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THE EFFECT OF PRODUCT DESIGN MODULARITY ON SUSTAINABLE SUPPLY CHAIN MANAGEMENT

THE EFFECT OF PRODUCT DESIGN MODULARITY ON SUSTAINABLE SUPPLY CHAIN MANAGEMENT

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Abstract

This thesis integrates between three major fields of study: product design, supply chain management and sustainability. This thesis introduces product design modularity (PDM) as a product design methodology and evaluates its influence on supply chain operations. This is done with a view to assess whether adopting modularity in design enhances a supply chain's economic, environmental and social performance.

The research conducted within this thesis follows a pragmatic philosophy with the focus being on the research questions instead of on the type of data available. Abductive reasoning is used to collect and present quantitative and qualitative data to answer whether modularity in design leads to more sustainable supply chain operations.

A conceptual framework integrating PDM and sustainable supply chain management (SSCM) is developed within the thesis. The conceptual framework presents all supply chain processes affected by product design. The framework further differentiates these effects into economic, environmental, or social categories depending on which aspect of sustainability is impacted by PDM.

The research implements a case study strategy. The case study focuses on a washing machines product family for a well-known white goods electronics manufacturer in Egypt. The case study follows a comparative approach, where the analysis is structured around assessing the effects modules with differing designs (one has a modular design and the other has an integral design) have on the economic, environmental and social performance of a supply chain.

To assess the effect of PDM on SSCM analytical hierarchy processing (AHP) has been used. The hierarchy focuses on presenting a holistic view to sustainability by considering economic, environmental, and social supply chain aspects simultaneously. Supply chain processes influenced by product design modularity make up the criteria within the hierarchy. The model develops pairwise comparisons that assess the effect modular versus integral components have on the sustainability of supply chain operations within the case study. Data collected and analysed within the case provided that the modular component led to improved economic, environmental and social performance when compared to the integral component.

This research presents PDM as a viable solution, which supply chains can adopt to become more sustainable. The integration of product design and supply chain design allows for the decision making process to be sufficiently flexible to overcome the common barriers supply chains face when attempting to implement sustainable procedures. This research offers a guide to assist supply chains improve their sustainability through providing a cause and effect relationship linking product design decisions to a supply chain's economic, environmental and social performance. In turn this allows companies to include sustainability considerations and have more control on the sustainability of their operations from the product design stage. From an academic perspective, assessing the effect different product design approaches (modular versus integral) have on the sustainability of supply chain operations offers tangible solutions for improving SSCM. The conceptual framework presented an integrated review for all supply chain processes affected by product design. Furthermore, the framework classifies these processes depending on which aspect of sustainability they affect. From a practical perspective, the AHP model developed provides an analytical tool to assist product designers in choosing the best product design alternatives to improve sustainability within a supply chain.

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Dedications and Acknowledgements

I would like to dedicate this work to my parents who have always encouraged me to be the best version of myself, my wife and my daughter, whom have been patient and provided me with support throughout the PhD process.
I would also like to thank my supervisor for always challenging me to do better.

List of abbreviations

PDM – Product Design Modularity
SSCM – Sustainable Supply Chain Management
SALSA – Search Appraisal Synthesis Analysis
JIT- Just In Time
SCI