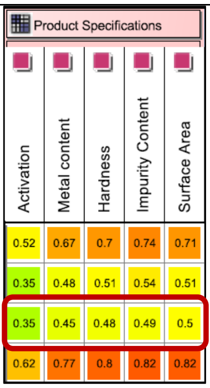
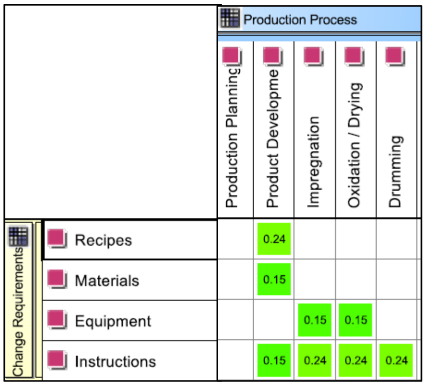
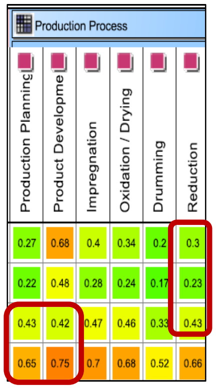
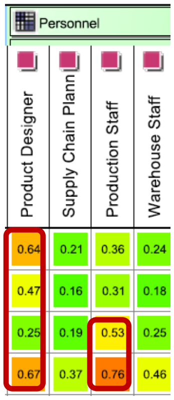
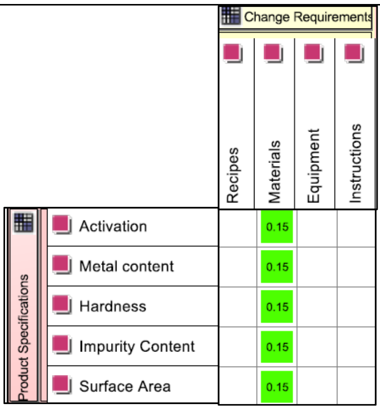
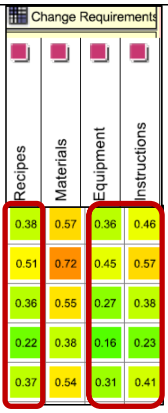
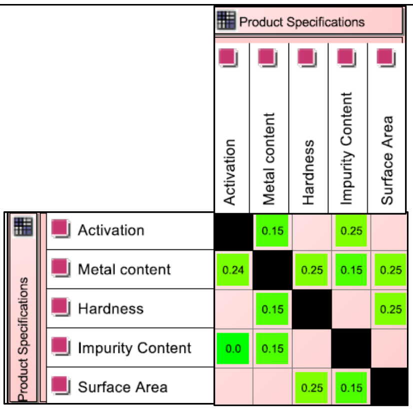
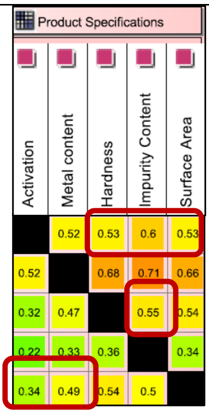


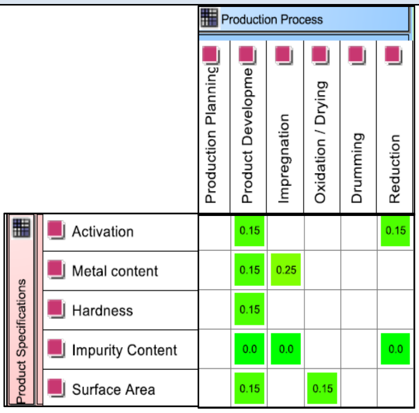
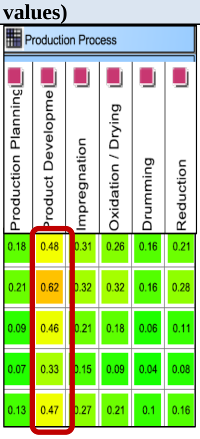
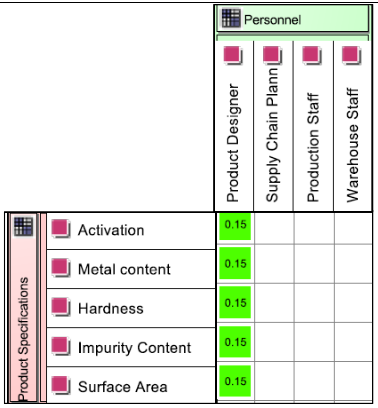
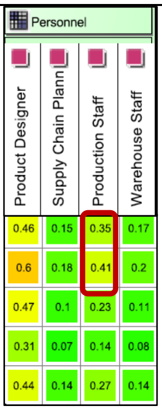
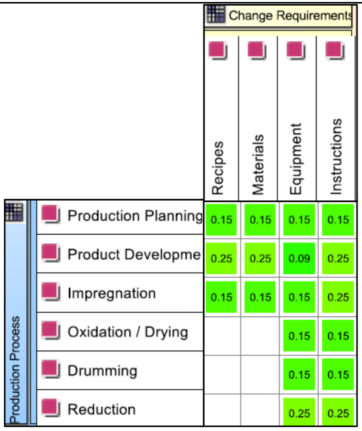
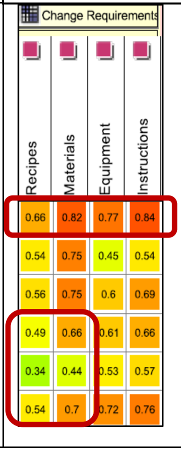
Figure 7.24: Numerical representation of them directly (a) and indirectly (b) connected risk values for for the element of the production system

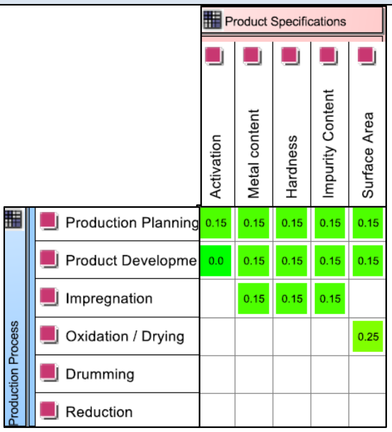
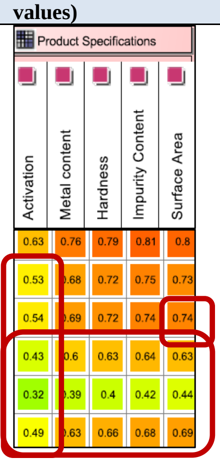
Figure 7.24 (a) and (b) based on data in Table 7.9 indicates the differences between the original input data and the final results. Unfortunately, due to plant closure, the comparison could not be assessed by manufacturing personnel and was undertaken instead by the author. Only those risks at the high end of the spectrum were analysed further.

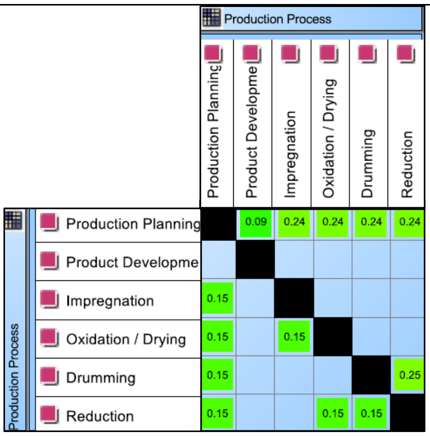
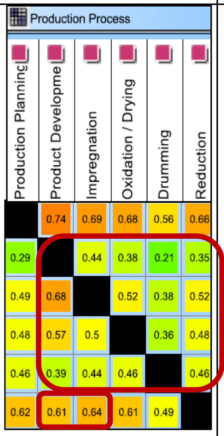
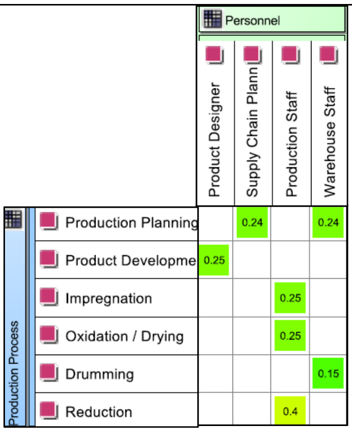
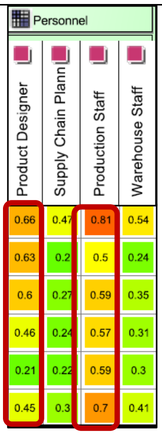
Table 7.10: The comparison of the direct and indirect risk values for the element of the production system

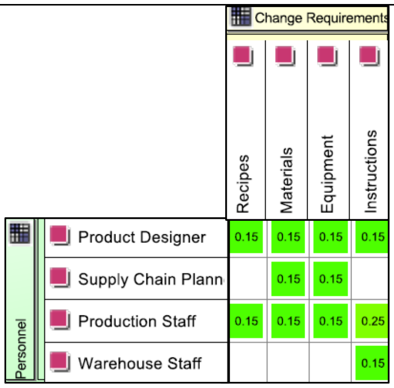
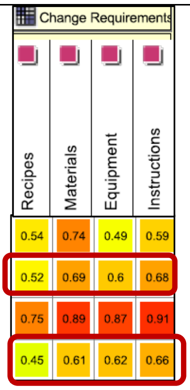
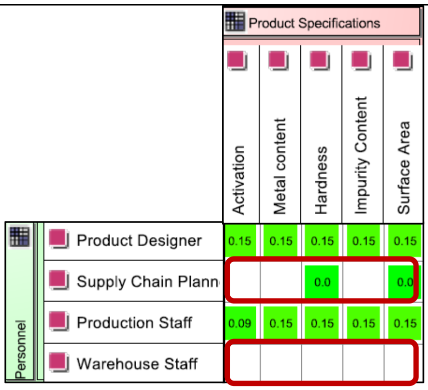
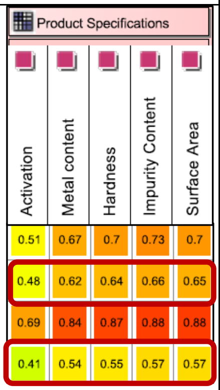
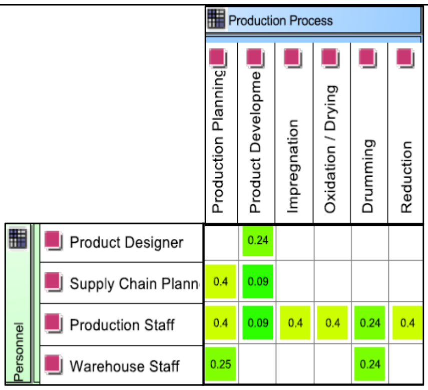
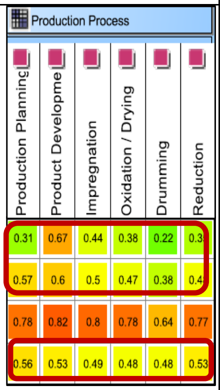
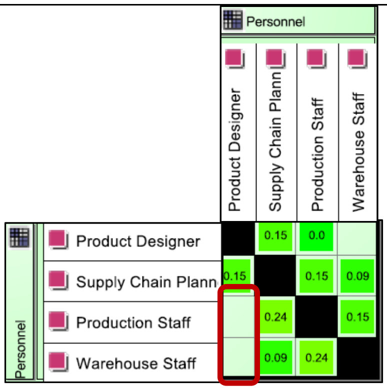
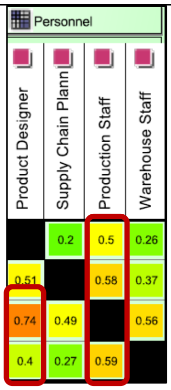
<table>
<tr><th>No</th><th>The input data
(the direct connected Risk=Likelihood x Impact values)</th><th>The CPM Algorithm results
(the indirectly connected risk values)</th><th>Comparison of the input data and final results</th></tr>
<tr><td>1</td><td>

<table>
<tr><th>Change Requirements</th><th></th><th colspan="4">Change Requirements</th></tr>
<tr><th></th><th></th><th>Recipes</th><th>Materials</th><th>Equipment</th><th>Instructions</th></tr>
<tr><td>Change Requirements</td><td>Recipes</td><td></td><td>0.24</td><td></td><td></td></tr>
<tr><td></td><td>Materials</td><td>0.15</td><td></td><td></td><td>0.09</td></tr>
<tr><td></td><td>Equipment</td><td></td><td></td><td></td><td>0.15</td></tr>
<tr><td></td><td>Instructions</td><td>0.15</td><td>0.24</td><td>0.24</td><td></td></tr>
</table>
</td><td>

<table>
<tr><th colspan="4">Change Requirements</th></tr>
<tr><th>Recipes</th><th>Materials</th><th>Equipment</th><th>Instructions</th></tr>
<tr><td></td><td>0.76</td><td>0.48</td><td>0.61</td></tr>
<tr><td>0.39</td><td></td><td>0.33</td><td>0.39</td></tr>
<tr><td>0.38</td><td>0.5</td><td></td><td>0.57</td></tr>
<tr><td>0.66</td><td>0.84</td><td>0.79</td><td></td></tr>
</table>
</td><td>Unexpected change propagation towards the *Materials, Equipment and Instruction* when changes initiated on all the elements of *Change Requirements*.
This result makes sense, for instance, the company changed one of the reduction reactors but considered only possible impact on the *Instruction* and it was updated. But the reactor start-up process required some changes on the process temperatures and pressures, so *Recipes* also updated. The software picked it up.</td></tr>
<tr><td>2</td><td>

<table>
<tr><th>Change Requirements</th><th></th><th colspan="5">Product Specifications</th></tr>
<tr><th></th><th></th><th>Activation</th><th>Metal content</th><th>Hardness</th><th>Impurity Content</th><th>Surface Area</th></tr>
<tr><td>Change Requirements</td><td>Recipes</td><td>0.15</td><td>0.15</td><td>0.15</td><td>0.15</td><td>0.15</td></tr>
<tr><td></td><td>Materials</td><td>0.09</td><td>0.09</td><td>0.09</td><td>0.09</td><td>0.09</td></tr>
<tr><td></td><td>Equipment</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>Instructions</td><td>0.15</td><td>0.15</td><td>0.15</td><td>0.15</td><td>0.15</td></tr>
</table>
</td><td>

<table>
<tr><th colspan="5">Product Specifications</th></tr>
<tr><th>Activation</th><th>Metal content</th><th>Hardness</th><th>Impurity Content</th><th>Surface Area</th></tr>
<tr><td>0.52</td><td>0.67</td><td>0.7</td><td>0.74</td><td>0.71</td></tr>
<tr><td>0.35</td><td>0.48</td><td>0.51</td><td>0.54</td><td>0.51</td></tr>
<tr><td>0.35</td><td>0.45</td><td>0.48</td><td>0.49</td><td>0.5</td></tr>
<tr><td>0.62</td><td>0.77</td><td>0.8</td><td>0.82</td><td>0.82</td></tr>
</table>
</td><td>CPM algorithm found unexpected change propagation on *Equipment* with initiated changes on all *Production Specifications.* However, it did not receive direct change propagation in the workshop.</td></tr>
<tr><td>3</td><td>

<table>
<tr><th>Change Requirements</th><th></th><th colspan="5">Production Process</th></tr>
<tr><th></th><th></th><th>Production Planning</th><th>Product Developme</th><th>Impregnation</th><th>Oxidation / Drying</th><th>Drumming</th></tr>
<tr><td>Change Requirements</td><td>Recipes</td><td></td><td>0.24</td><td></td><td></td><td></td></tr>
<tr><td></td><td>Materials</td><td></td><td>0.15</td><td></td><td></td><td></td></tr>
<tr><td></td><td>Equipment</td><td></td><td></td><td>0.15</td><td>0.15</td><td></td></tr>
<tr><td></td><td>Instructions</td><td></td><td>0.15</td><td>0.24</td><td>0.24</td><td>0.24</td></tr>
</table>
</td><td>

<table>
<tr><th colspan="6">Production Process</th></tr>
<tr><th>Production Planning</th><th>Product Developme</th><th>Impregnation</th><th>Oxidation / Drying</th><th>Drumming</th><th>Reduction</th></tr>
<tr><td>0.27</td><td>0.68</td><td>0.4</td><td>0.34</td><td>0.2</td><td>0.3</td></tr>
<tr><td>0.22</td><td>0.48</td><td>0.28</td><td>0.24</td><td>0.17</td><td>0.23</td></tr>
<tr><td>0.43</td><td>0.42</td><td>0.47</td><td>0.46</td><td>0.33</td><td>0.43</td></tr>
<tr><td>0.65</td><td>0.75</td><td>0.7</td><td>0.68</td><td>0.52</td><td>0.66</td></tr>
</table>
</td><td>Unexpected change propagation on *Equipment* and *Instructions* with changes on the *Production Planning*.</td></tr>
</table>

<table>
<tr><th>No</th><th>The input data
(the direct connected Risk=Likelihood x Impact values)</th><th>The CPM Algorithm results
(the indirectly connected risk values)</th><th>Comparison of the input data and final results</th></tr>
<tr><td>4</td><td>
<table>
<tr><th>Change Requirements</th><th>Personnel: Product Designer</th><th>Supply Chain Plann</th><th>Production Staff</th><th>Warehouse Staff</th></tr>
<tr><td>Recipes</td><td>0.15</td><td></td><td>0.15</td><td></td></tr>
<tr><td>Materials</td><td></td><td></td><td></td><td>0.15</td></tr>
<tr><td>Equipment</td><td></td><td></td><td>0.15</td><td></td></tr>
<tr><td>Instructions</td><td></td><td></td><td>0.25</td><td></td></tr>
</table></td><td>
<table>
<tr><th>Personnel: Product Designer</th><th>Supply Chain Plann</th><th>Production Staff</th><th>Warehouse Staff</th></tr>
<tr><td>0.64</td><td>0.21</td><td>0.36</td><td>0.24</td></tr>
<tr><td>0.47</td><td>0.16</td><td>0.31</td><td>0.18</td></tr>
<tr><td>0.25</td><td>0.19</td><td>0.53</td><td>0.25</td></tr>
<tr><td>0.67</td><td>0.37</td><td>0.76</td><td>0.46</td></tr>
</table></td><td>Change propagation towards Product Designer to the Materials, Equipment and Instructions. Changes on Warehouse Staff give an unexpected 46% of the risk on Instructions, which was not expected.</td></tr>
<tr><td>5</td><td>
<table>
<tr><th>Product Specifications</th><th>Change Requirements: Recipes</th><th>Materials</th><th>Equipment</th><th>Instructions</th></tr>
<tr><td>Activation</td><td></td><td>0.15</td><td></td><td></td></tr>
<tr><td>Metal content</td><td></td><td>0.15</td><td></td><td></td></tr>
<tr><td>Hardness</td><td></td><td>0.15</td><td></td><td></td></tr>
<tr><td>Impurity Content</td><td></td><td>0.15</td><td></td><td></td></tr>
<tr><td>Surface Area</td><td></td><td>0.15</td><td></td><td></td></tr>
</table></td><td>
<table>
<tr><th>Change Requirements: Recipes</th><th>Materials</th><th>Equipment</th><th>Instructions</th></tr>
<tr><td>0.38</td><td>0.57</td><td>0.36</td><td>0.46</td></tr>
<tr><td>0.51</td><td>0.72</td><td>0.45</td><td>0.57</td></tr>
<tr><td>0.36</td><td>0.55</td><td>0.27</td><td>0.38</td></tr>
<tr><td>0.22</td><td>0.38</td><td>0.16</td><td>0.23</td></tr>
<tr><td>0.37</td><td>0.54</td><td>0.31</td><td>0.41</td></tr>
</table></td><td>CPM algorithm predicts unexpected risk through Recipes, Equipment and Instructions towards all elements of Product Specifications.</td></tr>
<tr><td>6</td><td>
<table>
<tr><th>Product Specifications</th><th>Product Specifications: Activation</th><th>Metal content</th><th>Hardness</th><th>Impurity Content</th><th>Surface Area</th></tr>
<tr><td>Activation</td><td></td><td>0.15</td><td></td><td>0.25</td><td></td></tr>
<tr><td>Metal content</td><td>0.24</td><td></td><td>0.25</td><td>0.15</td><td>0.25</td></tr>
<tr><td>Hardness</td><td></td><td>0.15</td><td></td><td></td><td>0.25</td></tr>
<tr><td>Impurity Content</td><td>0.0</td><td>0.15</td><td></td><td></td><td></td></tr>
<tr><td>Surface Area</td><td></td><td></td><td>0.25</td><td>0.15</td><td></td></tr>
</table></td><td>
<table>
<tr><th>Product Specifications: Activation</th><th>Metal content</th><th>Hardness</th><th>Impurity Content</th><th>Surface Area</th></tr>
<tr><td></td><td>0.52</td><td>0.53</td><td>0.6</td><td>0.53</td></tr>
<tr><td>0.52</td><td></td><td>0.68</td><td>0.71</td><td>0.66</td></tr>
<tr><td>0.32</td><td>0.47</td><td></td><td>0.55</td><td>0.54</td></tr>
<tr><td>0.22</td><td>0.33</td><td>0.36</td><td></td><td>0.34</td></tr>
<tr><td>0.34</td><td>0.49</td><td>0.54</td><td>0.5</td><td></td></tr>
</table></td><td>The elements of Product Specification propagate risk between each other. For instance, change initiating on Impurity Content of a catalyst, such as a reduction in impurity, will affect the Hardness of catalyst that CAM software picked up with the 55% risk. In addition, increasing the Metal Content of the catalyst indirectly may affect the Surface Area of the catalyst. Catalyst Surface Area increases reaction in the refinery process.</td></tr>
</table>

<table>
<tr><th>No</th><th>The input data
(the direct connected Risk=Likelihood x Impact values)</th><th>The CPM Algorithm results
(the indirectly connected risk values)</th><th>Comparison of the input data and final results</th></tr>
<tr><td>7</td><td>
<table>
<tr><th>Product Specifications</th><th>Production Process
Production Planning</th><th>Product Developme</th><th>Impregnation</th><th>Oxidation / Drying</th><th>Drumming</th><th>Reduction</th></tr>
<tr><td>Activation</td><td></td><td>0.15</td><td></td><td></td><td></td><td>0.15</td></tr>
<tr><td>Metal content</td><td></td><td>0.15</td><td>0.25</td><td></td><td></td><td></td></tr>
<tr><td>Hardness</td><td></td><td>0.15</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Impurity Content</td><td></td><td>0.0</td><td>0.0</td><td></td><td></td><td>0.0</td></tr>
<tr><td>Surface Area</td><td></td><td>0.15</td><td></td><td>0.15</td><td></td><td></td></tr>
</table></td><td>
<table>
<tr><th>Production Process
Production Planning</th><th>Product Developme</th><th>Impregnation</th><th>Oxidation / Drying</th><th>Drumming</th><th>Reduction</th></tr>
<tr><td>0.18</td><td>0.48</td><td>0.31</td><td>0.26</td><td>0.16</td><td>0.21</td></tr>
<tr><td>0.21</td><td>0.62</td><td>0.32</td><td>0.32</td><td>0.16</td><td>0.28</td></tr>
<tr><td>0.09</td><td>0.46</td><td>0.21</td><td>0.18</td><td>0.06</td><td>0.11</td></tr>
<tr><td>0.07</td><td>0.33</td><td>0.15</td><td>0.09</td><td>0.04</td><td>0.08</td></tr>
<tr><td>0.13</td><td>0.47</td><td>0.27</td><td>0.21</td><td>0.1</td><td>0.16</td></tr>
</table></td><td>Any changes coming from the <i>Product Development</i> process surely must affect the element of <i>Product Specification.</i></td></tr>
<tr><td>8</td><td>
<table>
<tr><th>Product Specifications</th><th>Personnel
Product Designer</th><th>Supply Chain Plann</th><th>Production Staff</th><th>Warehouse Staff</th></tr>
<tr><td>Activation</td><td>0.15</td><td></td><td></td><td></td></tr>
<tr><td>Metal content</td><td>0.15</td><td></td><td></td><td></td></tr>
<tr><td>Hardness</td><td>0.15</td><td></td><td></td><td></td></tr>
<tr><td>Impurity Content</td><td>0.15</td><td></td><td></td><td></td></tr>
<tr><td>Surface Area</td><td>0.15</td><td></td><td></td><td></td></tr>
</table></td><td>
<table>
<tr><th>Personnel
Product Designer</th><th>Supply Chain Plann</th><th>Production Staff</th><th>Warehouse Staff</th></tr>
<tr><td>0.46</td><td>0.15</td><td>0.35</td><td>0.17</td></tr>
<tr><td>0.6</td><td>0.18</td><td>0.41</td><td>0.2</td></tr>
<tr><td>0.47</td><td>0.1</td><td>0.23</td><td>0.11</td></tr>
<tr><td>0.31</td><td>0.07</td><td>0.14</td><td>0.08</td></tr>
<tr><td>0.44</td><td>0.14</td><td>0.27</td><td>0.14</td></tr>
</table></td><td>Undesirable change propagation on <i>Production Specifications</i> elements of <i>Activation</i> and <i>Metal Content</i> is associated with change on <i>Production Staff.</i>
In catalyst production, the Metal Content and Activation are the most critical specs of catalyst. The experience of <i>Production Staff</i> may significantly affect the product quality or product specifications.</td></tr>
<tr><td>9</td><td>
<table>
<tr><th>Production Process</th><th>Change Requirements
Recipes</th><th>Materials</th><th>Equipment</th><th>Instructions</th></tr>
<tr><td>Production Planning</td><td>0.15</td><td>0.15</td><td>0.15</td><td>0.15</td></tr>
<tr><td>Product Developme</td><td>0.25</td><td>0.25</td><td>0.09</td><td>0.25</td></tr>
<tr><td>Impregnation</td><td>0.15</td><td>0.15</td><td>0.15</td><td>0.25</td></tr>
<tr><td>Oxidation / Drying</td><td></td><td></td><td>0.15</td><td>0.15</td></tr>
<tr><td>Drumming</td><td></td><td></td><td>0.15</td><td>0.15</td></tr>
<tr><td>Reduction</td><td></td><td></td><td>0.25</td><td>0.25</td></tr>
</table></td><td>
<table>
<tr><th>Change Requirements
Recipes</th><th>Materials</th><th>Equipment</th><th>Instructions</th></tr>
<tr><td>0.66</td><td>0.82</td><td>0.77</td><td>0.84</td></tr>
<tr><td>0.54</td><td>0.75</td><td>0.45</td><td>0.54</td></tr>
<tr><td>0.56</td><td>0.75</td><td>0.6</td><td>0.69</td></tr>
<tr><td>0.49</td><td>0.66</td><td>0.61</td><td>0.66</td></tr>
<tr><td>0.34</td><td>0.44</td><td>0.53</td><td>0.57</td></tr>
<tr><td>0.54</td><td>0.7</td><td>0.72</td><td>0.76</td></tr>
</table></td><td>Any change initiating within the elements of <i>Change Requirements</i> will significantly impact <i>Production Planning.</i>
<i>Recipes and Materials</i> changes impact the Production process of <i>Oxidation & Drying, Drumming and Reduction</i>, which can be expected.</td></tr>
</table>

<table>
<tr><th>No</th><th>The input data
(the direct connected Risk=Likelihood x Impact values)</th><th>The CPM Algorithm results
(the indirectly connected risk values)</th><th>Comparison of the input data and final results</th></tr>
<tr><td>10</td><td>
<table>
<tr><th></th><th colspan="5">Product Specifications</th></tr>
<tr><th>Production Process</th><th>Activation</th><th>Metal content</th><th>Hardness</th><th>Impurity Content</th><th>Surface Area</th></tr>
<tr><td>Production Planning</td><td>0.15</td><td>0.15</td><td>0.15</td><td>0.15</td><td>0.15</td></tr>
<tr><td>Product Developme</td><td>0.0</td><td>0.15</td><td>0.15</td><td>0.15</td><td>0.15</td></tr>
<tr><td>Impregnation</td><td></td><td>0.15</td><td>0.15</td><td>0.15</td><td></td></tr>
<tr><td>Oxidation / Drying</td><td></td><td></td><td></td><td></td><td>0.25</td></tr>
<tr><td>Drumming</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Reduction</td><td></td><td></td><td></td><td></td><td></td></tr>
</table></td><td>
<table>
<tr><th colspan="5">Product Specifications</th></tr>
<tr><th>Activation</th><th>Metal content</th><th>Hardness</th><th>Impurity Content</th><th>Surface Area</th></tr>
<tr><td>0.63</td><td>0.76</td><td>0.79</td><td>0.81</td><td>0.8</td></tr>
<tr><td>0.53</td><td>.68</td><td>0.72</td><td>0.75</td><td>0.73</td></tr>
<tr><td>0.54</td><td>.69</td><td>0.72</td><td>0.74</td><td>0.74</td></tr>
<tr><td>0.43</td><td>0.6</td><td>0.63</td><td>0.64</td><td>0.63</td></tr>
<tr><td>0.32</td><td>.39</td><td>0.4</td><td>0.42</td><td>0.44</td></tr>
<tr><td>0.49</td><td>.63</td><td>0.66</td><td>0.68</td><td>0.69</td></tr>
</table></td><td>Unexpected results obtained with changes initiating in any Product Specifications affecting Production Process of *Oxidation & Drying*, *Drumming and Reduction.* In addition, changes to the *Surface Area* of catalysts created a 74% risk to the *Impregnation* process.

If we look at the whole production system if any request coming from product improvement that requires changes in the product specifications as well as recipes and instructions these affect the Production Process. In this view, product specifications may influence the production process indirectly.</td></tr>
<tr><td>11</td><td>
<table>
<tr><th></th><th colspan="6">Production Process</th></tr>
<tr><th>Production Process</th><th>Production Planning</th><th>Product Developme</th><th>Impregnation</th><th>Oxidation / Drying</th><th>Drumming</th><th>Reduction</th></tr>
<tr><td>Production Planning</td><td></td><td>0.09</td><td>0.24</td><td>0.24</td><td>0.24</td><td>0.24</td></tr>
<tr><td>Product Developme</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Impregnation</td><td>0.15</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Oxidation / Drying</td><td>0.15</td><td></td><td>0.15</td><td></td><td></td><td></td></tr>
<tr><td>Drumming</td><td>0.15</td><td></td><td></td><td></td><td></td><td>0.25</td></tr>
<tr><td>Reduction</td><td>0.15</td><td></td><td></td><td>0.15</td><td>0.15</td><td></td></tr>
</table></td><td>
<table>
<tr><th colspan="6">Production Process</th></tr>
<tr><th>Production Planning</th><th>Product Developme</th><th>Impregnation</th><th>Oxidation / Drying</th><th>Drumming</th><th>Reduction</th></tr>
<tr><td></td><td>0.74</td><td>0.69</td><td>0.68</td><td>0.56</td><td>0.66</td></tr>
<tr><td>0.29</td><td></td><td>0.44</td><td>0.38</td><td>0.21</td><td>0.35</td></tr>
<tr><td>0.49</td><td>0.68</td><td></td><td>0.52</td><td>0.38</td><td>0.52</td></tr>
<tr><td>0.48</td><td>0.57</td><td>0.5</td><td></td><td>0.36</td><td>0.48</td></tr>
<tr><td>0.46</td><td>0.39</td><td>0.44</td><td>0.46</td><td></td><td>0.46</td></tr>
<tr><td>0.62</td><td>0.61</td><td>0.64</td><td>0.61</td><td>0.49</td><td></td></tr>
</table></td><td>The Catalyst *Production Process* is semi-continuous and the elements may directly affect each other in sequence, for instance, if the stirrer of *Reduction* reactor is broken then the *Drumming* process has to stop. But it indirectly may influence in the quality of catalysts: for instance, any changes to the reduction process may not affect *Impregnation* process physically, but if the catalyst has an impurity during the *Reduction* process, the problem may come from the Impregnation process. The software picked this up with a 52% risk.</td></tr>
<tr><td>12</td><td>
<table>
<tr><th></th><th colspan="4">Personnel</th></tr>
<tr><th>Production Process</th><th>Product Designer</th><th>Supply Chain Plann</th><th>Production Staff</th><th>Warehouse Staff</th></tr>
<tr><td>Production Planning</td><td></td><td>0.24</td><td></td><td>0.24</td></tr>
<tr><td>Product Developme</td><td>0.25</td><td></td><td></td><td></td></tr>
<tr><td>Impregnation</td><td></td><td></td><td>0.25</td><td></td></tr>
<tr><td>Oxidation / Drying</td><td></td><td></td><td>0.25</td><td></td></tr>
<tr><td>Drumming</td><td></td><td></td><td></td><td>0.15</td></tr>
<tr><td>Reduction</td><td></td><td></td><td>0.4</td><td></td></tr>
</table></td><td>
<table>
<tr><th colspan="4">Personnel</th></tr>
<tr><th>Product Designer</th><th>Supply Chain Plann</th><th>Production Staff</th><th>Warehouse Staff</th></tr>
<tr><td>0.66</td><td>0.47</td><td>0.81</td><td>0.54</td></tr>
<tr><td>0.63</td><td>0.2</td><td>0.5</td><td>0.24</td></tr>
<tr><td>0.6</td><td>0.27</td><td>0.59</td><td>0.35</td></tr>
<tr><td>0.46</td><td>0.24</td><td>0.57</td><td>0.31</td></tr>
<tr><td>0.21</td><td>0.22</td><td>0.59</td><td>0.3</td></tr>
<tr><td>0.45</td><td>0.3</td><td>0.7</td><td>0.41</td></tr>
</table></td><td>Based on the CAM results, *Product Designer* and *Production Staff* significantly affect the *Production Process*, which makes sense at the operational level.</td></tr>
</table>

<table>
<tr>
<td>13</td>
<td>
Change Requirements
<table>
<tr><th>Personnel</th><th>Recipes</th><th>Materials</th><th>Equipment</th><th>Instructions</th></tr>
<tr><td>Product Designer</td><td>0.15</td><td>0.15</td><td>0.15</td><td>0.15</td></tr>
<tr><td>Supply Chain Plann</td><td></td><td>0.15</td><td>0.15</td><td></td></tr>
<tr><td>Production Staff</td><td>0.15</td><td>0.15</td><td>0.15</td><td>0.25</td></tr>
<tr><td>Warehouse Staff</td><td></td><td></td><td></td><td>0.15</td></tr>
</table></td>
<td>
Change Requirements
<table>
<tr><th>Recipes</th><th>Materials</th><th>Equipment</th><th>Instructions</th></tr>
<tr><td>0.54</td><td>0.74</td><td>0.49</td><td>0.59</td></tr>
<tr><td>0.52</td><td>0.69</td><td>0.6</td><td>0.68</td></tr>
<tr><td>0.75</td><td>0.89</td><td>0.87</td><td>0.91</td></tr>
<tr><td>0.45</td><td>0.61</td><td>0.62</td><td>0.66</td></tr>
</table></td>
<td>Any changes to the elements of <i>Change Requirements</i> developed unexpected risks on <i>Supply Chain Plan</i> and <i>Warehouse Staff.</i></td>
</tr>
<tr>
<td>14</td>
<td>
Product Specifications
<table>
<tr><th>Personnel</th><th>Activation</th><th>Metal content</th><th>Hardness</th><th>Impurity Content</th><th>Surface Area</th></tr>
<tr><td>Product Designer</td><td>0.15</td><td>0.15</td><td>0.15</td><td>0.15</td><td>0.15</td></tr>
<tr><td>Supply Chain Plann</td><td></td><td></td><td>0.0</td><td></td><td>0.0</td></tr>
<tr><td>Production Staff</td><td>0.09</td><td>0.15</td><td>0.15</td><td>0.15</td><td>0.15</td></tr>
<tr><td>Warehouse Staff</td><td></td><td></td><td></td><td></td><td></td></tr>
</table></td>
<td>
Product Specifications
<table>
<tr><th>Activation</th><th>Metal content</th><th>Hardness</th><th>Impurity Content</th><th>Surface Area</th></tr>
<tr><td>0.51</td><td>0.67</td><td>0.7</td><td>0.73</td><td>0.7</td></tr>
<tr><td>0.48</td><td>0.62</td><td>0.64</td><td>0.66</td><td>0.65</td></tr>
<tr><td>0.69</td><td>0.84</td><td>0.87</td><td>0.88</td><td>0.88</td></tr>
<tr><td>0.41</td><td>0.54</td><td>0.55</td><td>0.57</td><td>0.57</td></tr>
</table></td>
<td>Unforeseen highest risks received on <i>Supply Chain Planner</i> and <i>Warehouse Staff</i> when changes occurred on any the elements of <i>Product Specifications</i>.
Probably these indirect risks can come about out in related to the failed products that required taking action by the <i>Supply Chain Planner</i> on the SAP system.
The movement of the out-off specs products to the blocked location of Warehouse by the <i>Warehouse Staff.</i></td>
</tr>
<tr>
<td>15</td>
<td>
Production Process
<table>
<tr><th>Personnel</th><th>Production Planning</th><th>Product Developme</th><th>Impregnation</th><th>Oxidation / Drying</th><th>Drumming</th><th>Reduction</th></tr>
<tr><td>Product Designer</td><td></td><td>0.24</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Supply Chain Plann</td><td>0.4</td><td>0.09</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Production Staff</td><td>0.4</td><td>0.09</td><td>0.4</td><td>0.4</td><td>0.24</td><td>0.4</td></tr>
<tr><td>Warehouse Staff</td><td>0.25</td><td></td><td></td><td></td><td>0.24</td><td></td></tr>
</table></td>
<td>
Production Process
<table>
<tr><th>Production Planning</th><th>Product Developme</th><th>Impregnation</th><th>Oxidation / Drying</th><th>Drumming</th><th>Reduction</th></tr>
<tr><td>0.31</td><td>0.67</td><td>0.44</td><td>0.38</td><td>0.22</td><td>0.3</td></tr>
<tr><td>0.57</td><td>0.6</td><td>0.5</td><td>0.47</td><td>0.38</td><td>0.4</td></tr>
<tr><td>0.78</td><td>0.82</td><td>0.8</td><td>0.78</td><td>0.64</td><td>0.77</td></tr>
<tr><td>0.56</td><td>0.53</td><td>0.49</td><td>0.48</td><td>0.48</td><td>0.53</td></tr>
</table></td>
<td>Unpredicted results towards <i>Supply Chain Planner</i>, <i>Warehouse Staff</i> and <i>Product Designer received</i> when initiating changes occurred on the element of the Production Process.</td>
</tr>
<tr>
<td>16</td>
<td>
Personnel
<table>
<tr><th>Personnel</th><th>Product Designer</th><th>Supply Chain Plann</th><th>Production Staff</th><th>Warehouse Staff</th></tr>
<tr><td>Product Designer</td><td></td><td>0.15</td><td>0.0</td><td></td></tr>
<tr><td>Supply Chain Plann</td><td>0.15</td><td></td><td>0.15</td><td>0.09</td></tr>
<tr><td>Production Staff</td><td></td><td>0.24</td><td></td><td>0.15</td></tr>
<tr><td>Warehouse Staff</td><td></td><td>0.09</td><td>0.24</td><td></td></tr>
</table></td>
<td>
Personnel
<table>
<tr><th>Product Designer</th><th>Supply Chain Plann</th><th>Production Staff</th><th>Warehouse Staff</th></tr>
<tr><td></td><td>0.2</td><td>0.5</td><td>0.26</td></tr>
<tr><td>0.51</td><td></td><td>0.58</td><td>0.37</td></tr>
<tr><td>0.74</td><td>0.49</td><td></td><td>0.56</td></tr>
<tr><td>0.4</td><td>0.27</td><td>0.59</td><td></td></tr>
</table></td>
<td>Any changes in any <i>Personnel</i> element indirectly create a big impact on the <i>Product Designer</i> and <i>Production Staff.</i></td>
</tr>
</table>

The risk model for decision making

A risk model illustrated in Figure 7.2.3 is a graphical representation that is used to develop prioritisation arrangements identify high and low-risk events. The evaluation of design work through ordering risk estimates enable solutions to be selected relatively effortlessly. In this case study, due to various change requirements (e.g. process, material changes) within the manufacturing site, updating the Operational Instruction is always being required. Therefore, in this section, a combined risk plot was developed to review the initiating change towards *Instruction* to *Material* elements. In Figure 7.25, the initiating changes on '*Instructions'* affect the elements that fall on the lowest left side of the chart with a low likelihood. This suggests that '*Impurity Content'* is relatively more robust to changes when compared with other elements; this also appears on the low middle part of the chart, indicating low impact, and thus is relatively robust or adaptable to changes when compared with other elements. So, impurity content of the catalyst is the least critical as it is unlikely to be changed, and the impact of change is low even if a change is required. There are no elements that fall on the lower left of the chart having a relatively low impact and likelihood. *Activation*, *Surface Area*, *Materials* and *Hardness* of catalyst or absorbent have less than 50% of the combined risk and reside in the low part of the upper top left of the chart. They are at moderate risk of change and impact relatively mildly if a change is required. The elements with over 75% of the combined risk, such as *'Production Staff', 'Production Planning', 'Reduction'*, fall on the upper right of the 3-step change analysis chart and have relatively high impact and likelihood; these elements are the most critical as they are both likely to be changed and causes a high impact to other elements when a change is required.

Table 7.11: The elements for the change requirements of the production system

Element No	Elements Name
1	Recipes
2	Materials
3	Equipment
4	Instructions
5	Activation
6	Metal content
7	Hardness
8	Impurity content
9	Surface Area
10	Production Planning
11	Product Development
12	Impregnation
13	Oxidation & Drying
14	Drumming
15	Reduction
16	Product Designer
17	Supply Chain Planner
18	Production Staff
19	Warehouse Staff

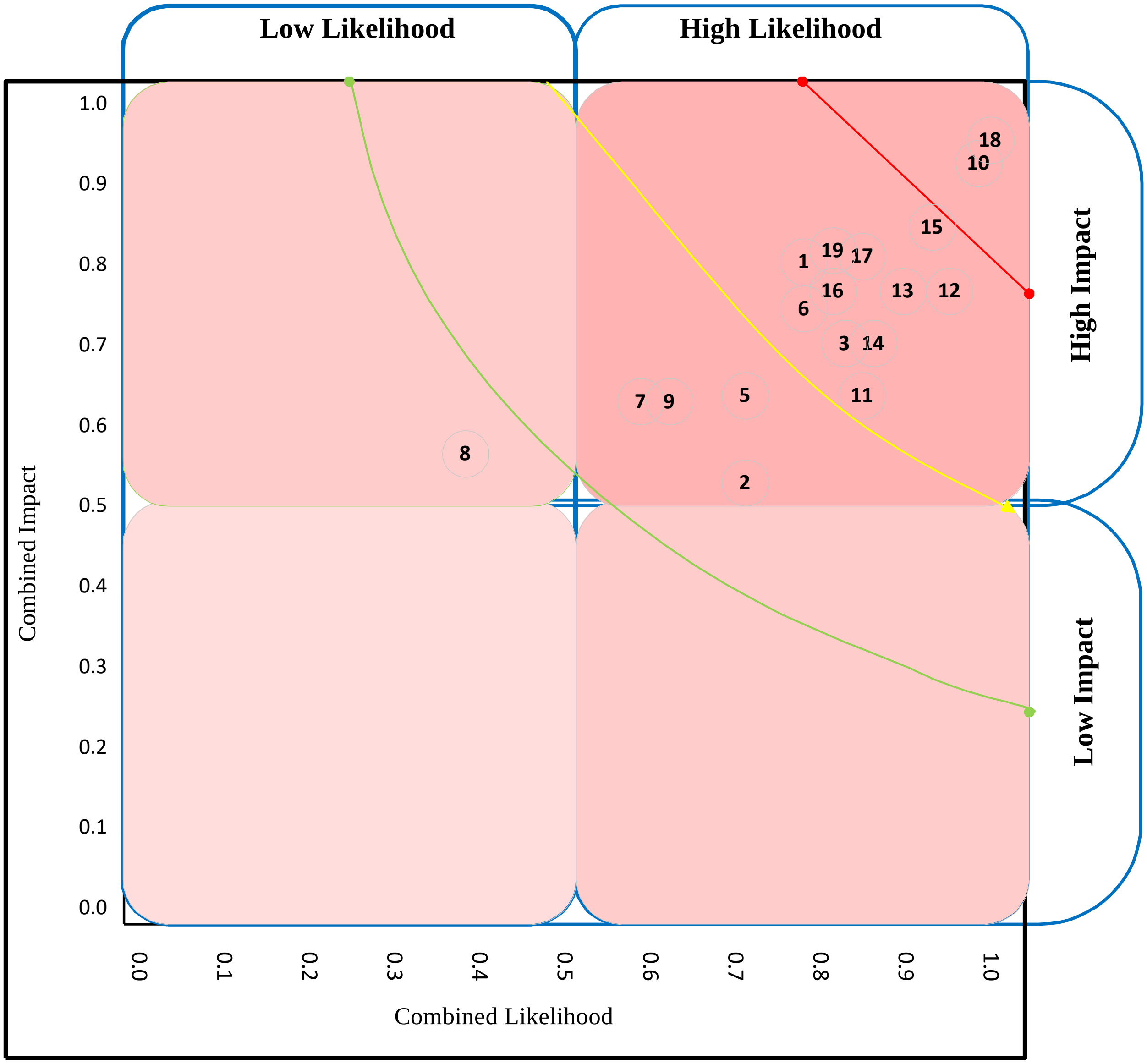


Figure 7.25: The Combined Risk Plot for the Instruction (E4)

CAM software enables the conversion of the combined risk plot to the prioritised change risk list for a change initiator. The prioritisation list separates high and low-risk elements and supports the design effort: when ordering risk estimates, designers can select solution proposals which require less effort to implement. For instance, Table 7.10 shows such a prioritised change risk list for changes resulting from *Instructions (E4)* of production. From the list, it can be seen that the *Production Staff (E18), Production Planning (E10) and Reduction (E15)* are at the highest risk if the operational *Instructions* are changed. The purpose of using prioritisation schemes also supports propagation path examination to identify elements that are critically vulnerable to the effects of change. In a situation where risk-based measures of the design effort provide the only basis for identifying elements for assessments, it is still possible to take on risk beyond that which is desired. Such a prioritised list can help avoid oversight of change impacts on those elements. However, manufacturing experts can use their experience to put things into context and provide better change assessment. For example, given that the '*Instructions*' is also closely connected to the '*Warehouse Staff*' as well as '*Production Staff*', the changed dependency between them also should be 'higher'. However, the combined risk elements path said dependency was 'low'.

Table 7.12: Prioritised change risk list for the change initiator: *Instruction (E4)*

Priority No	**Affected Elements**		**Risk value %**
	Name	**Element No**	
1	**Production Staff**	**E18**	**91**
2	**Production Planning**	**E10**	**84**
3	**Reduction Process**	**E15**	**76**
4	Impregnation Process	E12	69
5	Supply Chain Planner	E17	68
6	Oxidation & Drying	E13	66
7	Warehouse Staff	E19	66
8	Recipes	E1	61
9	Product Designer	E16	59
10	Metal Content of Catalyst	E6	57
11	Drumming	E14	57
12	Equipment	E3	57
13	Product Development	E11	54
14	Activation of Catalyst	E5	46
15	Surface Area of Catalyst	E9	41
16	Materials	E2	39
17	Hardness of Catalyst	E7	38
18	Impurity Content of Catalyst	E8	23

The core of the study consists of the network analysis of change requests, and the development of a set of indices that make possible a quantification of change activity by subsystem area. Based on the results from the CAM software, some of the operation elements are not robust or adaptable to changes. The companies can thus re-evaluate the suitability of standardising such elements and try to improve their change robustness or adaptability based on the prioritised change risk. In general, the results from the case study suggest that the changeability assessment can provide insights for industrial application. This case study using the developed method demonstrates that assessing the changeability of system elements is feasible in an industrial context and can be used to help provide insights.

The applications of the system change method (SCM) not only support examining change prediction but also capture knowledge, support systematic process management and potentially improve manufacturing productivity by employee’s engagement. In this case study, experts systematically reviewed the connectivity in the system and change example is selected from the experience. The model building application provides for capturing past knowledge of the change. The multi-layered matrix allows employees to be able to understand the different levels of the system as a whole.

7.5 Chapter Summary

This chapter introduced three case studies where the CPM method and the software tool have been applied. The software tool was also formally verified and tested against the requirements stated in Chapter 4. The first case study was performed at a UK construction manufacturing company and was focused on risk assessments of changes to a kitchen assembly system to satisfy business process improvement through reducing kitchen cycle time. The second case study was completed for the kitchen supplier of the construction company and assessed the impacts of possible customer preference on the kitchen units. The final case study was executed at a petrochemical manufacturing company analysing instruction changes in production. The experts’ reviews of the method applications showed that CAM software may be a valuable tool, allowing analyses to achieve further insights into change propagation. However, it should be considered that more users reviews are needed for the reliability of the method application. The specific challenges of the case studies and the method evaluation are discussed in the next chapter.

8 Evaluation of the System Change Method

8.1 Chapter Overview

The previous chapter presented the answer to the sixth question of this thesis (RQ6: How well does the developed system change method perform in real case studies?*)* by presenting three case studies. This chapter evaluates the proposed system change method through three types of evaluation: *the support evaluation*, *the application evaluation* and *the success evaluation*. The chapter ends by presenting a summary.

8.2 Method Evaluation

The Design Research Methodology (DRM) (Blessing and Chakrabarti 2009) distinguishes three types of evaluation of a developed method.

1. The *support evaluation* process comprises a regular assessment of the functionality, reliability and completeness of the utility of the plan.
2. The *application evaluation* process involves the evaluation of the practice of the proposed method, assessing whether the technique is usable or feasible for the planned change.
3. The *success evaluation* process looks at the benefit of the proposed method and improvements in the defined success criteria.

The 'support evaluation' was planned for all four DRM stages include the method was utilised in the verification of the practice. Meanwhile, the 'application evaluation' involves the technique of usability that can refer to both verification and validation of the method. However, the 'success evaluation' more considers the effectiveness of the technique about the method validation (IEEE 2012).

The requirement of ECM methods developed in Chapter 4 refers to all three types of evaluation proposed in DRM (Blessing and Chakrabarti 2009). The review of the system change method (SCM) is made against the derived requirements (Chapter 4) by following the three DRM evaluation types, adapted from Hamraz (2013). Input related requirements are evaluated during the support and application evaluation. An evaluation of the method against the elements for ECM methods created in Chapter 4 will be assessed for the SCM and referred to the application evaluation n. On the other hand, the output related requirements are evaluated during the success evaluation. The output-associated needs, such as the author's view on the value of method output for each case study, the author's opinion on the added benefit of including addition layer in the CPM analysis and the company's view of the value of method output, are included. In the next three subsections, the outcomes of these evaluations will be reviewed for the proposed SCM.

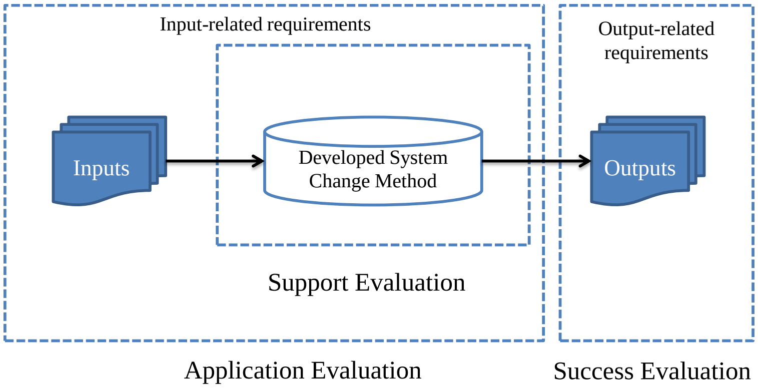


Figure 8.1: DRM evaluation types and method requirements (adapted from Hamraz 2013)

In Figure 8.1, “Application Evaluation” refers to the verification of this study, which is includes all the activities associated with the system change method, assessing whether the technique is usable or feasible for the planned change. Rigorous applications of case studies of cause and effect are subjected to strong methods of verification. On the other hand, “Success Evaluation” addresses the validation of this study, which is checking whether the proposed method applicable to the industrial needs.

8.2.1 Support evaluation

The internal functionality, reliability and completeness of the system change method (SCM) have been reviewed continuously and enhanced all through the development stage of the *Prescriptive Study*. The research project followed the DRM stages. The parts of this review process marked in blue relate to the support evaluation. The aspects of the support evaluation are classified as follows:

- *Academic review:* The SCM was reviewed monthly with the thesis supervisor as well as occasionally discussed with the experts and other researchers from academia. The work was reviewed more formally by the thesis supervisor. After the second year, the work was discussed with the supervisor again. The work was presented at the Graduate Student Conference at Cambridge University Engineering Department. Two conference papers were developed and published based on this work (Olmez and Clarkson 2013; Olmez *et al.* 2017).

- *Industrial review:* A regular review meeting was set up with the UOP Honeywell stakeholders. The smaller model was first built and tested for the UOP Honeywell case study (Olmez and Clarkson 2017a). Secondly, the application of the method was discussed at a case study meeting with the design experts at Laing O'Rourke and the method applied to a Kitchen Assembly System (KAS) (Olmez *et al.* 2018). Another case study was reviewed with the kitchen design expert from Jewson Ltd for the Kitchen Design System (KDS). The work was presented at the LOR Graduate Development Program and Innovation event at the University of Cambridge.

The feedback from the academic and industrial support was used to improve and develop the final version of the method. The other method evaluations are presented in the following application and success evaluation sections.

8.2.2 Application evaluation

The application evaluation aims to assess whether or not the developed system change method can be used for the planned task, i.e. the focus is on its utilitiy and usability. The system change approach is proposed to be applied to complex manufacturing systems and supply chain systems by system engineers or designers who are responsible for manufacturing changes. The model building requires knowledge about the system design structure and working techniques of the method. The method instruction plays a vital role for the method users. The implementation of the Change Prediction Method (CPM) into the Cambridge Advanced Modeller (CAM) software has already been used frequently in research and industry (Wynn *et al.* 2006; Wynn 2007; Wynn *et al.* 2010). Training and instruction have been taken from the EDC software engineer. CPM enables the system change method (SCM) is successfully applied as a module in CAM.

To assess whether it is practical to apply the proposed method to complex manufacturing systems, three different case study examples in two very different industries were chosen: *Kitchen Assembly System* and *Kitchen Design System* in a construction company, and *Change Requirements* for production systems in a petrochemical manufacturing company. The method successfully was applied to all three case studies, but only the effectiveness of the first two cases was evaluated because, unfortunately, the petrochemical company closed. In this case, the application evaluation, assessing SCM against the developed set of requirements in Chapter 4, was undertaken only by the author.

Requirements-based evaluation

The assessment results of the system change method (SCM) compares with the change prediction method (CPM) and multi-layer network (MLN) methods in Table 8.1. The methods were rated against *21 design requirements* under *five categories*. For this rating, the related publications are listed in Chapter 4 (Table 4.1) and application of case studies were reviewed and a colour shade scale is used from poor (1) to excellent (10) to rate these concepts. It should be noted that this rating was led only by one person and the assessment is subjective. Nevertheless, for the comparison of these methods for this thesis, it is adequate.

The unweighted score shows that CPM and MLN decrease with SCM capacity from 27 and 35 to 15. Basically, SCM which is the combination of CPM and MLN may support a better in functional, physical, operational and technical representation. Although SCM is not good as CPM in model development especially in Resources: Tools, Software and Easy to Model Development. The proposed method may improve system performance and execution both at one level and across multiple levels. The representation of multiple connection types between elements of the system architecture support capturing the inter-layer connectivity of the system elements and dependencies. The SCM can be used to find solutions to changes, thereby considering system behaviors it may be better than CPM in the ability of architectural representation of the system domains, elements, and their connectivity.

In spite of MLN is being better in decomposing systems and determining propagation paths and developing solutions with expert knowledge, the SCM allows change modeling and change analysis by quantifying and examining system ability to engage in change, and in identifying different operational policies, it may be better than MLN. SCM may support better numerical linkage values and algorithm for change risk calculation, and capture the inter-layer connectivity of system elements and dependency. On the other hand, the relationship of a functional change to cost was highly evident; the commercial importance of effective change management is not practical for SCM as well as CPM and MLN. In building the proposed method, undertaking expert interviews, finding the necessary information, retrieving available documentation about the system's architecture, and undertaking the dependency analysis were all highly demanding, but necessary to define propagation paths and develop the solution process.

Table 8.1: Assessment and comparison of the system change method (SCM) with CPM and MLN

No	Category	Requirements	CPM score	MLN score	SCM method	The rationale of the System Change Method (SCM)
1	Functional Representation	System Modelling Competency	◑	◕	◕	Good: system model shows the links between elements or systems, but at a high level only without hierarchical decomposition.
2		Change Modelling Competency	◕	◔	◕	Good: change propagation along with all possible links; but only at the component level
3		Change Analysis Competency	◕	◔	◕	Average: based on estimated direct likelihood and impact values; considering all direct and indirect links; but limited accuracy and only at a component level
4	Operational Representation	System Performance and Execution	◔	◕	◕	Good: multi-level system performance can be expected
5		Resiliency (Robustness and Adaptability)	◕	◔	◕	Good: quantifies and examines the system's abilities to engage in change and demonstrates different operational policies.
6		Model Usability	◕	◕	◕	Good: runs calculation, identifies the changed element, read imposed change risk to another element, but expert knowledge is required to determine propagation paths and develop solutions
7		Economic Viability	◑	◑	◑	Average: the relationship of operational change to cost was highly evident and indicating the commercial importance of effective change management
8	Technical Representation	The range of Product, Process, Organisation	●	●	●	Excellent: relative simplicity of the technique makes it applicable to products, process, and to an organisation of high complexity
9		Available Methods, Tools, Data	◕	◑	◑	Average; expert interviews; necessary information; available documentation about the system's architecture and dependency analysis
10		Documentation, Regulation	◕	◑	◕	Good: documenting by import/export to XML and Excel files and available regulations
11	Physical Representation	System Design Process	◕	◕	◕	Good: manually modified to adapt to other systems
12		Architectural	◑	◕	●	Excellent: to show multiple connection types between elements
13		System Elements and Dependency	◔	◕	●	Excellent: to capture the inter-layer connectivity of system elements and dependency
14		Decomposing	◔	●	◕	Good: models, systems and elements
15	Model Development	Resources: Tools, Software	●	◕	◕	Good: any tools to capture two matrices (DSMs) and MDM can be used, the CAM tool and CPM module are freely available
16		Easy to Model Development	●	◕	◑	Average; expert knowledge is required to determine propagation paths and develop solutions
17		Consistency	◕	◑	◕	Good: definition of system elements and connections
18		Results for Solution	◔	◑	◕	Good: the SCM could be used to find solutions for changes, taking into account system behaviours.
19		Adaptability	◕	◕	◕	Good: existing models can be used to a certain extent and need to be manually modified to adapt to other products
20		Numerical Analysis Competency	●	◔	●	Excellent: numerical linkage values and algorithm for change risk calculation
21		Cost-Benefit of Model Development	◕	◕	◕	Good: any system model can use for change modelling, and average cost: no need to buy the tools.
The unweighted sum assessment result			**27**	**37**	**15**	

Rating Scale:

○ Poor (1) ◔ Fair (3) ◑ Average (5) ◕ Good (7) ● Excellent (10)

8.2.3 Success evaluation

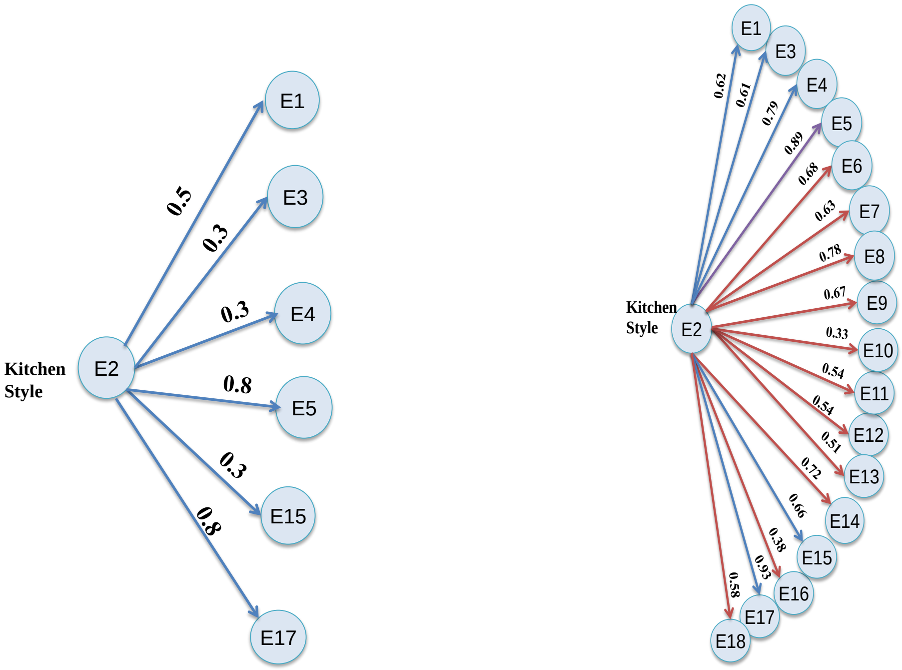
The success evaluation aims to identify whether or not the developed system change method (SCM) has the expected influence and thus can support success; i.e. the focus is on its usefulness. The suggested method can be applied to predict manufacturing changes and sustain their execution. The success of the change method is to assess the historical data (Clarkson and Hamilton 2000). Therefore, this thesis focuses on historic change cases and reviews predicted changes and their change propagation. The outcomes are compared in practice with the results from the data that applied the SCM against the effect of the condition without the model. Evaluation of real practical implementation in manufacturing environments is expensive and a potential risk to companies, so it is not achievable in practice. However, researchers can utilise experiment groups for this process. (e.g. Clarkson and Hamilton 2000, Wyatt *et al.* 2012). The change record has to distinguish between *initiated* and *affected changes* (Giffin *et al.* 2009) to demonstrate the SCM for investigating the change propagation; change effects predicted using direct connections are distinguished from those predicted using indirect links. These results of case studies in this thesis show that predictability can be improved by considering the indirect relationships between elements (Cohen *et al.* 2000; Ollinger and Stahovich 2004; Keller 2007).

The strategy is for evaluating historical change cases with change tools by building prediction change paths to find out actual change paths. A similar approach was also applied to the helicopter case study by Clarkson *et al.* (2004). The change request data has to differentiate between initiated and effected changes. To evaluate the performance of the SCM, as to whether the prediction is sensible, the following assessments were considered: (1) Author's view on the value of method output for each case study; (2) Author's view on the added benefit of including addition layer in the CPM analysis; (3) Company's view of the value of method output.

1. Author’s view on the value of method output for each case study

The value of the system change method (SCM) was reviewed by evaluating the outcome of case studies for insight into system structure. The method was performed treating the pilot change cases separately: *the Kitchen Assembly System* and *the Kitchen Design System.* The model building and evaluation were supported by the companies' experts. The SCM suggested for the change cases was found to be “beneficial” in cases where there are dependencies between the initiating and affected elements within the database, which supports the answer of the main research question in Chapter 1 that predicting changes in designing a system will be helped by the proposed method. The method captures the elements that influence the design of a resilient manufacturing system (RMS). The author reviewed the change propagations on a case-by-case basis, enabling proposed solutions to be compared for a single change problem.

The change propagation paths between any two elements can be assessed with SCM, which determines whether a change can be allowed to spread between a pair of elements. The purpose is to examine the effects of change propagating through different paths particularly in conditions where a propagation path is considered relevant to the company's risk acceptance. The propagation path investigation for the kitchen assembly system is presented in Figure 8.2 and 8.3. An example is that an initiating change on *Kitchen Style (E2)* can directly propagate *six changes* within the kitchen assembly system [Figure 8.2 (a)]; the potential *eleven propagation paths* with the red arrows were discovered after the CAM application [as shown in Figure 8.2 (b)].

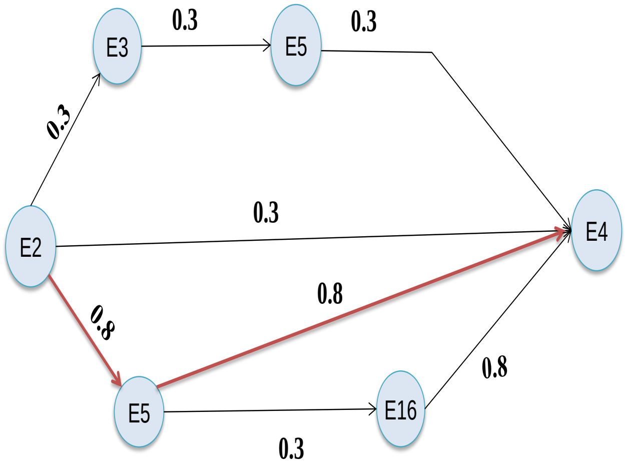


(a) Direct likelihood connection of E2 (b) Direct and Indirect likelihood connections of E2

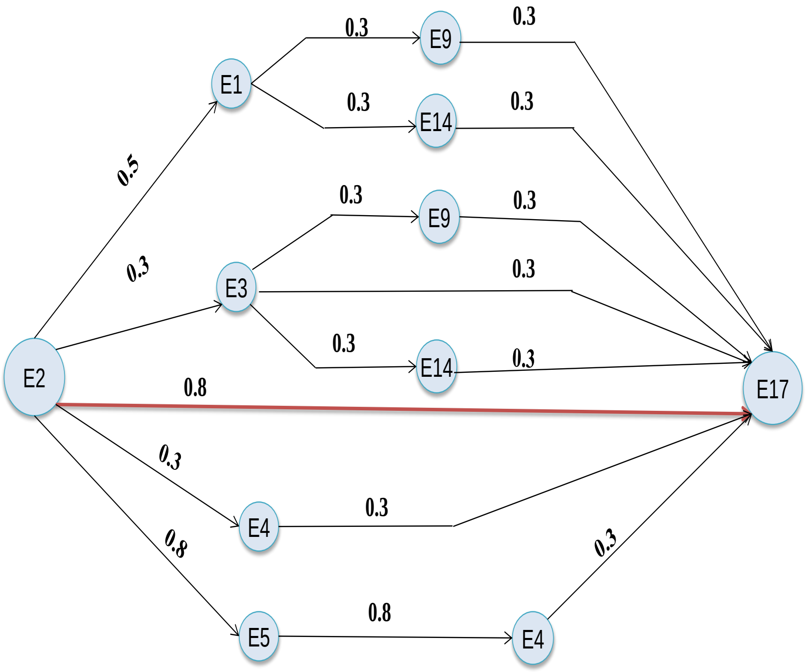
Figure 8.2: Change propagation paths of E1 due to the direct connections.

Some elements will not be affected by a proposed change, but a lack of awareness of the connections in design work is likely to have significant implications for the entire change process: some elements are highly likely to be affected. For example, Figure 8.3 illustrates the likelihood of change propagating along paths between E2 and E4, E2 and E17, and E2 and E6. The DSM in Appendix 2 as well as Figure 8.3 (a) and (b) indicate that E2 is interconnected with direct connections to E4 with a low degree (0.3) and with a very high degree to E17 (0.8) and with indirect connections to all other elements.

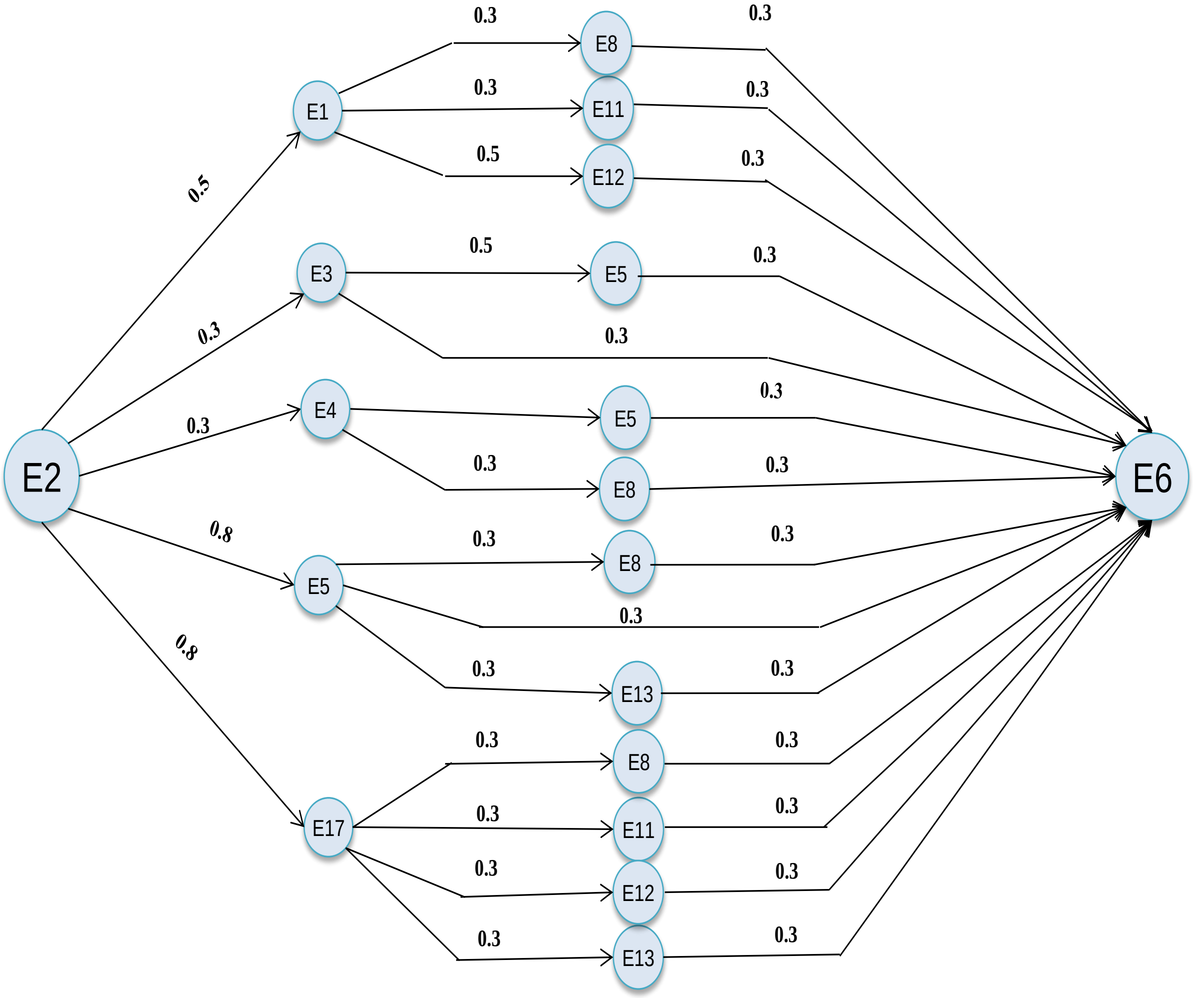
Although there are no direct connections between E2 to E6 [Figure 8.3 (c)], indirect connections to all other elements are highly interconnected at the element level. Figure 8.3 shows that there is more than one possible solution for a single change problem. A different way of solving the same issue may follow different propagation paths. The benefit of analysing these change cases with the proposed method may appear questionable because the technique suggests that all elements are directly or indirectly affected; the advantage, however, comes from a systematic approach to identifying the effects and avoiding oversights. The propagation paths assessment through the CPM application supports decision making and brings value to system design.



(a)



(b)



(c)

Figure 8.3: Direct likelihood connections for the selected 3-step change propagation paths

The author assessed the success of the CAM algorithm and how the combined likelihood numbers give rise to big indirect numbers by using the multi-layer likelihood equations of CPM Algorithm, described in Chapter 6, Section 6.4.1 and Appendix 1. Table 8.2 compares the direct likelihood values with the combined likelihood values of the 3-step CAM application (Appendix 2) and the combined likelihood values calculated by using the likelihood equations for the selected system elements (details of the calculations are presented in Appendix 2). The comparison strategy is to assess the lower and higher direct likelihood values as well as the propagation paths between any two elements in the same layer and different layers. The small variations between the two different combined likelihood values (Table 8.2) come from the fact that the simulation only produces approximate results (Ariyo *et al.* 2007). Based on the direct likelihood values within the connectivity model, some elements are affected by change more often than others. The likelihood of change propagating between two parts is estimated by counting how frequently the elements within the system are affected by a changed initial component (Ariyo et al. 2007).

Table 8.2: Comparison of the combined likelihood values of CAM and the author

The connected elements	Direct results	The combined likelihood (CAM)	The combined likelihood (calculated by the author)
E2 to E4 [Figure 8.3 (a)]	0.3	0.79	0.80
E2 to E17 [Figure 8.3 (b)]	0.8	0.93	0.90
E2 to E6 [Figure 8.3 (c)]	0	0.68	0.72

In principle, combined likelihood values result from going through all propagation paths. It counts how often elements that are part of a particular system are affected by an initiating change. In addition, supports the identification of the potential volume of change. In Table 8.3, three alter-native connected elements examined with their likelihood values.

- The direct likelihood value between E2 to E4 is *0.3* but the indirect likelihood value from CAM is *0.79*. A change to *Kitchen Style* (E2) automatically implies a change to the *Suppliers* (E4) as a direct effect. The reason for obtaining a high indirect likelihood value, as Figure 8.3 (a) reveals, is that there is a propagation path through E2-E5-E4 (Kitchen Style, Appliances, and Suppliers), which, drawn using red arrows, has extraordinarily high likelihood values *(0.8-0.8).* An investigation of changes between the *Kitchen Style* and *Suppliers* indicates a high potential for effects on the *Appliances* and *Suppliers*, more than the other elements, which shows that the indirect likelihood values between the two elements lead to changes through the intermediate parts. This connection is an example of intra-system connectivity (Chapter 6), which describes a relationship between two elements within the same layer.
- The direct likelihood value between E2 to E17 is *0.8* while the indirect likelihood value obtained from CAM is *0.93*. The intermediate elements have mainly low influences, but the direct connection likelihood value dominates the combined likelihood results [Figure 8.3 (b)]. This connection is an example of the inter-system connectivity (Chapter 6), which refers to the connections between elements of two separate layers.
- There is no direct likelihood connection between E2 to E6, yet the indirect likelihood value obtained from CAM is *0.68.* E6 has no direct dependency on the initiating element (E2). Although some intermediate elements have a single causal influence, some have multiple causes [Figure 8.3 (c)]. As a result, each cause has a different degree of impact on the likelihood of a change which drives the

combined likelihood values. When a design engineer is sure that an initiated change will not affect another element, then such propagation path should be excluded from the assessment. This connection is also an example of the inter-system connectivity referring to elements being connected in two separate layers.

The CPM technique enables identification of influences during likelihood estimation by accounting for direct connections and indirect connections between elements. This information is useful when prioritising assessments of large numbers of potential propagation paths. The design change effects for evaluations are helpful in cases where design engineers are required to analyse alternative ways to carry out a change to a complex system. To this end, it is significant that the CPM tool enables us to accept or reject the change and the possibilities of change propagating along specific paths. It is essential to ignore unnecessary propagation paths. During the propagation analysis, design engineers should also consider the elements with low likelihood values but which, however, have functional dependencies on the changed element.

2. Author’s view on the added value of including an additional layer in the CPM analysis:

The method explores how changes impact on system design. For example, each element and layer contributes to the deeper understanding the design connections. In the method validation, added each layer affects the other layers within the system, which may give more connections because of the added layers. In the single-layer change propagation, focusing only the first layer on inspecting how the system layers contribute to the prediction capability of the system change model (SCM), the corresponding risk matrices were calculated and compared for four model matrices. For instance, in *Case Study 1(CS1)*:

1. Direct risk of all layers,
2. Single-layer change propagation using only the *kitchen requirements* layer (Forward CPM(L1)),
3. Double-layer change propagation using the *kitchen requirements* and *kitchen installation* layers (Forward CPM(L1L2)),
4. Triple-layer change propagation using the *kitchen requirements, kitchen installation, and kitchen assembly process* layers (Forward CPM (L1L2L3)).
5. Four-layer change propagation using the *kitchen requirements, kitchen installation, kitchen assembly process layers* and *the manufacturing organisation* layers (Forward CPM (L1L2L3L4))

The CPM algorithm was applied using six steps of propagation to obtain the combined risk matrices. The results within the layers were combined to the element level using the maximum operation. Table 8.3 summarises the metrics calculated for all the alternative combinations of matrices. Figure 8.3 represents the average connectivity value (possible) for all the matrices.

Table 8.3: Risk matrices calculated taking different numbers of layers into account

System	Matrix	Sum of connectivity risk values for L1 (%) A	Available number of connectivity for L1 B	Possible number of connectivity for L1 C	Available average connectivity risk value A/B	Possible average connectivity risk values (A/C)	The density of connectivity population B/C*100
Kitchen Assembly System (CS1)	Direct risk (L1)	57	5	12	11.4	4.8	42
	CPM L1	75	9	12	8.3	6.3	75
	CPM L1 in L1L2	146	12	12	12.2	12.2	100
	CPM L1in L1L2L3	273	12	12	22.8	22.8	100
	CPM L1 in L1L2L3L4	514	12	12	42.8	42.8	100
Kitchen Design (CS2)	Direct risk (L1)	1064	56	210	19.0	5.1	27
	CPM L1	3200	76	210	42.1	15.2	36
	CPM L1 in L1L2	3200	76	210	42.1	15.2	36
	CPM L1in L1L2L3	3200	76	210	42.1	15.2	36
Change Requirements for Production System (CS3)	Direct risk (L1)	141	7	12	20.1	11.8	58
	CPM L1	161	12	12	13.4	13.4	100
	CPM L1 in L1L2	268	12	12	22.3	22.3	100
	CPM L1in L1L2L3	502	12	12	41.8	41.8	100
	CPM L1 in L1L2L3L4	676	12	12	56.3	56.3	100

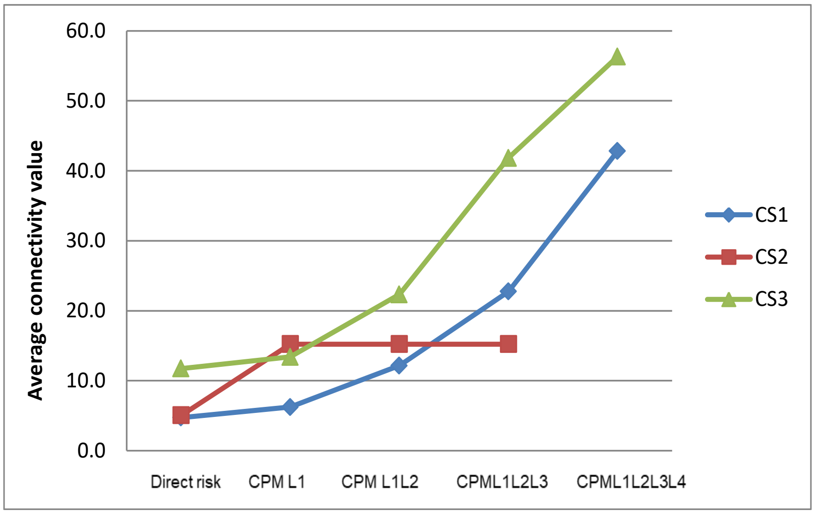


Figure 8.4: Comparison of single-layer to multi-layer change propagation analysis for the cases

Assessment of Figure 8.3 and Table 8.3: the effect of layers on the risk propagation:

- For the *CS1and CS3*, the distribution of the average connectivity value shows steadily increasing values: the more layers considered in the change propagation model, the higher the average connectivity value. However, in *CS2*, the distribution of the average connectivity value does not increase even when more layers are added to the CPM application, and its profile is flattened (Figure 8.3). The reason is, as seen in Figure 7.14, that there are many parts of the matrix not directly connected; for instance, there are no connections between the elements of L2 & L1; L2 & L2; or L1 & L3. Figure 7.14 clearly shows that L1 connects to L2, but L2 cannot connect to L1.

- Similarly, L3 is connected L1, but L1 cannot connect to L3. Therefore, these loops are broken. This particular case shows that change propagation does not give more information. The example shows that if these layers are one-directional, the propagation expected may not be seen. For future work, the direct connections in *CS2* need to be reviewed again.
- The density of the input matrix reflects the average connectivity value for direct risk. In *CS2*, the frequency of connectivity population compared to that of *CS1* and *CS3* is quite low, due to some parts of the matrix being directly linked to each other.
- The shape of the curve in *CS1* and *CS3* indicates how many additional connections between the elements become available when considering other layers. The gradient depends on the characteristics of the four different layers of the network reflected in the connectivity population density in Table 8.4 This analysis indicates how each layer adds additional information to the model and highlights the benefit of a multi-layer approach over a single-layer approach. However, as most single-layer approaches such as CPM consider influences from other layers indirectly in the connection values of their single-layer, it is challenging to compare multi-layer methods to single-layer methods directly.

Unexpected change propagation

Comparing the findings from the three case studies shows that there are two main reasons why changes may unexpectedly propagate within a system during the engineering systems change process:

- Propagation due to forgetfulness or oversight (Direct);
- Propagation due to insufficient system knowledge because the role played by an element in a system is not known, or because there is a lack of overview of the system (Indirect).

3. Company’s view of the value of method output

In separate meetings, the method was presented and the method analysis was carried out with company experts in Laing O’Rourke and Jewson Ltd. After a presentation, a discussion and question and answer session were held to ascertain that the experts adequately understood the method, who were then asked to give feedback. Each meeting took around two hours and was recorded. The important opinions were transcribed and analysed. It should be considered that the company representatives comments on method capability and method are subjective.

Case study 1 (Laing O’Rourke)

The first meetings for the KAS were held with Senior Process Engineer Adam Robinson at Laing O'Rourke's manufacturing site. The change method was introduced, and he ~~appreciated~~ interested in the method's concept and process which allows viewing a system at different levels of decomposition. The second meeting was conducted with the following participants: the general manager of LOR; Steve Jones, Adam Robinson, and Dr Tariq Masood from IFM at the University of Cambridge. The dependency analysis was developed in the meeting. Adam Robinson highlighted the challenges of the numerical use of the model in particular: "the quantification of the connections is quite demanding because every element has different associations and influences that exist between a change element.” The third meeting was held with participants Adam Robinson and Dr Tariq Masood once more. The participants were asked to give feedback for the method application of the case.

Overall, Mr Robinson found beneficial at the results of the system change method, and he stated: "It is quite a useful tool; it is interesting for me because you can get quite narrow-minded when you look at the processes. The model can be applied to different cases with involvement of everybody else’s experiences. When you look at the module you can see by doing a little change here you make a huge impact elsewhere. I think the tool is quite useful; it gives you different angles to think of the system. Otherwise in daily life don't have time stop to think." Mr Robinson also indicated that the system change method could be used in practice to review changes. "When we are looking at the kitchen example, the tool makes me think about every part of the kitchen design system that involved in it. For instance, if I request a change from a designer, such as moving water pipes somewhere else. I can think to change in water supply impact on x, w, z than assess the effect with the team. Certainly, it is beneficial for a bigger team. Also, when you consider a small change with no planning, it will be good to use the tool. The model can be used in any design practices.”

Case Study 2 (Jewson LTD)

The second case study evaluation meetings were conducted with Brian East, who supported the early phases of Kitchen Design model building. He is a sector director at Jewson Ltd who are the assembly partners for LOR kitchen designs and now modularises these designs. Mr East was involved in decomposing the kitchen design system (KDS) into layers and elements.

Mr East was convinced that a tool would be useful to support KDS: "The benefits that I can see with this type of approach. Assuming that the engineers are working on a new kitchen development process having this type of model can capture the knowledge of how a change in one part of a kitchen could propagate to have an impact on other parts of the kitchen design system. That’s a tool for really improving the quality of kitchen 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 the designer traditionally dealt with the impact of design changes is just from knowledge, which is a way of capturing knowledge a design engineer can use to make sure they consider several manufacturing processes. But that's very much at a component level and is not 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 implement it practically."

He referred to the necessary effort as his primary concern: "The difficulty of it, having implemented it, is just the overheads that it requires to create and maintain the tool. For it to be useful, it requires quite an investment of 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 work on this." Furthermore, he added the complexity of developing a model as a challenge: "in fact, the matrices and dependencies, even I am struggling with some of it. So, I think the complexity of the tool is a challenge. I can see certainly some potential, but I have some hesitations." He concluded: "So, while I can see it being essential and useful, there are some practical difficulties that I have with actually being able to implement it at the moment."

Would you prefer to use this software in the future: "I suppose in the real world I live in, the risk of customers will always be there? We already know changes coming from the customer will already affect the other design elements. If after the design, the customer says I don't like that wall that height yes, it gives a high risk to the other elements. I can say right straightforward if the customer says I want to change US fridge freezer this may affect the whole kitchen. It is like a jigsaw - when you change one position; it changes all of them; it is quite straightforward. People who have less experience can get the benefit of the software, but experienced can pick the possible changes easily without software. The model shows everything connected to everything. I suppose small changes may not be high risk.”

To summarise the company's views, the model provided a broad, integrated overview of a system and presented how all systems interact with each other. In addition, it helps to see what has not been seen before. Moreover, it provides a way to predict change impact and detect possible changes earlier. The method can be a potential tool to improve decision making in engineering change management. The cost of building the model is acceptable; the idea is to develop a generic model for the particular type of product of supply chain in the forms of ongoing product development. In this way, there would be no need to create a model every time.

8.3 Chapter Summary

This chapter has described the application of the multi-levelled system description for risk assessments and practice in a case-by-case change propagation investigation of the evaluation of change requests. The results suggest that the proposed method may improvethe predictability of change.

In summary:

1. The *Support evaluation* continuously confirmed internal reliability and completeness of the method.
2. The *Application evaluation* showed that the method could be used in the situations for which it is intended.
3. The *Success evaluation* indicated that the method contributes to an improvement in change management and provide direction to further improvement.

9 Conclusions

9.1 Chapter Overview

This chapter summarises and concludes the thesis. Section 9.2 outlines the key outcomes and research contributions from the answers to the six research questions addressed. In Section 9.3, the benefit of the system change method (SCM) is presented by revisiting the introduction to discuss the outcomes based on the objectives and hypotheses of this research. The research limitations are discussed in Section 9.4, and opportunities for further work are highlighted in Section 9.5. The thesis is concluded in Section 9.6.

9.2 Key Findings and Research Contributions

This thesis has the main research question first introduced in Chapter 1:

> **The Main Research Question:**
> How can change prediction inform the design of resilient manufacturing systems?

Designing a resilient manufacturing system as described in Section 1.1.3 helped to focus on the research area to meet this aim. The main research question is driven by the following research questions (Chapter 1). The first research question focuses on exploring and understanding resiliency:

> **RQ1** What are the characteristics of a manufacturing system that make it resilient to manufacturing change.

The systematic literature review (Chapter 2: Table 2.1 and Table 2.2) of approximately 800 publications that were conducted to answer RQ1 identified 37 relevant papers, leading to the first research questions.

Characterisation of resilient to manufacturing change: This thesis found that *robustness or adaptability* is the key characteristic of manufacturing systems that make the system resilient in the presence of change (Section 2.4.2). Resiliency is the ability of manufacturing systems to respond to changes through a rapid redesign of the architectural approach. Three key aspects lead the design of engineering systems to make them more resilient: (1) having a robust or adaptable system behaviour towards changes; (2) changing quickly and effortlessly; (3) understanding system complexity.

The second research question focuses on a systematic literature search and categorisation and these results were used to identify available RMS methods :

> **RQ2** What is the role of engineering change prediction approaches in the long-term delivery of resillint manufacturing systems?

The systematic literature review (Section 2.5) was used to answer to RQ2 and can be summarised under the following research contributions:

Engineering Change Prediction approaches: 15 existing ECM methods were drawn from an extensive literature review. Table 2.4 in Chapter 2 provides an overview and brief description of current ECM methods with their references for modelling and analysing RMSs which were identified and classified according to the change management strategies (managing complexity and changeability). The most weighted sum assessment results generated six engineering change methods, tools needed to design a robust or adaptable manufacturing system by predicting the effect of changes. Change prediction tools can be used for change assessments. The prediction tools must encompass and quantify risk estimation. The Change Prediction Method (CPM) technique has several key benefits (Chapter 4, Chapter 5). For example:

- Dependency models can reduce the effort required to build a change prediction model (Chapter 5).
- Hierarchically structured multi-layered network risk models support more change queries than comparable single-levelled models (Chapter 8).
- Models of indirect dependency improve prediction of propagation paths between elements (Chapter 8).

The answers to RQ1 and RQ2 provided both a motivation and a useful basis for the development of a comprehensive design for an RMS and directed the formulation of four other detailed research questions, RQ3 to RQ6. Overall, the main research question was thus decomposed into six logically successive questions, RQ1 to RQ6, to direct this research. RQ3 concerns the *design requirements* for a change method to design an RMS, which were extracted from the investigations of RQ1 and RQ2.

RQ3 What are the requirements for the system change methods to be used in the context of designing a resilient manufacturing system?

The answer to RQ3 includes the development of a set of 21 requirements for ECM methods and the comparative assessment of *six possible ECM methods* against them (Chapter 4). So, the main contributions of the answer of the RQ3 can be described below:

ECM methods requirements: A comprehensive set of 21 requirements for ECM methods were developed (Table 4.1 in Chapter 4). These requirements were obtained from the publications on the 15 unique ECM methods identified (Chapter 2) with industrial experiences from the case studies. The defined requirements can provide direction for the development of future methods. The answer to RQ4 covers the conceptual design of a system change method (SCM) for RMS (Chapter 5). The contributions of this answer are summarised below.

The fourth research question leads to exploring the best concepts for presenting an RMS:

RQ4 What are the suitable concepts for a system change method to support the delivery of resilient manufacturing system?

Searching the most suitable concept for the system change method (SCM) supports the evaluation of the most appropriate engineering change methods (ECM). The selected concept is capable of supporting the system change method to assess change risk in the multi-levelled system description.

The assessment of six possible ECM methods: A comparative evaluation of the six most likely ECM methods was made using the set of requirements as standard criteria. These six methods were selected from the list of 15 unique ECM methods. For each technique, a detailed assessment table including the scores and justifications was reviewed (Table 4.2, Appendix 2, 3, 4, 5, 6) and in the end, all scores were summarised in a combined table (Table 4.3, Chapter 4). This table highlights the relative strengths and weaknesses of each method for each requirement. The method which best meets any particular requirements can thus be selected using this table. The table can also be used to generate ideas to, so the table can be used to generate ideas to improve any of the six compared methods.

Conceptual design of the system change method (SCM): A concept was created according to method requirements were developed systematically. A broad engineering change management concept was synthesised from conceptual ideas which were identified through the comparison to meet each model requirement of manufacturing system complexity and changeability. The proposed system change method is a combination of two approaches: (1) using MLN as a network-based model to represent the structure and connectivity of systems and their elements (2) using CPM to quantify and simulate changes. This novel approach can assist engineers in predicting undesired change propagation effects, especially those that can influence the system characteristics with the introduction of new changes. The conceptual design can act as a support tool for constructing a successful change process.

The question five helps to present the detail design of the selected concept:

RQ5 What are the detailed elements required to understand the chosen change method concept for resilient manufacturing systems?

The answer to RQ5 includes the detail design of the SCM, including the presentation of how the multi-layered network within the change propagation method overcomes the challenges of manufacturing system complexity and changeability (Chapter 6). Accordingly, the contributions of this answer can be summarised under the following heading.

Detail design of the system change method: The novel method supports to describe how to analyse change propagation and identify the connectivity and dependencies that can exist within the manufacturing system layers and elements. The SCM consists of 5 stages as illustrated in Figure 6.1: Stage 1, Decompose the system; Stage 2, Capture dependencies between layers and elements; Stage 3, Quantify the MLN connectivity to compute predictive matrix; Stage 4, Compute combined change propagation; and Stage 5, Use the change risk method for decision making. The key role of the SCM is to predict and analyse the MLN of change propagation in the context of the system complexity and changeability.

The question six is about application of the developed system change method in real industrial example:

RQ6 How well does the developed system change method perform in real case studies?

The answer to RQ6 comprises the application of the developed method to three industrial cases studies and subsequent evaluation (Chapter 8). The main contributions of this answer can be summarised under four headings.

1.Application of the system change method to a Kitchen Assembly System: The novel technique was developed for kitchen requirements in the assembly process (Figure 7.2). The system connectivity with elements and layers was quantified, and the combined risk within the MLN matrix was calculated (Figure 7.6). Subsequently, the risk model was used for numerical change propagation analysis.

2. Application of the system change method to design a Kitchen Design System: The novel method(SCM) was also used for kitchen design changes (Figure 7.12). The method provides a broad view of a kitchen design system and aids in understanding and predicting change impacts on the system elements (Figure 7.17).

3.Application of the system change method to change requirements: The novel method was developed for change requirements of the catalyst production system (Section 7.19). The case study shows that the suggested method can be used for assessing system complexity and changeability, so using an SCM is a feasible method to understand and predict change impacts on the production system elements (Figure 7.22). These three case studies in two different industries contribute to the understanding of the role of designing an RMS in practice. The first and second case studies are made up of new arrangements of the original design. The SCM was applied to possible required changes from the customer requirements. In the third industrial case study, the method was applied to changes in past experiences. The time spent in applying this method reflects the challenge of designing an RMS to better understand change propagation networks.

4.Evaluation of the system change method: The SCM method was evaluated using the evaluation types of DRM (Section 8.2). It was shown that the technique is feasible, with reasonable modelling effort, for complex manufacturing system designs, and valuable to improve engineering change methods. An assessment of the method against the requirements emphasised that this SCM improves on CPM in three aspects: (1) it enables the prediction of risk across multiple layers and at different levels of detail in the system architecture; (2) prediction of change propagation can be made through dependency analysis; and (3) modelling changes revealed different characteristics of systems such as robustness and adaptability. The method helps assess the degree of interactions within elements in a network structure. The SCM needs accurate data to run CPM, and thus, it requires skill to formulate and put it into practice.

9.3 Contribution of the System Change Method

The novel contribution of this research is described in four aspects below:

1. **Explore key characteristics of the resilient manufacturing system:** The thesis describes resiliency as the ability of manufacturing systems to respond to changes through a rapid redesign using an architectural approach and determines the adaptability and robustness of the whole manufacturing enterprise. So, robustness or adaptability is the key system life-cycle properties for a manufacturing system that makes it resilient to changes (Chapter2 - Section 2.3).
2. **Understanding engineering change prediction methods** to establish key characteristics of the resilient manufacturing system: One of the challenges is ensuring that risk estimates are consistent between and across systems and elements. The strength of the change prediction method is in its capability to assess interactions between systems and their elements. It is essential to understand what elements of the system are subject to direct changes and how such changes can propagate to impact elements that have no direct dependencies. Risk assessment across layers of a system can give valuable insight into how an element change interacts within the system. This research presents the interactions

between the product, the process, and the organisation in change propagation and describes how these interactions influence the way a change propagates. The needs to satisfy limitations from functional, operational, technical and physical requirements were highlighted as the critical drivers for propagating changes (Chapter 4). The strategy of manufacturing system breakdown shows that a system decomposition process is applicable for change prediction. The system description has a vital role when assessing connectivity between the change initiator and affected elements. The thesis provides a theoretical insight into the hierarchical decomposition of architectural structure for complex systems.

3. **Propose a novel model to use in the resilient manufacturing systems design** is presented in Figure 5.5 (Chapter 5). It supports a better understanding of the system design process according to method requirements which were developed systematically in Chapter 4. The concept is designed using a combination of two methods: the MLN approach as a network-based model to represent the structure and connectivity of systems, and the CPM approach to quantify and simulate the connectivity of networks. The concept of the model reduces input information preferences when creating hierarchical risk models. The proposed method is a novel approach which models manufacturing systems as a network of its subsystems and elements and uses their relations to describe and predict change propagation. The model building practice is relying on prediction information from experts; thus, it is challenging to avoid subjectivity during the model building. The design concept is capable to prevent the unnecessary inputs data of elements and systems. Its ability reducing the risk of changes by the consistent estimation of risk across all hierarchy levels of a system. In overview, it was learned that manufacturing changes and their propagation are essential for complex system design, and change prediction method (CPM) may appropriate tool for change management.
4. **Verify/ validate the model in case studies**: Change management practices in all sectors, the effort required to build connectivity model is a significant barrier to the use of matrix-based tools. In this research, a novel approach to building the connectivity model was proposed. The proposed novel concept may reduce the effort per person that goes into the model construction..

9.4 Research Limitations

This section discusses the methodological limitations of the research, which fall into several areas.

Method Development:

- *The level of detail in system decomposition:* The study does not provide a direct reason for the level of information for system decomposition. The required data for the prediction method has a significant influence on the quality of change propagations. A broad understanding of fundamental interactions is necessary for the successful application of the prediction approach. Change assessment in practice is influenced by factors such as knowledge across an organisation, constraints in protocols for proposing change requests, team structures and time pressures.

- *The accuracy of data:* Having a close model link to the change system and estimating the probabilities are significant challenges. Ensuring the availability of precise information is challenging when developing the system change method. Even though it's hard to get accurate data, it doesn't matter too much as you are identifying risk areas, and not trying to give an exact quantification of risk. But if the data isn't accurate, risk prediction can't be made. This research is limited in that a quantified accurate prediction of risk is not possible.

Method Application:

- *More case studies*: Risk is currently estimated based on the design effort associated with the propagation of changes. However, in some cases, this estimation does not reflect the actual value of carrying out a change. To fully understand indirect dependencies in predicting change using the system change method (SCM), it is essential to repeat change experiments with different systems or case studies to optimise the technique. Future work should include applying the methods developed in this research to more case studies to strengthen its standardisation empirically (see also Section 9.5 below, *Future Work*).
- *Limited time*: The time limitation is especially challenging for manufacturing design research. Successful design research requires more involvement and validation of industrial practices. However, the timing of case studies might not always fit appropriately within PhD projects. The time limitation provides a particular challenge for researchers in justifying the work empirically.

Method Evaluation:

- *The verification of change predictions:* Verifying change predictions during a manufacturing change process is complicated. Although a possible alternative is to compare the prediction against records of change cases, such information is also rarely available in practice. For instance, neither of the case study companies described in this thesis maintain such records. Therefore, the practicality of this work can only be evaluated through expert interviews.
- *Quantitative evaluation*: Evaluation of change propagation results quantitatively would repeatedly require producing correct predictions until improved results are seen. It is extremely difficult for one to collect enough data for case studies as this would be unfeasibly time-consuming.
- *The validation of the method:* This research was undertaken as an academic research project collaboration between the Engineering Design Centre (EDC) and two industrial manufacturing companies: UOP Honeywell and Laing O'Rourke. The most up-to-date version of the CPM tool

has been used in this thesis, applying it to several change requirements. Nevertheless, the CPM results should be assessed against historical change cases. Due to the Honeywell UOP manufacturing plant in the UK having been closed down, the method application could not be validated in the third case study. However, the evaluation of the method application was made in the first and second case studies.

9.5 Future Work

1. Method and Tools

- *The software tool:* Continue to improve the software system that has already been implemented. The application of the software tool can support investigating how to indicate characteristic system behaviours such as the robustness or adaptability of a system. The CAM software and the method will thus continue to be evaluated and validated,
- *Alternative data sources:* The data was collected from technical documents and expert interviews to automate the process for prediction model building. Further research is required to develop alternative data sources: techniques which facilitate or even partly automate information collecting can significantly reduce the model-building effort.
- *The method:* It is of interest to design manufacturing systems with different attributes (such as flexibility), and as the SCM developed here provides a representation of the manufacturing system architecture, it could thus be applied to optimise it. The application of the MLN approach to flexible system architecture is a very encouraging research area that could be further explored.
- *Identification of change request:* It is crucial to anticipate the sources of change to avoid its occurrence. Further research is needed to develop systems for early identification of change requests based on high priority issues at each stage of the system lifecycle.

2. Change Analysis

- *A better understanding of change propagation:* Change propagation can affect different aspects of a system and a complete model of change propagation can involve several thousand elements and dependencies, making it unrealistic to create and maintain. This is especially true for matrix-based approaches. One approach to deal with this issue is to develop purpose-driven modelling supports that address specific requirements. In this way, only a set of predefined factors would be considered in the analysis.

- *Risk quantification methods*: Future work will concentrate on improving and developing standardised risk quantification methods and defining standard work procedures to reduce the variability in estimating dependency, likelihood and impact values.
- *Change impact profile*: The CPM tool enables the assessment of the implication of change propagation in terms of the associated design effort, but the analysis shows that design does not always reflect the actual cost of making a change. A better understanding of the effects of change propagation may help to create a "change impact profile" for proposed changes. In addition, the economic feasibility and organisational implications of the change should be considered.

3. **Case Studies**
    - *Method applications to more industrial case studies:* For testing and evaluation purposes, the SCM was applied to three case studies. For further evaluation and improvement, it must be used in more industrial case studies at different levels of detail.
    - *Day-to-day manufacturing change*s: The techniques developed in the course of this research have been evaluated against past cases of change; a better assessment of the usefulness of the predictive tool may be accomplished by testing the technique against day-to-day industrial manufacturing changes. The evaluation of historical data may not necessarily reflect the exact conditions under which changes occur. Continuously assessing engineering changes in practice with this method can increase the reliability of the validation.

9.6 Chapter Summary

Designing a resilient manufacturing system (RMS) is vital to ensure against any changes to the success and continuity of a manufacturing organisation in a competitive environment. This thesis has primarily focused on developing a method to evaluate the design of RMSs. Modelling manufacturing changes might influence decisions. Manufacturing engineers and designers can interact with the method in early detection of engineering changes in a variety of contexts. This support is an effective and efficient solution to achieve successful change management.

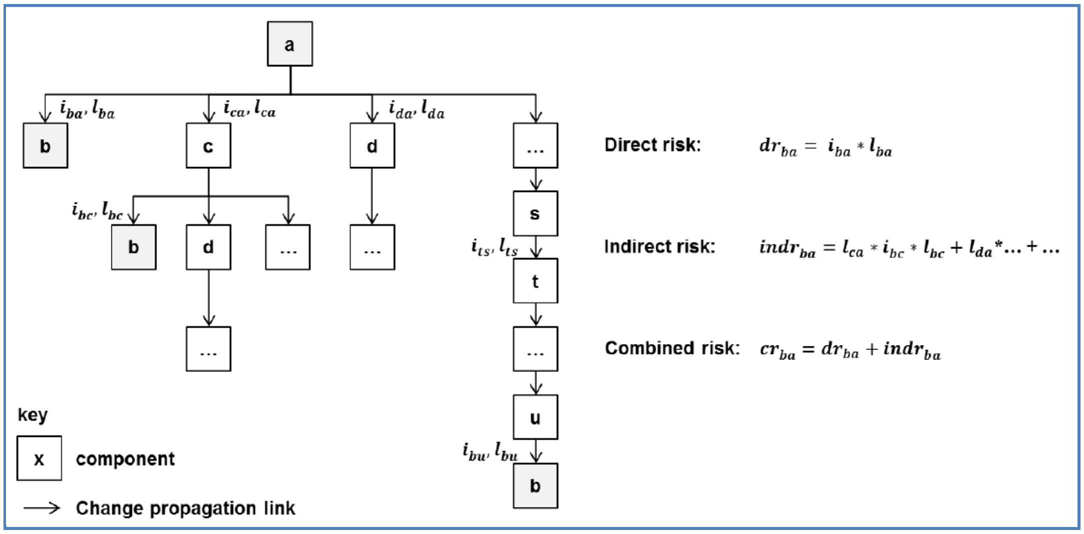
Based on research in engineering and manufacturing change management, this thesis contributed with a set of requirements for a comparative assessment of current engineering change methods. As a result of the evaluation, the system change method (SCM) was proposed. Thereby, the thesis provides a theoretical viewpoint to understand the nature of modelling in designing an RMS. The application of this novel method was successfully demonstrated in three industrial case studies of two widely-respected manufacturing companies. The idea of change prediction was put forward based on the existing CPM methodology. The predictability of change propagation was enhanced through the use of hierarchical structured multi-layered system descriptions. By assessing historical change cases, it was shown that there are benefits in using multi-layered network system descriptions in change predictions.

In summary, the contributions of this thesis have implications beyond engineering change methods (ECM), and several advantages of the method have been highlighted. The thesis advances the current understanding of manufacturing changes and indicates that the system change method (SCM) has the potential to improve the current practice of a manufacturing change management by designing a resilient manufacturing (RMS), and provides promising opportunities for further research and development.

Appendix

Appendix 1: CPM Algorithm (Clarkson *et al.* 2004)

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



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

Where

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

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

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)

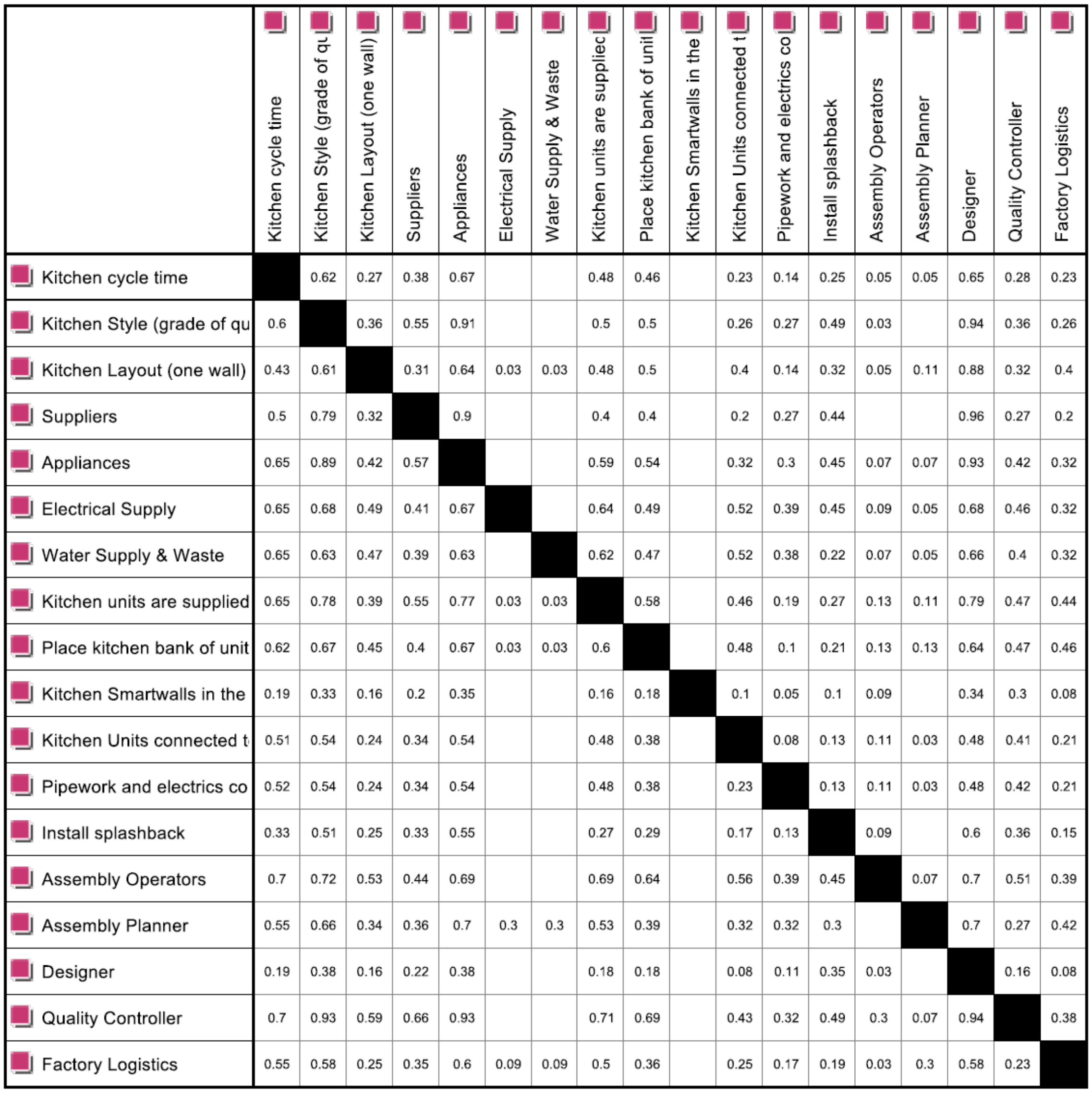
Variables: cl- the combined likelihood

cr-combined risk

i– direct impact

l– the direct likelihood

Appendix 2: 3-Steps indirect likelihood CAM results for Kitchen Assembly System



	Kitchen cycle time	Kitchen Style (grade of qu	Kitchen Layout (one wall)	Suppliers	Appliances	Electrical Supply	Water Supply & Waste	Kitchen units are supplie	Place kitchen bank of uni	Kitchen Smartwalls in the	Kitchen Units connected t	Pipework and electrics co	Install splashback	Assembly Operators	Assembly Planner	Designer	Quality Controller	Factory Logistics
Kitchen cycle time	■	0.62	0.27	0.38	0.67			0.48	0.46		0.23	0.14	0.25	0.05	0.05	0.65	0.28	0.23
Kitchen Style (grade of qu	0.6	■	0.36	0.55	0.91			0.5	0.5		0.26	0.27	0.49	0.03		0.94	0.36	0.26
Kitchen Layout (one wall)	0.43	0.61	■	0.31	0.64	0.03	0.03	0.48	0.5		0.4	0.14	0.32	0.05	0.11	0.88	0.32	0.4
Suppliers	0.5	0.79	0.32	■	0.9			0.4	0.4		0.2	0.27	0.44			0.96	0.27	0.2
Appliances	0.65	0.89	0.42	0.57	■			0.59	0.54		0.32	0.3	0.45	0.07	0.07	0.93	0.42	0.32
Electrical Supply	0.65	0.68	0.49	0.41	0.67	■		0.64	0.49		0.52	0.39	0.45	0.09	0.05	0.68	0.46	0.32
Water Supply & Waste	0.65	0.63	0.47	0.39	0.63		■	0.62	0.47		0.52	0.38	0.22	0.07	0.05	0.66	0.4	0.32
Kitchen units are supplied	0.65	0.78	0.39	0.55	0.77	0.03	0.03	■	0.58		0.46	0.19	0.27	0.13	0.11	0.79	0.47	0.44
Place kitchen bank of unit	0.62	0.67	0.45	0.4	0.67	0.03	0.03	0.6	■		0.48	0.1	0.21	0.13	0.13	0.64	0.47	0.46
Kitchen Smartwalls in the	0.19	0.33	0.16	0.2	0.35			0.16	0.18	■	0.1	0.05	0.1	0.09		0.34	0.3	0.08
Kitchen Units connected t	0.51	0.54	0.24	0.34	0.54			0.48	0.38		■	0.08	0.13	0.11	0.03	0.48	0.41	0.21
Pipework and electrics co	0.52	0.54	0.24	0.34	0.54			0.48	0.38		0.23	■	0.13	0.11	0.03	0.48	0.42	0.21
Install splashback	0.33	0.51	0.25	0.33	0.55			0.27	0.29		0.17	0.13	■	0.09		0.6	0.36	0.15
Assembly Operators	0.7	0.72	0.53	0.44	0.69			0.69	0.64		0.56	0.39	0.45	■	0.07	0.7	0.51	0.39
Assembly Planner	0.55	0.66	0.34	0.36	0.7	0.3	0.3	0.53	0.39		0.32	0.32	0.3		■	0.7	0.27	0.42
Designer	0.19	0.38	0.16	0.22	0.38			0.18	0.18		0.08	0.11	0.35	0.03		■	0.16	0.08
Quality Controller	0.7	0.93	0.59	0.66	0.93			0.71	0.69		0.43	0.32	0.49	0.3	0.07	0.94	■	0.38
Factory Logistics	0.55	0.58	0.25	0.35	0.6	0.09	0.09	0.5	0.36		0.25	0.17	0.19	0.03	0.3	0.58	0.23	■

Calculation of the indirect likelihood between the *Kitchen Style (E2)* to *Suppliers (E4)*:

$L_{42}= 1-\{(1-\ell_{42})\ (1-\ell_{32}*\ell_{53}*\ell_{45})\ (1-\ell_{52}*\ell_{45})\ (1-\ell_{52}*\ell_{165}*l_{416})\}$

$L_{42}=1- \{(1- 0.3)\ (1-0.3*0.3*0.3)\ (1-0.8*0.8)\ (1-0.8*0.3*0.8)\} =$ **0.80**

Calculation of the indirect likelihood between the *Kitchen Style (E2*) to *Electrical Supply (E6)*

$L_{62}= \{(1- \ell_{12}*\ell_{81}*\ell_{68})\ (1-\ell_{12}*\ell_{61})\ (1-\ell_{12}*\ell_{11}*\ell_{611})\ (1-\ell_{12}*\ell_{121}*\ell_{612})\ (1-\ell_{32}*\ell_{63})\ (1-\ell_{32}*\ell_{53}*\ell_{65})$

$(1-\ell_{42}*\ell_{54}*\ell_{65})\ (1-\ell_{42}*\ell_{84}*\ell_{68})\ (1-\ell_{52}*\ell_{85}*\ell_{68})\ (1-\ell_{52}*\ell_{65})\ (1-\ell_{52}*\ell_{135}*\ell_{613})\ \ (1-\ell_{172}*\ell_{817}*\ell_{68})$

$(1-\ell_{172}*\ell_{1117}*l_{611})\ (1-\ell_{172}*\ell_{1117}*\ell_{611})\ (1-\ell_{172}*\ell_{217}*\ell_{612})\ (1-\ell_{172}*\ell_{1317}*\ell_{613})$

L_{62}=1- {(1-0.5*0.3*0.3) (1-0.5*0.3) (1-0.5*0.3*0.3) (1-0.5*0.5*0.3) (1-0.3*0.3)

(1-0.3*0.5*0.3) (1-0.3*0.5*0.3) (1-0.3*0.3*0.3) (1-0.3*0.3*0.3) (1-0.8*0.3*0.3) (1-0.8*0.3)

(1-0.8*0.3*0.3) (1-0.8*0.3*0.3) (1-0.8*0.3*0.3) (1-0.8*0.3*0.3) (1-0.8*0.3*0.3)} **= 0.72**

Calculation of the indirect likelihood between the *Kitchen Style (E2)* to *Quality Controller (E17*): as stated in the propagation paths:

$L_{172}= 1- \{(1-\ell_{172})\ (1-\ell_{12}*\ell_{91}*\ell_{179})\ (1-\ell_{12}*\ell_{141}*\ell_{1714})\ (1-\ell_{32}*l_{93}*l_{179})\ (1-\ell_{32}*\ell_{173})$

$(1-\ell_{32}*\ell_{143}*\ell_{1714})\ (1-\ell_{42}*\ell_{174})\ (1-\ell_{52}*\ell_{45}*\ell_{174})$

L_{172}= 1- {(1-0.8) (1-0.5*0.3*0.3) (1-0.5*0.3*0.3) (1-0.3*0.3*0.3) (1-0.3*0.3) (1-0.3*0.3*0.3)

(1-0.3*0.3) (1-0.8*0.8*0.3) = **0.90**

Appendix 3 Rating and rationales of DSM/MDM

(Danilovic and Browning 2004; Maurer and Lindemann 2007)

No	Category	Method Requirements (MR)	DSM/MDM Score	The rationale for the DSM/MDM score
1	**Functional Representation**	System Modelling Competency	●	Good: product model shows the links between elements or systems; at high-level hierarchical decomposition and
2		Change Modelling Competency	●	Fair: does not show how changes propagate through the matrix
3		Change Analysis Competency	●	Fair: change between elements with manual analysis using matrix
4	**Operational Representation**	System Performance and Execution	●	Good: multi-level of a system can be executed
5		Built Resiliency (Robustness and Adaptability)	●	Fair:: the system abilities cannot be quantified and examined to engage to change
6		Model Usability	●	Good: DSM-based techniques can provide a well-structured approach to model EC propagation,
7		Economic Viability	●	Average: the relationship of operational change to cost was highly evident and the commercial importance of effective
8	**Technical Representation**	The range of Product, Process, Organisational	●	Excellent: applied to structure-, task-, organization-, and parameter analysis
9		Available Information, Data etc.	●	Average: subjective information from expert interviews;
10		Documentation, Regulation.	●	Average: limited use of available documentation, available regulations
11	**Physical Representation**	System Design	●	Good: visualization of complex network structures
12		Architectural	●	Good: highlighting the system's architecture (or designed structure
13		System Elements and Dependency	●	Good: represent the elements comprising a system and their interactions,
14		Decomposing	●	Excellent: visualization of complex network structures can be decomposed its parts and elements
15	**Model Development and Application**	Resources: Tools, Software	●	Good: any tools to capture two matrices (DSMs) can be used
16		Easy to Model Development	●	Good: identify domains, elements, connections
17		Consistency	●	Average: rely on expert knowledge
18		Results for Solution	●	Average: the solutions generated can be abstract depending on the level of granularity used for the analysis
19		Adaptability	●	Good: existing models can be used to a certain extent and need to be manually modified to adapt to other systems
20		Numerical Analysis Competency	●	Fair: the matrix generated as an abstract, without specified numerical values.
21		Cost-Benefit of Model Development	●	Good: Good: low cost (only expert interviews but no buying or programming of tools needed)

Appendix 4: Rating and rationales of the method from Chen & Li (Li and Chen 2010)

No	**Category**	**Method Requirements**	**Chen &Li Score**	**The rationale for Chen & Li score**
1	**Functional Representation**	System Modelling Competency	●	Good: Applied on a range of complex products, with DSM/ DMM can identify the connections within the system
2		Change Modelling Competency	●	Fair: not modelling change propagation within each of the domains
3		Change Analysis Competency	●	Fair: an only manual analysis using design dependency matrix
4	**Operational Representation**	System Performance and Execution	●	Average: Change propagation only between parameters and functions but not within each of these domains
5		Built Resiliency (Robustness and Adaptability)	●	Good: expert estimations with rationales based on functions and elements
6		Model Usability	●	Average: when an element change is requested, the method suggests redesign strategies based on decomposition patterns
7		Economic Viability	●	Average: the model can be built only by an expert could be very complicated
8	**Technical Representation**	The range of Product, Process, Organisational	●	Good: applied on air-cooled condenser; potentially applicable to complex systems
9		Available Information, Data etc.	●	Average: Matrix needs detail information
10		Documentation, Regulation.	●	Average:
11	**Physical Representation**	System Design	●	Good: the capability of Design Dependency Matrix
12		Architectural	●	Average: Design Dependency Matrix needs more information
13		System Elements and Dependency	●	Average: Design Dependency Matrix needs more information
14		Decomposing	●	Good: hierarchical decomposition not supported
15	**Model Development and Application**	Resources: Tools, Software	●	Good: Matlab-based software available and need support to capture the dependency
16		Easy to Model Development	●	Average: determine change element, apply decomposition, select redesign policy
17		Consistency	●	Average: not clear how to model connections, this could cause inconsistencies
18		Results for Solution	●	Excellent: redesign policies identify parameters to meet the changes
19		Adaptability	●	Good: existing models can be adapted to other products
20		Numerical Analysis Competency	●	Fair: inadequate to the matrix
21		Cost-Benefit of Model Development	●	Good: accessible to free software

Appendix 5: Rating and rationales of the Redesign IT method (Ollinger and Stahovich 2004)

No	Category	Method Requirements	Redesign IT	The rationale for ADVICE score
1	**Functional Representation**	System Modelling Competency	●	Good: Product modelling competency, it may apply to system modelling competency
2		Change Modelling Competency	●	Average: only causal change propagation along with connections between quantities;
3		Change Analysis Competency	●	Average: causal change propagation along with links between quantities; but no consideration of indirect change impacts over several steps
4	**Operational Representation**	System Performance and Execution	●	Fair: presumably limited; not specified in the paper
5		Built Resiliency (Robustness and Adaptability)	●	Good: abstract change plans as solutions
6		Model Usability	●	Good: identify the quantity to be changed, run the program, choose proposed change options
7		Economic Viability	●	Excellent: in change prediction, solution support and low cost in reasonably low effort to assess change plans if software available for free
8	**Technical Representation**	The range of Product, The process, Organisational cover	●	Good: broad; applied on diesel engine; potentially applicable to more complex products
9		Available Information, Data etc.	●	Average: expert interviews; detailed information needed;
10		Documentation, Regulation.	●	Average: limited use of available documentation
11	**Physical Representation**	System Design	●	Excellent: it generates alternative redesign plans
12		Architectural	●	Fair: only one level; 'quantities' may refer to elements, attributes, behaviours, or flows
13		System Elements and Dependency	●	Fair: dependency relations need to be mapped; not clear how to select quantities
14		Decomposing	●	Fair: only one level; 'quantities' may refer to components, attributes, behaviours, or flows; hierarchical decomposition not explicitly supported
15	**Model Development and Application**	Resources: Tools, Software	○	Poor: RedesignIT computer program not available (no link in the paper, Google search shows no results)
16		Easy to Model Development	●	Average: quantities, their constraints, and relations need to be mapped; not clear how to select quantities
17		Consistency	●	Average: causality assures consistency; not clear which quantities, constraints, and relations to include
18		Results for Solution	●	Good: abstract change plans as solutions
19		Adaptability	●	Good: existing models can be used to a certain extent and need to be manually modified to adapt to another system
20		Numerical Analysis Competency	●	Fair: the redesign plans it generates are abstract, without specified numerical values.
21		Cost-Benefit of Model Development	●	Average: cost (much information is needed and potentially buying of a graphics editor software)

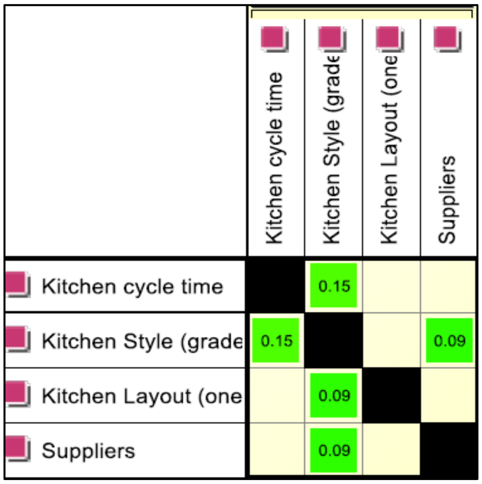
Appendix 6: Rating and rationales of C-Far method (Cohen *et al.* 2000)

No	Category	Method Requirements (MR)	C-Far Score	The rationale for C-Far score
1	**Functional Representation**	System Modelling Competency	◐	Average: attribute-component product model; difficult for complex products
2		Change Modelling Competency	◐	Average: change propagation along with connections between attributes, but only for the pre-selected path
3		Change Analysis Competency	◐	Average: change prediction considering multiple indirect links, but only for selected paths
4	**Operational Representation**	System Performance and Execution	◐	Average: Due to the limitation of the techniques the performance capability average
5		Built Resiliency (Robustness and Adaptability)	◐	Average: the attribute relation graphs could be used to find solutions for changes
6		Model Usability	○	Poor: change path depiction and impact estimation for source-target selection; no critical paths etc.
7		Economic Viability	○	Poor: the very high cost (extensive information and potentially a graphics editor software is needed)
8	**Technical Representation**	The range of Product, The process, Organisational cover	◐	Average: limited to average complexity concerning the extreme amount of data and calculations
9		Available Information, Data etc.	◐	Average: expert interviews; detailed information;
10		Documentation, Regulation.	◐	Average: limited use of available documentation (EXPRESS schema)
11	**Physical Representation**	System Design	◐	Average: identify the path, multiply matrices along the path very complicated
12		Architectural	●	Good: architectural representation of elements and subsystems
13		System Elements and Dependency	◐	Average: considering multiple indirect connections, for designated paths
14		Decomposing	●	Good: systems, elements, and properties
15	**Model Development and Application**	Resources: Tools, Software	●	Good: any tools to capture matrices, but if graphs needed then a graphics editor software required
16		Easy to Model Development	○	Fair: complicated entity relations and matrices (C-FAR matrix, Semi-C-FAR matrix)
17		Consistency	◐	Average: building a connection between elements; not clear which characteristics to include; change receiver path
18		Results for Solution	◐	Average: the characteristic relation diagrams could be used to find solutions for change
19		Adaptability	●	Good: existing models can be used to a certain extent and need to be manually modified to adapt to other products
20		Numerical Analysis Competency	●	Excellent: numerical linkage values and algorithm for change impact calculation
21		Cost-Benefit of Model Development	○	Fair: the high cost (extensive information and potentially a graphics editor software is needed)

Appendix 7: Rating and rationales of the ADVICE method (Kocar and Akgunduz 2010)

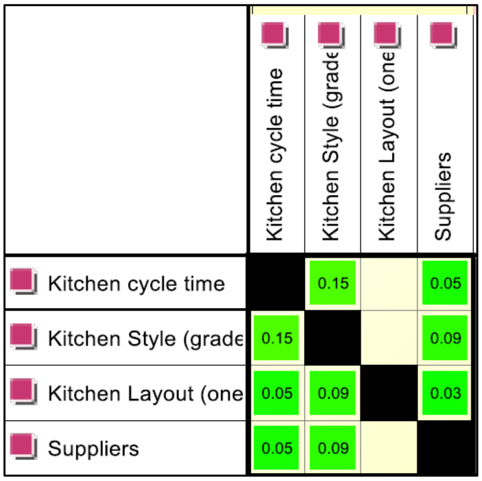
No	Category	Method Requirements (MR)	ADVICE	The rationale for ADVICE score
1	**Functional Representation**	System Modelling Competency	●	Fair: cannot support in the case of uncommon changes where no similar experience is available
2		Change Modelling Competency	●	Average: Change modelling capability can capture change details and patterns, but does not show how changes
3		Change Analysis Competency	●	Fair: prediction capability depends on historic change data and quality of data mining
4	**Operational Representation**	System Performance and Execution	●	Average: change prioritisation and graphical representation useful; interactive; supports the whole EC lifecycle; but
5		Built Resiliency (Robustness and Adaptability)	●	Average: probably changeable to keep up-to-date, but with a certain amount of effort
6		Model Usability	●	Average: change prioritisation and graphical representation useful; interactive; supports the whole EC lifecycle; but
7		Economic Viability	●	Average: medium benefit (supports communication, graphical representation, data mining etc.) and medium-
8	**Technical Representation**	The range of Product, Process, Organisational	●	Fair: only applied on a table; probably not applicable to more complex products
9		Available Information, Data etc.	●	Average: average; extensive information needed for prioritisation and propagation agent; use of available
10		Documentation, Regulation.	●	Average: Documented in BOM, CAD, user entry, change database;
11	**Physical Representation**	System Design	●	Average:
12		Architectural	●	Good: using the BOM structure
13		System Elements and Dependency	●	Good: visualization and pattern mining technique to represent product models and find out dependencies
14		Decomposing	●	Good: to support the level of decomposition: product, elements, and attribute by using a structural approach
15	**Model Development and Application**	Resources: Tools, Software	●	Fair: expensive tools required and not accessible, i.e. virtual reality platform, 3D CAD, the data mining software
16		Easy to Model Development	●	Fair: complicated set up of all parts, e.g. prioritisation agent, propagation agent
17		Consistency	●	Good: consistency based on BOM and CAD information
18		Results for Solution	●	Poor: no solutions provided
19		Adaptability	●	Average: average; potentially much content of the model has to be re-done
20		Numerical Analysis Competency	●	Average: priority indices; uses probabilities and impacts from CPM, but not further elaborated
21		Cost-Benefit of Model Development	●	Fair: the high cost (much information and programming tools are needed)

Appendix 8: Kitchen Assembly System risk matrix calculated considering different numbers of layers



	Kitchen cycle time	Kitchen Style (grade	Kitchen Layout (one	Suppliers
Kitchen cycle time		0.15		
Kitchen Style (grade	0.15			0.09
Kitchen Layout (one		0.09		
Suppliers		0.09		

Direct risk of Layer 1

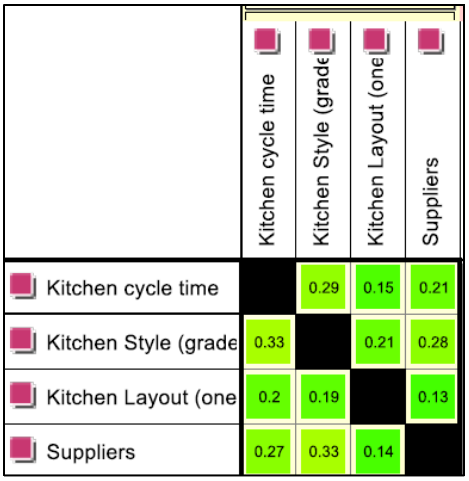


	Kitchen cycle time	Kitchen Style (grade	Kitchen Layout (one	Suppliers
Kitchen cycle time		0.15		0.05
Kitchen Style (grade	0.15			0.09
Kitchen Layout (one	0.05	0.09		0.03
Suppliers	0.05	0.09		

CPM - Layer 1

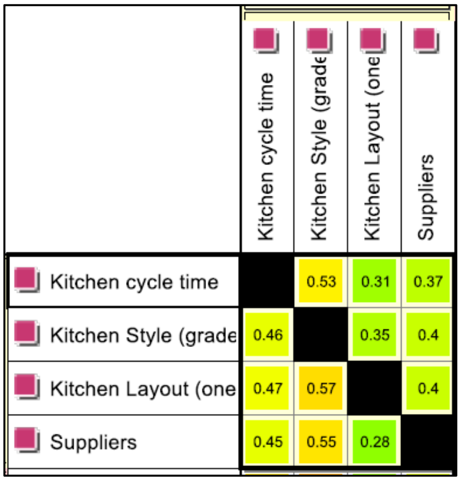
	Kitchen cycle time	Kitchen Style (grade	Kitchen Layout (one	Suppliers
Kitchen cycle time		0.15	0.05	0.08
Kitchen Style (grade	0.15		0.13	0.2
Kitchen Layout (one	0.05	0.09		0.05
Suppliers	0.14	0.28	0.09	

CPM L1 in L1L2



	Kitchen cycle time	Kitchen Style (grade	Kitchen Layout (one	Suppliers
Kitchen cycle time		0.29	0.15	0.21
Kitchen Style (grade	0.33		0.21	0.28
Kitchen Layout (one	0.2	0.19		0.13
Suppliers	0.27	0.33	0.14	

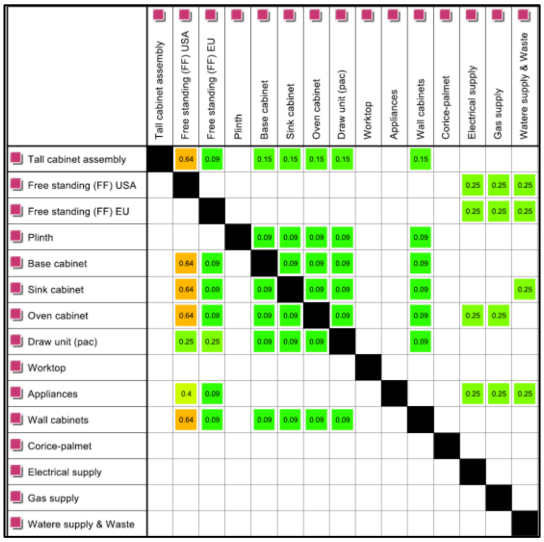
CPM L1 in L1L2L3



	Kitchen cycle time	Kitchen Style (grade	Kitchen Layout (one	Suppliers
Kitchen cycle time		0.53	0.31	0.37
Kitchen Style (grade	0.46		0.35	0.4
Kitchen Layout (one	0.47	0.57		0.4
Suppliers	0.45	0.55	0.28	

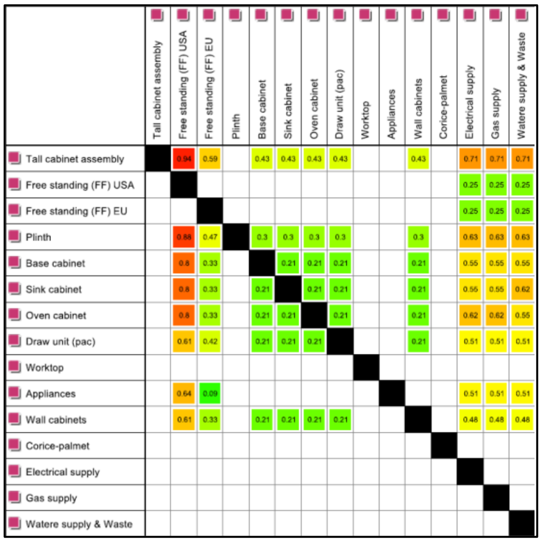
CPM L1 in L1L2L3L4

Appendix 9: Kitchen Design risk matrix calculated considering different numbers of layers



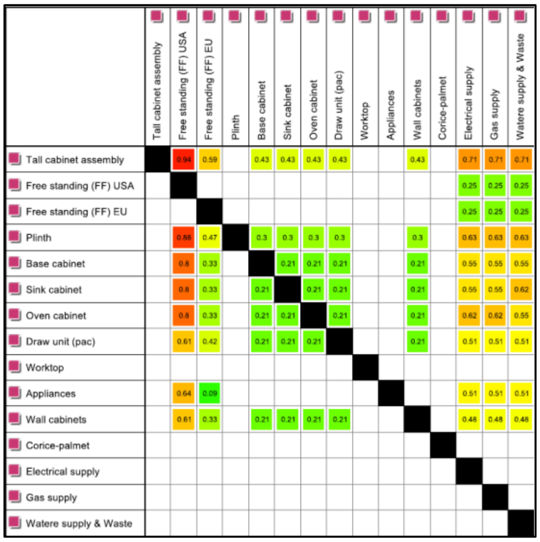
	Tall cabinet assembly	Free standing (FF) USA	Free standing (FF) EU	Plinth	Base cabinet	Sink cabinet	Oven cabinet	Draw unit (pac)	Worktop	Appliances	Wall cabinets	Corice-palmet	Electrical supply	Gas supply	Watere supply & Waste
Tall cabinet assembly	■	0.64	0.09		0.15	0.15	0.15	0.15			0.15				
Free standing (FF) USA		■											0.25	0.25	0.25
Free standing (FF) EU			■										0.25	0.25	0.25
Plinth				■	0.09	0.09	0.09	0.09			0.09				
Base cabinet		0.64	0.09		■	0.09	0.09	0.09			0.09				
Sink cabinet		0.64	0.09		0.09	■	0.09	0.09			0.09				0.25
Oven cabinet		0.64	0.09		0.09	0.09	■	0.09			0.09		0.25	0.25	
Draw unit (pac)		0.25	0.25		0.09	0.09	0.09	■			0.09				
Worktop									■						
Appliances		0.4	0.09							■			0.25	0.25	0.25
Wall cabinets		0.64	0.09		0.09	0.09	0.09	0.09			■				
Corice-palmet												■			
Electrical supply													■		
Gas supply														■	
Watere supply & Waste															■

Direct risk of Layer 1

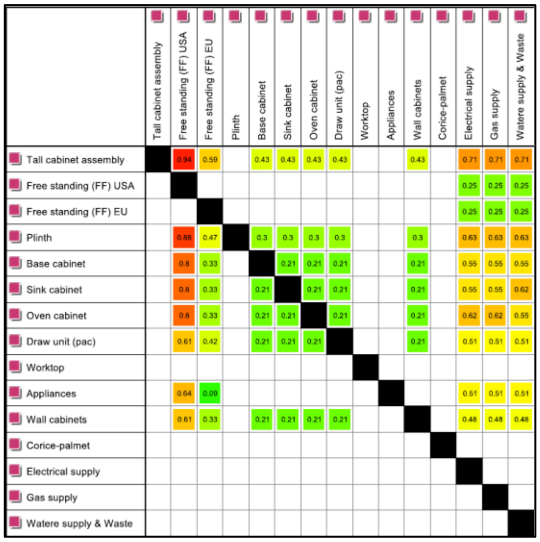


	Tall cabinet assembly	Free standing (FF) USA	Free standing (FF) EU	Plinth	Base cabinet	Sink cabinet	Oven cabinet	Draw unit (pac)	Worktop	Appliances	Wall cabinets	Corice-palmet	Electrical supply	Gas supply	Watere supply & Waste
Tall cabinet assembly	■	0.94	0.59		0.43	0.43	0.43	0.43			0.43		0.71	0.71	0.71
Free standing (FF) USA		■											0.25	0.25	0.25
Free standing (FF) EU			■										0.25	0.25	0.25
Plinth		0.88	0.47	■	0.3	0.3	0.3	0.3			0.3		0.63	0.63	0.63
Base cabinet		0.8	0.33		■	0.21	0.21	0.21			0.21		0.55	0.55	0.55
Sink cabinet		0.8	0.33		0.21	■	0.21	0.21			0.21		0.56	0.55	0.62
Oven cabinet		0.8	0.33		0.21	0.21	■	0.21			0.21		0.62	0.62	0.55
Draw unit (pac)		0.61	0.42		0.21	0.21	0.21	■			0.21		0.51	0.51	0.51
Worktop									■						
Appliances		0.64	0.09							■			0.51	0.51	0.51
Wall cabinets		0.61	0.33		0.21	0.21	0.21	0.21			■		0.48	0.48	0.48
Corice-palmet												■			
Electrical supply													■		
Gas supply														■	
Watere supply & Waste															■

CPM - Layer 1



	Tall cabinet assembly	Free standing (FF) USA	Free standing (FF) EU	Plinth	Base cabinet	Sink cabinet	Oven cabinet	Draw unit (pac)	Worktop	Appliances	Wall cabinets	Corice-palmet	Electrical supply	Gas supply	Watere supply & Waste
Tall cabinet assembly	■	0.94	0.59		0.43	0.43	0.43	0.43			0.43		0.71	0.71	0.71
Free standing (FF) USA		■											0.25	0.25	0.25
Free standing (FF) EU			■										0.25	0.25	0.25
Plinth		0.88	0.47	■	0.3	0.3	0.3	0.3			0.3		0.63	0.63	0.63
Base cabinet		0.8	0.33		■	0.21	0.21	0.21			0.21		0.55	0.55	0.55
Sink cabinet		0.8	0.33		0.21	■	0.21	0.21			0.21		0.55	0.55	0.62
Oven cabinet		0.8	0.33		0.21	0.21	■	0.21			0.21		0.62	0.62	0.55
Draw unit (pac)		0.61	0.42		0.21	0.21	0.21	■			0.21		0.51	0.51	0.51
Worktop									■						
Appliances		0.64	0.09							■			0.51	0.51	0.51
Wall cabinets		0.61	0.33		0.21	0.21	0.21	0.21			■		0.48	0.48	0.48
Corice-palmet												■			
Electrical supply													■		
Gas supply														■	
Watere supply & Waste															■

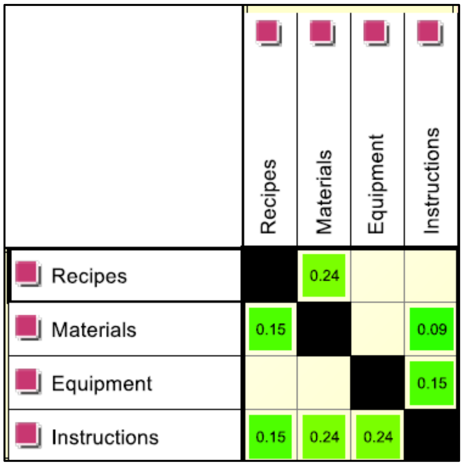


	Tall cabinet assembly	Free standing (FF) USA	Free standing (FF) EU	Plinth	Base cabinet	Sink cabinet	Oven cabinet	Draw unit (pac)	Worktop	Appliances	Wall cabinets	Corice-palmet	Electrical supply	Gas supply	Watere supply & Waste
Tall cabinet assembly	■	0.94	0.59		0.43	0.43	0.43	0.43			0.43		0.71	0.71	0.71
Free standing (FF) USA		■											0.25	0.25	0.25
Free standing (FF) EU			■										0.25	0.25	0.25
Plinth		0.88	0.47	■	0.3	0.3	0.3	0.3			0.3		0.63	0.63	0.63
Base cabinet		0.8	0.33		■	0.21	0.21	0.21			0.21		0.55	0.55	0.55
Sink cabinet		0.8	0.33		0.21	■	0.21	0.21			0.21		0.55	0.55	0.62
Oven cabinet		0.8	0.33		0.21	0.21	■	0.21			0.21		0.62	0.62	0.55
Draw unit (pac)		0.61	0.42		0.21	0.21	0.21	■			0.21		0.51	0.51	0.51
Worktop									■						
Appliances		0.64	0.09							■			0.51	0.51	0.51
Wall cabinets		0.61	0.33		0.21	0.21	0.21	0.21			■		0.48	0.48	0.48
Corice-palmet												■			
Electrical supply													■		
Gas supply														■	
Watere supply & Waste															■

CPM L1 in L1L2

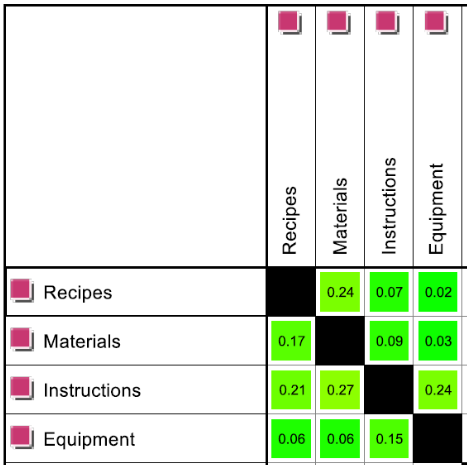
CPM L1 in L1L2L3

Appendix 10: Change Requirements risk matrix calculated considering different numbers of layers



	Recipes	Materials	Equipment	Instructions
Recipes		0.24		
Materials	0.15			0.09
Equipment				0.15
Instructions	0.15	0.24	0.24	

Direct risk of Layer 1

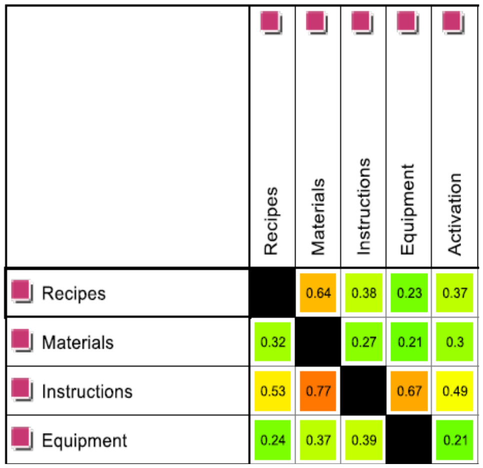


	Recipes	Materials	Instructions	Equipment
Recipes		0.24	0.07	0.02
Materials	0.17		0.09	0.03
Instructions	0.21	0.27		0.24
Equipment	0.06	0.06	0.15	

CPM - Layer 1

	Recipes	Materials	Instructions	Equipment
Recipes		0.55	0.16	0.05
Materials	0.17		0.09	0.03
Instructions	0.29	0.61		0.24
Equipment	0.1	0.24	0.15	

CPM L1 in L1L2



	Recipes	Materials	Instructions	Equipment	Activation
Recipes		0.64	0.38	0.23	0.37
Materials	0.32		0.27	0.21	0.3
Instructions	0.53	0.77		0.67	0.49
Equipment	0.24	0.37	0.39		0.21

CPM L1 in L1L2L3

	Recipes	Materials	Instructions	Equipment
Recipes		0.76	0.61	0.48
Materials	0.4		0.39	0.34
Instructions	0.67	0.86		0.8
Equipment	0.38	0.52	0.55	

CPM L1 in L1L2L3L4

Bibliography

Ahern, F.Jack, (2011), *From fail-safe to safe-to-fail: sustainability and resilience in the new urban world*, 100th Volume SI, Elsevier Editorial System(tm) for Landscape and Urban Planning Landscape and Urban Planning Journal. LAND-D-11-00011R1

Abech, M.P., Berg, G.A., Delis, M.G., Guimaraes, L.B.M. and Woods, D.D. (2006) 'Analysing resilience of a distribution plant', *Proceedings of the Systems and Information Engineering Design Symposium, IEEE*, Charlottesville, pp. 216-221.

Ahmed, S. and Kanike, Y. (2007) 'Engineering change during a product's lifecycle', *International Conference on Engineering Design (ICED'07),* Paris, France, 633–634.

Ahmad, N., Wynn, D.C. and Clarkson, P.J. (2009) 'An MDM-based approach to managing engineering change processes across domains of the design process', *International DSM Conference (DSM'09).* Greenville, SC, USA, 299-312.

Ahmad, N., Wynn, D.C. & Clarkson, P.J., 2010a. Development and evaluation of a tool to estimate the impact of design change. International Design Conference (DESIGN'10). Dubrovnik, Croatia, 105-116.

Ahmad, N. (2011) 'Supporting the management of the engineering change process through crossdomain traceability model', Ph.D. thesis. *University of Cambridge*.

Ahmad, N., Wynn, D.C. and Clarkson, P.J. (2013) 'Change impact on a product and its redesign process: a tool for knowledge capture and reuse', *Research in Engineering Design*, 24 (3), 219-244.

Albers, A., Braun, A., Sadowski, E., Wynn, D.C., Wyatt, D.F. and Clarkson, P.J. (2011) 'System architecture modelling in a software tool based on the contact and channel approach (C&C-A)'. *Journal of Mechanical Design*, 133 (10), 101006-8.

AlGeddawy, T. and ElMaraghy, H. (2011) 'Manufacturing Systems Synthesis Using Knowledge Discovery', *CIRP Annals*, 60 (1), In Press.

AlGeddawy, T. and ElMaraghy, H.A. (2009), "Changeability effect on manufacturing systems design", in ElMaraghy, H. (Ed.), Changeable and Reconfigurable Manufacturing Systems, Springer, London, pp. 267-284

Alleman, G.B. (2002) 'Architecture–Centered ERP Systems in the Manufacturing Domain' , Niwot, Colorado 80503.

Allen, M.P, Datta, P.P. and Christopher, M. (2006) 'Improving The Resilience And Performance Of Organizations Using Multi-Agent Modelling Of A Complex Production – Distribution Systems', *Palgrave Macmillan Ltd,* 1460–3799/06, www.palgrave-journals.com/rm

Ariyo, O.O., Keller, R., Eckert, C.M. and Clarkson, P.J. (2007a) ‘Predicting change propagation on different levels of granularity: An algorithmic view’, *International Conference on Engineering Design (ICED'07),* Paris, France, 655-656.

Ariyo, O.O., Eckert, C.M. and Clarkson, P.J. (2007b) ‘Prioritising engineering change propagation risk estimates’, *International Conference on Engineering Design (ICED’07),* Paris, France, 691–692.

Ariyo, O.O., 2007. Change propagation in complex design: Predicting detailed change cases with multi-levelled product models. PhD thesis. *University of Cambridge*.

Aryani, A., Ian D. P. , Hamilton, M., Schmidt, H. and Winikoff, M. (2009) ‘Change Propagation Analysis Using Domain Information’, *Australian Software Engineering Conference,* DOI: 10.1109/ASWEC.31.

Azadeh, A. and Salehi, V. (2014) ‘Modeling and Optimizing Efficiency Gap between Managers and Operators in Integrated Resilient Systems: the Case of a Petrochemical Plant Process Safety and Environmental Protection’, 92 (6) (2014), pp. 766-778

Byard, P., Thomas, A., Francis, M., Fisher, R. and White, R.T.G. (2015) ‘Profiling the resiliency and sustainability of UK manufacturing companies’, *Journal of Manufacturing Technology Management,* Vol. 27 Iss 1 pp. 82 – 99, http://dx.doi.org/10.1108/JMTM-06-2014-0086

Bhamra, R., Dani, S., Burnard, K. (2011a) ‘Resilience: The concept, a literature review and future directions’. *International Journal of Production Research* 49(18), pp.5375–5393

Bellgran, M. and Säfsten, K. (2004) ‘Production System Design and Evaluation for Increased System Robustness’, P*roceedings of Second World Conference on POM and 15th Annual POM Conference, ORCID* iD: 0000-0002-0216-4493

Benkamoun, N., ElMaraghy, W., Huyet, A.L. and Kouiss, K. (2014) ‘Architecture framework for manufacturing system design’, *Procedia CIRP, - Elsevier,* Volume 17, pp. 88-93

Bennett, D.J. and Forrester, P.L. (1993) ‘Market-focused production systems: design and implementation’. *Prentice Hall.*

Berkley, R.A. and Wallace, M. (2010) ‘A Framework for Establishing Critical Infrastructure Resilience Goals’. *National Infrastructure Advisory Report.*

Blessing, L. T. M., Chakrabarti, A., and Wallace, K. M. (1995) ‘A Design Research Methodology’, *International Conference on Engineering Design (ICED'95),* (pp. 46-55). Prague, Czech Republic.

Blessing, L. M. T. (2002) ‘What Is This Thing Called Design Research?’ *Proceedings of 2002 Int'l CIRP Design Seminar* (Hong Kong, China, May 16-18, 2002). pp. 1-6

Blessing, L.T.M. and Chakrabarti, A. (2009), ‘DRM, a design research methodology’*, Springer,* London, UK.

Bock, C. and Feeney, A.B. (2013) ‘Engineering Change Management Concepts for Systems Modelling’, *National Institute of Standards and Technology*, http://dx.doi.org/10.6028/NIST.IR.7922

Browning, T.R. (2001) ‘Applying the design structure matrix to system decomposition and integration problems: A review and new directions’, *IEEE Transactions on Engineering Management*, 48 (3), 292-306.

Business Dictionary (2018) ‘the definitive record of the English language’, available online at http://www.businessdictionary.com.

Bryden Wood (2015). E5+ Strategic Briefing Report, Unpublished report

Brace, W. and Cheutet, V. (2011) ‘A framework to support requirements analysis in engineering design’, *Journal of Engineering Design*, Volume 23, Issue 12.

Caputo, A.C., Pelagagge.M.P, Salini, P., (2017) ‘Methodology to estimate resilience of manufacturing plants’, *Science Direct, IFAC PapersOnLine* 52-13 (2019) 808–813

Carpenter, S.R., Walker B.H., Anderies J.M. and Abel. N. (2001) ‘From metaphor to measurement: the resilience of what to what?’, *Ecosystems,* 4:765-781.

Ceglarek, D. and Jin, J. (2004) ‘Introduction: Modeling and Analysis for Complex Production Systems. Position Statement’, International Journal of Flexible Manufacturing Systems, *Springer,* Volume 16, Issue 1, pp 5–9.

Chalmeta, R., Williams, T.J., Lario, F. and Ros, L. (1997) ‘Developing An Object-Oriented Reference Model For Manufacturing’, Elsevier, Volume 30, Issue 1, pp. 351-356.

Chalupnik M. J., Wynn, D. C., Clarkson, P. J. (2013) “Comparison of ilities for protection against uncertainty in system design”, *J. Eng. Des.,* vol. 24, no. 12, pp. 814–829.

Chen, L. and Li, S. (2005) ‘Towards rapid redesign: Pattern-based redesign planning for large-scale and complex redesign problems’, *ASME Design Engineering Technical Conference (DETC'05).* Long Beach, CA, USA, 227-233. .

Clarkson, P. J. and Eckert, C. (2010). ‘Design process improvement: A review of current practice’. *Springer Science and Business Media,* London, UK.

Clarkson P.J. and Hamilton J.R. (2000). “Signposting,” a parameter-driven task-based model of the design process. Research in Engineering Design, 12(1), pp. 18–38.

Clarkson, P.J., Simons, C. and Eckert, C.M. (2001a) ‘Predicting change propagation in complex design’, *ASME Design Engineering Technical Conference (DETC'01).* Pittsburgh, PA, USA, 155-164.

Clarkson, P.J., Simons, C. and Eckert, C.M. (2001b). ‘Change prediction for product redesign’. *International Conference on Engineering Design (ICED'01).* Glasgow, UK, 557-584.

Clarkson, P.J., Simons, C. and Eckert, C.M. (2004). 'Predicting change propagation in complex design'. *Journal of Mechanical Design,* 126 (5), 788-797.

Clark, K. B. and Fujimoto, T. (1991) 'Product development performance. Strategy, organisation and management in the world auto industries', *Harvard Business School,* Boston, USA.

Cochran, D. S. (1994) 'The Design and Control of Manufacturing Systems', *Ph.D. Thesis,* Auburn University

Cochran, D.S., Arinez, J.F., Duda, J.W. and Linck, J. (2001), "A decomposition approach for manufacturing system design", *Journal of Manufacturing Systems*, Vol. 20 No. 6, pp. 371-389. https://doi.org/10.1016/S0278-6125(01)80058-3

Cordes, P.and Hülsmann, M. (2013) 'Dynamic Capabilities in Manufacturing Processes: A Knowledge-based Approach for the Development of Manufacturing Flexibilities. *In: Windt, K. (ed.) Robust Manufacturing Control, Springer,* Berlin, pp. 519–534.

Cohen, T., Navathe, S.B. and Fulton, R.E. (2000) 'C-FAR, change favourable representation', *CAD Computer Aided Design,* 32 (5), 321-338.

Collis, J. and Hussey, R. (2003) 'Business Research: A Practical Guide for Undergraduate and Postgraduate Student', Second Edition. Basingstoke, *Palgrave Macmillan.*

Crawley, E., De Weck, O., Magee, C, Moses, J., Seering, W., Schindall, J., Wallace, D., Whitney, D. (2004) 'The influence of architecture in engineering systems' *CiteSeer,* The Pennsylvania State University.

Danilovic, M. and Sandkull, B. (2002) 'Managing Complexity and Uncertainty in a Multiproject Environment', *International Research Network on Organizing by Projects (IRNOP V),* Rotterdam, Netherlands, pp.28-31

Danilovic, M. and Browning, T. R. (2005) 'The use of dependence structure matrix and domain mapping matrix in managing uncertainty in multiple project situations', *International Journal of Project Management 23* / 193–203

Danilovic, M. and Browning, T. R. (2007) "Managing complex product development projects with design structure matrices and domain mapping matrices", *International Journal of Project Management,* Vol 25, No. 3, pp. 300-314.

Deno, P. (2001) 'Global Engineering, Manufacturing and Enterprise Networks 'National Institute of Standards and Technology, *Springer Science and Business,* Media New York

De Weck, L.O. (2007) "On the role of DSM in designing systems and products for changeability", *In 9th International Design Structure Matrix Conference (DSM'07),* Munich, Germany.

Duffy, A.H.B. and Andreasen, M.M. (1995) 'Enhancing the Evolution of Design Science'. *International Conference on Engineering Design (ICED'95),* Prague, Czech Republic.

Duffy, A.H.B. and O'Donnell, F.J. (1999) 'A design research approach', *Design Science,* 33-40.

Dinh, L.T.T., Pasman, H. Gao, X. and Mannan, M.S. (2012) ‘Resilience engineering of industrial processes: Principles and contributing factors’, *J. Loss Prev. Process Ind.*, 25 (2012), pp. 233-241

Eckert, C.M., Clarkson, P.J. and Stacey, MK. (2003) ‘The spiral of applied research: A methodological view on integrated design research’, *International Conference on Engineering Design (ICED'03),* Stockholm, Sweden.

Eckert, C.M., Clarkson, P.J. and Zanker, W. (2004) ‘Change and customisation in complex engineering domains’, Research in Engineering Design, 15 (1), 1-21.

Eckert, C.M., Keller, R., Earl, P.C. and Clarkson, P.J. (2006) ‘Supporting change processes in design: Complexity, prediction and reliability’, *Reliability Engineering and System Safety,* 91 (2006) 1521–1534

Eckert, C.M., De Weck, O.L., Keller, R. and Clarkson, P.J. (2009) ‘Engineering change: Drivers, sources, and approaches in the industry’. International Conference on Engineering Design (ICED'09). Stanford, CA, USA, 47-58.

Eger, T., Eckert, C.M. and Clarkson, P.J. (2005) ‘The role of design freeze in product development’, *International Conference on Engineering Design (ICED'05).* Melbourne, Australia: CDROM 2005, 164-165.

Eger, T., Eckert, C.M. and Clarkson, P.J. (2007a) ‘Engineering change analysis during ongoing product development’, *International Conference on Engineering Design (ICED'07).* Paris, France, 629-630.

Eger, T., Eckert, C.M. and Clarkson, P.J. (2007b) ‘Impact of changes at different stages of product development’, *International Conference on Engineering Design (ICED'07).* Paris, France, pp. DS42.P.27.

Eppinger, S.D. & Browning, T.R. (2012) ‘Design structure matrix methods and applications’, *The MIT Press.* Cambridge, MA, USA.

Eppinger, S. D., Whitney, D. E., Smith, R. P. and Gebala, D. A. (1994) ‘A Model-Based Method for Organizing Tasks in Product Development’, *Research in Engineering Design,* **6** 1-13.

Earl, C. F., Eckert, C. M. and Clarkson, P. J. (2005) “Design change and complexity”, *In 2nd Workshop on Complexity in Design and Engineering,* University of Glasgow, UK.

ElMaraghy, H. A. (2009) ‘Changeability Effect on Manufacturing Systems Design Reconfigurable Manufacturing System’, *Springer,* London.

ElMaraghy H. (2006) ‘A complexity code for manufacturing systems’, ASME International Conference on Manufacturing Science & Engineering (MSEC), *American Society of Mechanical Engineers,* Ypsilanti, MI, United States. pp. 625–634.

ElMaraghy, W., ElMaraghy, H., Tomiyama, T., Monostori, L. (2012) ‘Complexity in engineering design and manufacturing’, *Elsevier,* Volume 61, Issue 2, pp. 793-814.

ElMaraghy, H.A. and Wiendahl, H.P. (2009), ‘Changeability – an introduction’, in ElMaraghy, H.A.

(Ed.), Changeable and Reconfigurable Manufacturing Systems, *Springer*, London, pp. 3-24.

Fei, G., Gao, J., Owodunni, D. and Tang, X. (2011a) 'A model-driven and knowledge-based methodology for engineering design change management', *Computer-Aided Design & Applications*, 8 (3), 373-382.

Fiksel, J. (2003) 'Designing Resilient', *Sustainable Systems. Environmental Science and Technology*, 37 (23): 5330–5339.

Fiksel, J. (2000) ' Designing Resilient, Sustainable Systems', *Environmental Science & Technology* / VOL. 37, NO. 23,

Fei, G., Gao, J., Owodunni, O.O. & Tang, X., (2011b) 'A method for engineering design change analysis using system modelling and knowledge management techniques'. *International Journal of Computer Integrated Manufacturing*, 24 (6), 535-551.

Flanagan, T., Eckert, C.M., Smith, J., Eger, T. & Clarkson, P.J. (2003) 'A functional analysis of change propagation'. *International Conference on Engineering Design (ICED'03).* Stockholm, Sweden, 441-442.

Fricke, E., Gebhard, B., Negele, H. and Igenbergs, E. (2000) 'Coping with changes: Causes, findings, and strategies', *Systems Engineering*, 3 (4), 169-179

Fricke E. and Schulz AP. (2005) 'Design for changeability (DfC): Principles to enable changes in systems throughout their entire lifecycle'. *Systems Engineering*, 8(4), pp.342–359

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T. and Rockström, J. (2010) 'Resilience thinking: integrating resilience, adaptability and transformability', *Ecology and Society* 15(4):20

Folke, C. (2006) 'Resilience: the emergence of a perspective for social-ecological systems analyses', *Global Environmental Change* 16:253-267.

Fraccascia, L., Giannoccaro, I., Albino, V., (2018) 'Resilience of Complex Systems: State of the Art and Directions for Future Research, Complexity', Vol.2018, Article ID 3421529, pp. 1-44, https://doi.org/10.1155/2018/3421529.

Framinan, J. and Ruiz, R. (2010) 'Architecture of manufacturing scheduling systems: Literature review and an integrated proposal, *European Journal of Operational Research*, 205 (2), pp. 237-246

Francalanzaa, E,, Borga, J and Constantinescu, C. (2014) 'Deriving a systematic approach to changeable manufacturing system design', *the 47th CIRP Conference on Manufacturing Systems*, Procedia CIRP 17 (2014) 166 – 171

Furtmeier, F. and Tommelein, I.D. (2010), "Explorative Application of the Multi-Domain Matrix Methodology in Lean Design", *Proceedings of the 18th Annual Conference of the International Group for Lean Construction*, Haifa, Israel, pp. 151-160.

Gao, F. (2010) 'Resilience analysis and measurement for water supply system', MS thesis, *University of Saskatchewan*, Canada.

Gardner, L. and Colwill, J. (2016) 'A framework and decision support tool for improving value chain resilience to critical materials in manufacturing', *Production & Manufacturing Research An Open Access Journal,* Volume 6, 2018 - Issue 1.

Giffin, M., De Weck, O.L., Bounova, G., Keller, R., Eckert, C.M. and Clarkson, P.J. (2009) 'Change propagation analysis in complex technical systems', *Journal of Mechanical Design,* 131 (8), 0810011-08100114.

Giffin, M. L. (2007) 'Change Propagation in Large Technical Systems' System Design & Management Program, *Massachusetts Institute of Technology,* MSc Thesis.

Glaser, B. G. and Strauss, A. L. (1967) The discovery of grounded theory: Strategies for qualitative research, Aldine publishing company, New York, USA.

Glaser BG.(1998) 'Doing Grounded Theory – Issues and Discussions'. *Sociology Press*.

Gershwin, S.B. (2006), 'How Do Quantity And Quality Really Interact? Precise Models Instead Of Strong Opinions', *Science Direct*, Volume 39, Issue 3, 2006, Pages 33-39.

Gunderson, L.H. (2000) 'Ecological resilience: in theory and application'. *Annual Review of Ecology and Systematics,* 31:425-439.

Gunderson, L. H. and Holling, C. S. (2002) 'Panarchy: understanding transformations in human and natural systems', *Island Press*, Washington D.C., USA.

Guenov, M.D. and Barker, S.G. (2005). Application of Axiomatic Design and Design Structure Matrix to the decomposition of engineering systems'. *Systems Engineering*, 8 (1), pp. 29-40.

Gu, X., Jun Ni, and Koren, Y. (2015) 'Manufacturing System Design for Resilience', *CIRP 25th Design Conference Innovative Product Creation,* Procedia CIRP 36-135 – 140, doi: 10.1016/j.procir.2015.02.075, www.sciencedirect.com,

Haq, I., R., Masood, T., Ahmad, B., Harrison, R., Raza, B. and Monfared, P. R. (2011) 'Product to Process Lifecycle Management In Assembly Automation Systems' *Proceedings of DET2011 7th International Conference on Digital Enterprise Technology,* Athens, Greece

Hamraz, B. (2013) Engineering change modelling using a Function-Behaviour-Structure scheme, Ph.D. thesis, University of Cambridge, UK.

Hamraz, B., Caldwell, N.H.M. and Clarkson, P.J. (2013) 'A holistic categorisation framework for literature on engineering change management. *Systems Engineering,* 16 (4), 473–505.

Hamraz, B., Caldwell, N.H.M. and Clarkson, P.J. (2012b) A matrix-calculation-based algorithm for numerical change propagation analysis. *IEEE Transactions on Engineering Management,* 60 (1), 186-198.

Hamraz, B., Caldwell, N.H.M. & John Clarkson, P. (2012c) 'A multidomain engineering change propagation model to support uncertainty reduction and risk management in design', *Journal of Mechanical Design,* 134 (10), 100905.01-14.

Hamel, G. and Valikangas, L. (2003) 'The Quest for Resilience', *Harvard Business Review Press.*

Haskins, C. K., Forsberg, M., Krueger, D. W. and Hamelin, R. D. (2010) “Systems Engineering Handbook”.

Hayes, R.H. and Wheelwright, S.C. (1979), ‘Link manufacturing process and product lifecycles’, *Harvard Business Review*.

Hauser, J.R. and Clausing, D. (1988) ‘The house of quality’. *Harvard Business Review,* pp.63-73.

Heinicke, M. (2014a) ‘Framework for Resilient Production Systems’ *the IFIP Advances in Information and Communication Technology book series* (IFIPAICT, volume 440)

Heinicke, M. (2014b), Implementation of resilient production systems by production control, Robust Manufacturing Conference (RoMaC 2014), Institute of Ergonomics, Manufacturing Systems and Automation, Otto von Guericke University, Universitätsplatz 2, Magdeburg 39106, Germany.

Heisel, M., Kaaniche, M., Romanovsky, A., and Troubitsyna, E. (2013) ‘Engineering Resilient Systems: Models, Methods and Tools’ The Dagstuhl Seminar 13022, www.dagstuhl.de/13022

Hein, H.P., Menon, V. and Morkos, B. (2015) ‘Exploring Requirement Change Propagation Through The Physical And Functional Domain’, *ASME- International Design Engineering Technical Conferences & Computers and Information in Engineering Conference,* August 2-5, Boston, Massachusetts, USA

Hamel, G., and Valikangas, L. (2003).’The quest for resilience’, *Harvard Business Review* Sep;81(9):52-63, 131.

Herrman,H., Stewart, D.E., Diaz-Granados N., Berger L.E., Jackson, Yuen, B. T. (2011) ‘What Is Resilience?’, *The Canadian Journal of Psychiatry,* Vol 56, No 5.

Holder K., Zech, A. Ramsaier, M. Stetter, R., Niedermeier, H. P., Rudolph, S. and Till, M. (2017) ‘Model-Based Requirements Management in Gear Systems Design Based On Graph-Based Design Languages’, *Applied Science*, 7, 1112; doi:10.3390/app7111112

Holland, J. H. (1998) ‘Emergence: From Chaos to Order’, Copyright *JASSS*, ISBN 0-201-14943-5, Redwood City, California: Addison-Wesley

Holling. C.S. (1973) ‘Resilience and Stability of Ecological Systems’, *Annual Review of Ecology and Systematics*, 4:1–23, ISSN 0066-4162. doi: 10.1146/annurev.es.04.110173.000245

Hollnagel, E. and Woods, D.D. (2006) ‘Resilience Engineering Precepts’ publication at: https://www.researchgate.net/publication/265074845

Hollnagel, E., Woods, D.D. and Leveson, N. (2007) ‘Resilience Engineering: Concepts and Precepts’, *Ashgate Publishing Ltd.*

Hoffmann, M. C., Shapiro, V. and Srinivasan, V. (2011) ‘Geometric Interoperability for Resilient Manufacturing’, *Computer Science Technical Reports*. Paper 1746. http://docs.lib.purdue.edu/cstech/1746

Hu, Y., Li, J, and Holloway, LE. (2013) 'Resilient control for serial manufacturing networks with advance notice of disruptions', *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 43(1):98–114.

Hu, Yao, (2013) 'The Modelling, Analysis and Control of Resilient Manufacturing Enterprises', Theses and Dissertations--Electrical and Computer Engineering. Paper 15.

Huang, G.Q. and Mak, K.L. (1999) 'Current practices of engineering change management in the UK manufacturing industries', *International Journal of Operations & Production Management*, ISSN 0144-3577, Volume 19, Issue 1, pp. 21 – 37

Huang, G.Q., Yee, W.Y. and Mak, K.L. (2003) 'Current practice of engineering change management in Hong Kong manufacturing industries'. *Journal of Materials Processing Technology*, 139 (1-3 SPEC), 481.

Hull, E., Jackson, K. and Dick, J. (2004) 'Requirements engineering', *Springer*, London

IEEE, 2012. IEEE Std 1012-2012 - Standard for system and software verification and validation. New York, NY, USA: Institute of Electrical and Electronics dEngineers (IEEE).

INCOSE UK Limited (2018) The International Council on Systems Engineering (INCOSE) Handbook England register no. 3641046 https://incoseonline.org.uk/Normal_Files/WhatIs/Systems_Thinking.aspx?CatID=What_Is_SE

Ismail, H. S., Poolton, J. and Sharifi, H. (2011) 'The Role of Agile Strategic Capabilities in Achieving Resilience in Manufacturing-based Small Companies.' International Journal of Production Research 49 (18): 5469–5487.

Ivanov, I. *and* Sokolov, B. (2013) 'Control and system-theoretic identification of the supply chain dynamics domain for planning, analysis and adaptation of performance under uncertainty', *European Journal of Operational Research*, Volume 224, Issue 2, 16, pp.313-323

Ivanov, D., Dolgui, A., Sokolov, B., Ivanova, M., (2017) 'Literature Review on Disruption Recovery in the Supply Chain', *International Journal of Production Research*, Vol. 55 (20), pp. 6158-6174.

Jackson, S. and Frries, L. J. T. (2013) 'Resilience Principles for Engineered Systems', Published online in Wiley Online Library (wileyonlinelibrary.com), DOI 10.1002/sys.21228.

Jackson, S. (2010) '' in Architecting a Resilient System from Architecting Resilient Systems: Accident Avoidance and Survival and Recovery from Disruptions', Published By *John Wiley & Sons, Inc.*, Hoboken, New Jersey, Published Simultaneously In Canada,

Janthong, N. (2011) 'A methodology for tracking the impact of changes in (re)designing of the industrial complex product', *IEEE International Conference on Industrial Engineering and Engineering Management*, Singapore, 1058-1062

Jarratt, T.A.W. (2004) 'A model-based approach to support the management of engineering changes', PhD thesis, *University of Cambridge*.

Jarratt, T.A.W., Eckert, C.M. and Clarkson, P.J. (2004a) ‘Development of a product model to support engineering change management’, *Fifth International Symposium on Tools and Methods of Competitive Engineering (TMCE'04).* Lausanne, Switzerland, 331-342.

Jarratt, T.A.W., Eckert, C.M. and Clarkson, P.J. (2004b) ‘The benefits of predicting change in complex products: application areas of a DSM-based prediction tool. *International Design Conference (DESIGN'04).* Dubrovnik, Croatia, 303-308.

Jarratt, T.A.W., Eckert, C.M. and Clarkson, P.J. (2004c) ‘Engineering change Design process improvement’, *Springer,* New York, NY, USA: 262-285.

Jarratt, T.A.W., Eckert, C.M., Caldwell, N.H.M. and Clarkson, P.J. (2011) ‘Engineering change: An overview and perspective on the literature’, *Research in Engineering Design,* 22 (2), 103-124.

Jin, X. and Gu, X. (2016) ‘Option-Based Design for Resilient Manufacturing Systems’, *International Federation of Automatic Control*, IFAC Papers On Line 49-12 (2016) 1602–1607

Jones, R. G. (1969) ‘Hierarchy: The Problem of the One and the Many. Hierarchical Structures’, *American Elsevier*, pp 284-285. New York,

Karlsson, M. (2008) ‘Towards a Resilient Production System Strategy for Implementation of Business Continuity Planning’ Uppsala University, ISSN: 1650-8319, UPTEC STS08 002, http://www.teknat.uu.se

Kahan J. H., Allen A.C., and George, J. K. (2009) ‘An Operational Framework for Resilience’, *Journal of Homeland Security and Emergency Management*, Volume 6, Issue 1, Article 83

Keller, R., Eckert, C.M. & Clarkson, P.J., 2005a. Multiple views to support engineering change management for complex products. *3rd International Conference on Coordinated and Multiple Views in Exploratory Visualization (CMV'05).* London, UK, 33-41.

Keller, R., Eger, T., Eckert, C.M. & Clarkson, P.J., 2005b. Visualizing change propagation. *International Conference on Engineering Design (ICED'05).* Melbourne, Australia, 62-63.

Keller, R., 2007. *Predicting change propagation: Algorithms, representations, software tools*. PhD thesis, University of Cambridge.

Kilpinen, M. S., Eckert, C. M. and Clarkson, P. J. (2009) “Assessing impact analysis practice to improve change management capability”, *In International Conference on Engineering Design (ICED’09),* Stanford, CA, USA.

Kim, Y.S. (2002) ‘A Decomposition-Based Approach for the Integration of Product Development and Manufacturing System Design’, *Massachusetts Institute of Technology*, PhD Thesis,

Kissel, M.S. and Lindemann, U. (2012) ‘Design for Adaptability – Identifying Potential for Improvement on an Architecture Basis’, *Nord Design*, Aalborg, Denmark

Kocar, V. and A. Akgunduz (2010) ‘ADVICE: a virtual environment for engineering change Management’, *Computers in Industry,* ISSN 0166-3615, Volume 61, Issue 1, pp. 15 – 28

Koch J, Maisenbacher S, Maurer M, Reinhart G, Zäh MF (2014). Structural modelling of extended manufacturing systems – an approach to support changeability by reconfiguration planning. In: Procedia CIRP: 47th CIRP Conference on Manufacturing Systems (CMS). p. 142-7.

Koch, J., Michelsa, N. and Reinharta, G. (2016), 'Context model design for a process-oriented Manufacturing Change Management', *48th CIRP Conference on Manufacturing Systems*, Procedia CIRP 41 (2016) 33 – 38, doi: 10.1016/j.procir.2015.12.111

Koh, E.C.Y. (2011) 'Managing change propagation in the development of complex products'. PhD. thesis. The *University of Cambridge*.

Koh, E.C.Y., Caldwell, N.H.M. & Clarkson, P.J., 2009a. Using a matrix-based method to model change propagation. International DSM Conference (DSM'09). Greenville, SC, USA, 271284.

Koh, E.C.Y., Caldwell, N.H.M. & Clarkson, P.J. (2012) 'A method to assess the effects of engineering change propagation', *Research in Engineering Design*, 23 (4), 329-351.

Koh, E.C.Y. & Clarkson, P.J., 2009. A modelling method to manage change propagation. International Conference on Engineering Design (ICED'09). Stanford, CA, USA, 253-264.

Koh, E.C.Y., Keller, R., Eckert, C.M. & Clarkson, P.J., 2007. Component classification: A changing perspective. International DSM Conference (DSM'07). Munich, Germany, 337-348.

Koh, E.C.Y., Keller, R., Eckert, C.M. & Clarkson, P.J., 2008b. Influence of feature change propagation on product attributes in concept selection. International Design Conference (DESIGN'08). Dubrovnik, Croatia, 157-166.

Koh, E.C.Y., Keller, R., Eckert, C.M. & Clarkson, P.J., 2009b. Change propagation modelling to support the selection of solutions in incremental change. International Conference on Research into Design (ICoRD'09). Bangalore, India, 199-206.

Kothari, C.R. (2004) 'Research Methodology: Methods and Techniques', (Second Edition), *New Age International Publishers.* ISBN 8122415229, 9788122415223.

Lee, H., Seol, H., Sung, N., Hong, Y.S. and Park, Y. (2010) 'An analytic network process approach to measuring design change impacts in modular products. *Journal of Engineering Design*, 21 (1), 75-91.

Levis, A. (1999) 'System Architectures', In A. P. Sage & W. B. Rouse, *Handbook of Systems Engineering and Management* (pp. 427–454). New York: John Wiley & Sons.

Li, S. and Chen, L., 2010. The pattern-based reasoning for the rapid redesign: A proactive approach. Research in Engineering Design, 21 (1), 25-42.

Liu, X., Zhang, W.J., Radhakrishnan, R., and Tu, Y.L. (2009) 'Manufacturing perspective of enterprise application integration: the state of the art review', *International Journal of Production Research* 46 (16), 4567-4596

Lindemann, U., Maurer. M. and Braun, T. (2009) 'Structural Complexity Management: An Approach for the Field of Product Design', *Springer-Verlag*, Berlin Heidelberg.

Lindemann, U. and Maurer, M. (2007) ‘Facing multi-domain complexity in product development. The Future of Product Development’, Berlin, Germany: Springer, 351-361.

Maalem, S. and Zarour, N. (2016) ‘Challenge of validation in requirements engineering’, *Journal of Innovation in Digital Ecosystems,* Volume 3, Issue 1, June 2016, Pages 15-21

Madni, A.M. and Jackson, S. (2009) ‘Towards a Conceptual Framework for Resilience Engineering’ *IEEE Systems Journal*, Volume: 3, Issue: 2, DOI: 10.1109/JSYST.2009.2017397, pp.181-191

Marchese, D., Reynolds, E., Bates, E. M., Morgan, H., Clark, S.S. and Linkov, I. (2018) ‘Resilience and sustainability: Similarities and differences in environmental management applications’, *Science of the Total Environment,* 613–614 (2018) 1275–1283.

Marden J.R., Arslan G. and Shamma J.S. (2009) ‘Cooperative control and potential games’ *IEEE Transactions on Systems, Man, and Cybernetics*, Part B, 39 (6), pp. 1393-1407

Maier, J. F., Wynn, D. C., Biedermann, W., Lindemann U. & Clarkson P. J., Simulating progressive iteration, rework and change propagation to prioritise design tasks, *Research in Engineering Design,* volume 25, pages283–307.

Martin-Breen P, Anderies, J.M. (2011) ‘Resilience: A Literature Review’, *Arizona State University,* New York

Maurer, M. and Lindemann, U. (2007) ‘Facing Multi-Domain Complexity in Product Development’, *CIDAD- Competency in Design and Development Working Paper Series*, ISSN 1861-079X – Nr. 01

Maurer, M. (2007) ‘Structural awareness in complex product design’, PhD thesis, *Technology University of Munich.* ISBN 978-3-89963-632-1, http://dnb.d-nb.de abrufbar.

Merdan M., Vallée, M., Moser, T. and Biffl, S.(2011) ‘A Layered Manufacturing System Architecture Supported with Semantic Agent Capabilities’ *Semantic Agent Systems*, Part of the Studies in Computational Intelligence book series (SCI, volume 344), pp 215-242

McManus, H. (2008) ‘Ility Space’ (Working Paper No. WP-2007-2-2). *MIT*, Cambridge, MA: Systems Engineering Advancement Research Initiative.

Mehrpouyan, H., Haley, B., Dong, A., Tumer I.Y. and Hoyle, C. (2015) ‘Resiliency analysis for complex engineered system design’, *Cambridge University Press,* 0890-0604/15, doi:10.1017/S0890060414000663

Morkos, B. and Summers, J.D. (2010) ‘Requirement change propagation prediction approach: Results from an industry case study’, *ASME Design Engineering Technical Conference (DETC'10),* Montreal, Quebec, Canada ASME, 111-121.

Morkos, B., Shankar, P. and Summers, J.D. (2012) ‘Predicting requirement change propagation, using higher order design structure matrices: an industry case study’, *Journal of Engineering Design,* Volume 23, 2012 - Issue 12, pp. 905-926.

Mu, D., Zhao, F., Seager, P.T. And Rao, P.C. (2010), Integration Of Resilience Perspective Into Sustainability Assessment Of Biofuel Production', *Proceedings Of The Asme International Design Engineering Technical Conferences & Computers And Information In Engineering Conference*, Idetc/Cie, Montreal, Quebec, Canada.

Myklebust, O. (2002), Enterprise Modelling supported by Manufacturing Systems Theory, PhD Thesis, *Norwegian University of Science and Technology*, Trondheim, p. 19.

Nylund, H., Salminen, K. and Andersson, P.H. (2009), "An approach to the integrated Design and Development of Manufacturing Systems", Proceedings of the 19th CIRP Design Conference, *Cranfield University Press*, pp. 448.

Nylund, H. and Andersson, P.H. (2012) 'A Holistic View on Design and Development of Manufacturing Systems', *Published by Elsevier*, 45th CIRP Conference on Manufacturing Systems, Procedia CIRP3 (2012) pp.388 – 393

Oliver, W. D., Kelliher, P. T. and Keegan, G.J. Jr. (1997) 'Engineering Complex Systems with Models and Objects, *McGraw-Hill.*

Ollinger, G.A. & Stahovich, T.F. (2000) 'RedesignIT - A model-based tool for managing design changes', *Journal of Mechanical Design*, 126 (2), 208-216.

Ollinger, G.A. and Stahovich, T.F. (2001) 'ReDesignIT – a constraint-based tool for managing design changes', *In Proceedings of ASME design engineering technical conferences*, Pittsburgh, USA, paper no. DETC2001/DTM-21702

Ollinger, G.A. & Stahovich, T.F. (2004) 'RedesignIT - A model-based tool for managing design changes', *Journal of Mechanical Design*, 126 (2), DOI: 10.1115/1.1666888

Olmez, H. and Clarkson, P.J. (2017) 'Change Propagation Analysis with Multilayer Network Models within Manufacturing Systems', *In 19th International Dependency and Structure Modelling Conference (DSM2017)*, The Design Society, Espoo, Finland.

Olmez H, Hassannezhad M, Ball NR, Clarkson PJ, (2018) 'Modelling Change with an Integrated Approach to Manufacturing System Design'. *In: Proceedings of the 15th International Design Conference (DESIGN2018)*, Dubrovnik, Croatia.

Otto, K.N. and Wood, K.L. (2001) 'Product design: Techniques in reverse engineering and new product development', *Englewood Cliffs*, NJ, USA: Prentice Hall.

Oxford University Press (2018) 'the definitive record of the English language', available online at *http://www.oed.com.*

Papakostas, N. and Mourtzis, D. (2007) 'An Approach for Adaptability Modelling In Manufacturing: Analysis Using Chaotic Dynamics', *Annals of CIRP: Manufacturing Technology* 56(1):491-494.

Pahl G. & Beitz W. (1998) 'Engineering Design a Systematic Approach', *Springer*.

Pahl, G., Beitz, W., Feldhusen, J.A. and Grote, K. H. (2007) ‘Engineering design: A systematic approach’, *Springer*, 3 ed. New York, NY, USA.

Pasqual, M.C (2010) ‘Multilayer Network Modelling of Change Propogation for Engineering Change Management’, MSc Thesis, *Massachusetts Institute of Technology*.

Pasqual, M.C. and de Weck, O.L. (2011) ‘Multilayer network model for analysis and management of change propagation’, *International Conference on Engineering Design (ICED'11).* Copenhagen, Denmark, 126-138.

Phoomboplab, T. (2012) ‘Self-Resilient Production Systems: Framework for Design Synthesis Of Multi-Station Assembly Systems’, Phd Thesis, *School Of Engineering, University Of Warwick*

Plehn, C., Steina, F., Neufvilleb, R. and Reinharta, G. (2016) ‘Assessing the Impact of Changes and their Knock-on Effects in Manufacturing Systems’, *49th CIRP Conference on Manufacturing Systems,* Procedia CIRP 57 -479 – 486, https://doi.org/10.1016/j.procir.2016.11.083

Rydzak, Felicjan, Piotr Magnuszewski, Jan Sendzimir, and Edward Chlebus. (2006) ‘A concept of resilience in production systems’. Proceedings of *the 24th International Conference of the System Dynamics Society,* Nijmegen, The Netherlands.

Reddi, K.R. & Moon, Y.B., 2009. A framework for managing engineering change propagation. International Journal of Innovation and Learning, 6 (5), 461 - 476.

Reddi, K.R. and Moon, Y.B., (2011a) ‘A framework for engineering change management in enterprise resource planning using service-oriented architecture’, *International Journal of Business Information Systems,* 8 (1), 46-65.

Reddi, K.R. and Moon, Y.B., (2011b) ‘System dynamics modelling of engineering change management in a collaborative environment’, *The International Journal of Advanced Manufacturing Technology,* 55 (9), 1225-1239.

Rios, J., Roy, R. and Lopez, A. (2007) ‘Design requirements change and cost impact analysis in airplane structure’, *International Journal of Production Economics*, 109 (1-2), 65-80.

Rutka, A., Guenov, M., Lemmens, Y., Schmidt-Schäffer, T., Coleman, P. and Riviere, A. (2006), ‘Methods for engineering change propagation analysis’, *25th Congress of the International Council of the Aeronautical Sciences (ICAS).* Stockholm, Sweden

Ross, M., Rhodes, D. H. and Hastings, D. E. (2008) ‘Defining changeability: Reconciling flexibility, adaptability, scalability, modifiability, and robustness for maintaining system lifecycle value’, *System Eng*ineering, vol. 11, no. 3, pp. 246–262.

Rouibah, K. and Caskey, K.R., (2003) ‘Change management in concurrent engineering from a parameter perspective’. *Computers in Industry,* 50 (1), pp.15-34.

Rutka, Guenov, Lemmens, Schmidt-Schäffer, Coleman, Rivière, Airbus (2006) ‘Methods For Engineering Change Propagation Analysis’, *25th International Congress Of The Aeronautical Science to Cranfield University,* 3EADS Germany, 4EADS CRC France

Schuh, G., Lenders, M., Nussbaum, C. and Kupke, D. (2009) ‘Design for Changeability: Change Reconfigurable Manufacturing System’, 251–66.

Scholz-Reiter B and Freitag M. (2007) ‘Autonomous Processes in Assembly Systems’, *CIRP Annals-ManufacturingTechnology*, 56(2):712–729

Schulz, A.P., Fricke, E. and Igenbergs, E. (2000) ‘Enabling Changes in Systems throughout the Entire Life-Cycle—Key to Success?, INCOSE International Symposium, Minneapolis, MN,

Seliger,G., Gleue, V., Heinemeier, H.J., and Kruger, S. (1989) ‘Computer Aided Planning Of Assembly Systems’, *6th IFAC/IFIP/IFORS/IMACS Symposium*, https://doi.org/10.1016/B978-0-08-037023-1.50108-4

Shadbolt, N., Olubode-Awosola, F., Rutsito, B. (2011) Resilience, To ‘Bounce Without Breaking’, In New Zealand Dairy Farm, *Businesse International Food & Agribusiness Management Association* , 21st Annual World Symposium , Frankfurt, Germany

Shapiro, D. (2016) ‘Modelling and AnalysingChanges in Evolutionary Design Processes’, Ph.D. thesis, University of Cambridge, UK.

Sheffi, Y. and Rice, Jr. (2005) ‘A supply chain view of the resilient enterprise’, *MIT Sloan Management Review*; 47(1): 41-48.

Simons, C.S., 2000. Change propagation in product design: A change prediction method. M.Phil. *The University of Cambridge*.

Simon, H. 1996 (1969; 1981) ‘The Sciences of the Artificial’, *MIT Press,* 3rd Edition.

Singh, (2014) ‘Integrating Robustness And Resilience In Change & Competitive Advantage Framework: Insights From Indian Pharmaceutical Industry’, Int. *J. of Strategic Change Management*, 2014 Vol.5, No.4, pp.348 - 376

Spena, P. R., Holzner, P., Rauch, E., Vidonia, R.and Matta, T.D. (2016) ‘Requirements for the Design of flexible and changeable Manufacturing and Assembly Systems: a SME-survey’, *48th CIRP Conference on Manufacturing Systems,* doi: 10.1016/j.procir.2016.01.018

Strauss, L. A. and Corbin, J. (1998) ‘Basics of Qualitative Research: Grounded Theory Procedures and Techniques’. *Sage*. 2nd edition.

Summers, J.D. and Shah, J.J. (2010) ‘Mechanical Engineering Design Complexity Metrics: Size, Coupling and Solvability’, *Journal of Mechanical Design* 132:021004–021011.

Steward, D.V. (1981) ‘The design structure system: a method for managing the design of complex Systems’, *IEEE Transactions on Engineering Management,* EM-28 (3), 71–74.

Suh, N.P. (1990) ‘The principles of design’, *Oxford University Press Inc,* New York, NY, USA.

Suh N.P. (2001) Axiomatic Design: Advances and Applications, Oxford University Press, New York, 2001.

Suh, E. S., de Weck, O. L. and Chang, D. (2007) “Flexible product platform: framework and case the study”, Research in Engineering Design, Vol 18, No. 2, pp. 6789.

Taysom, E. and Crilly, N., (2017) ‘Diagrammatic representation of System Lifecycle Properties’ *Engineering and Physical Sciences Research Council (EPSRC).*

Taguchi, G. (1993) ‘Taguchi on Robust Technology Development : Bringing Quality Engineering Upstream’, *ASME Press*, doi: 10.1115/1.800288

Tang, D., Xu, R., Tang, J., Xu, R.and He, R. (2010) ‘Product design knowledge management based on design structure matrix’. *Adv Eng Inform* 24(2):159–166. doi:10.1016/j.aei.2009.08.005

Terwiesch, C., and Loch, C.H. (1999) ‘Managing the Process of Engineering Change Orders: The The case of the Climate Control System in Automobile Development’, *Journal of Product Innovation Management*, ISSN 0737-6782, Volume 16, Issue 2, pp. 160 – 172.

Thomas, A.J., Byard, P. and Evans, R. (2012) ‘Identifying the UK's manufacturing challenges as a the benchmark for future growth’, *Journal of Manufacturing Technology Management*, Vol. 23 No. 2, pp. 142-156.

Thomas, Jerry R., Silverman, Stephen, Nelson, Jack (2015) ‘Research Methods in Physical Activity’ *Human Kinetics*, 7th Edith, ISBN: 978-4504-7044-5

Ungar, M., (2018) ‘Systemic Resilience: Principles and Processes for a Science of Change in Contexts of Adversity’, *Ecology and Society* 23(4):34.

Urken, A. B., Nimz, A. and Schuck, T. M. (2012)’Designing evolvable systems in a framework of robust, resilient and sustainable engineering analysis’, *Adv. Eng. Inform*., vol. 26, no. 3, pp. 553–562.

Ulrich K. (1995) ‘The role of product architecture in the manufacturing firm’, *Research Policy*, ISSN 0048-7333, Volume 24, Issue 3, pp. 419-440.

Ulrich, K. and Eppinger, S.D. (2010) Product design and development, *McGraw-Hill* 4th Edith. New York, USA.

Ullman, D.G., 2003. The Mechanical Design Process New York, NY, USA: McGraw-Hill.

Vallhage, J., Isakssona, O., Söderbergb, R. and Wärmefjord, K. (2013) ‘A framework for producibility and design for manufacturing requirements in a system engineering context, *2nd International Through-life Engineering Services Conference*, Procedia CIRP 11 / 145 – 150

Vasantha, G.V.A., Roy, R., Lelah, A. and Brissaud, D. (2012), “A review of the product–service systems design methodologies”, *Journal of Engineering Design*, Vol. 23 No. 9, pp. 635-659. https://doi.org/10.1080/09544828.2011.639712.

Vaughn, A., Fernandes, P. and Shields, J.T. (2002), Manufacturing System Design Framework Manual, *MIT*.

Weaver W. (1947) ‘Science and Complexity’, *American Scientist*, 36: 536, Rockefeller Foundation, New York City, 11http://www.ceptualinstitute.com/genre/weaver/weaver-1947b.htm.

Weber, C. (2005) ‘What Is “Complexity”?’, International Conference On Engineering Design Iced 05 Melbourne, August 15-18.

Wiesner, S., Nilssonb, S. and Thobena, K. D. (2017) ‘Integrating requirements engineering for different domains insystem development – lessons learnt from industrial SME cases’, *The 9th CIRP IPSS Conference: Circular Perspectives on Product/Service-Systems,* Procedia CIRP 64 351 – 356.

Walker, B.H, C.S. Holling, S.R. Carpenter, and A. Kinzig. (2004) ‘Resilience, adaptability and transformability in social-ecological systems’, *Ecology and Society* 9(2):5.

Wickel, M.C. and Lindemann, U. (2015) ‘How To Integrate Information About Past Engineering Changes In New Change Processes?’, *International Conference On Engineering Design, ICED15,* Politecnico Di Milano, Italy

Wright, I.C. (1997) ‘A review of research into engineering change management: implications for product design’, *Design Studies*, ISSN 0142-694X, Volume 18, Issue 1, pp. 33 – 42.

Wiendahl, H and Hernández, M.R. (2006) ‘The Transformable Factory - Strategies, Methods and Examples’, Reconfigurable Manufacturing Systems and Transformable Factories: 21st-century technologies, *Springer*, Berlin, Heidelberg, pp 383-93.

Wiendahl, H.P. (2005) ‘Justifying changeability: a methodical approach to achieving cost Effectiveness’, *International Journal for Manufacturing Science & Production,* Vol. 6 Nos 1/2, pp. 33-39

Wiendahl, H.-P., ElMaraghy, H. A., Nyhuis, P., Zäh, M. F., Wiendahl, H.-H., Duffie, N., Brieke, M., "Changeable Manufacturing - Classification, Design and Operation", *CIRP Annals - Manufacturing Technology*, 2, 2007, pp. 783–809.

Wyatt, D.F., Wynn, D.C., Jarrett, J.P. & Clarkson, P.J. (2012) ‘Supporting product architecture design using computational design synthesis with network structure constraints’. *Research in Engineering Design*, 23 (1), 17-52.

Wynn, D.C., 2007. Model-based approaches to support process improvement in complex product development. PhD thesis. The University of Cambridge.

Wynn, D.C., Eckert, C.M. & Clarkson, P.J., 2006. Modelling iteration in engineering design. International Conference on Engineering Design (ICED'07). Paris, France, 693-694.

Wynn, D.C., Wyatt, D.F., Nair, S.M.T. and Clarkson, P.J. (2010) ‘An introduction to the Cambridge Advanced Modeller’, *1st International Conference on Modelling and Management of Engineering Processes (MMEP'10)*. Cambridge, UK.

Yang, F. and Duan, G. (2011) ‘Developing a parameter linkage-based method for searching change propagation paths’, *Research in Engineering Design*, ISSN 0934-9839, 10/2012, Volume 23, Issue 4, pp. 353 – 372.

Zhang, Z., Li, X. and Liz, Z. (2014) ‘A closed-loop based framework for design requirement management’, *In Proceedings of the 21st ISPE Inc. International Conference on Concurrent Engineering*, Beijing, China, 8–11.

Zhang, W. and Luttervelt, C.A. (2011) ‘Toward a resilient manufacturing system’, *CIRP Ann. – Manuf. Technology,* Vol.60, pp. 469-472.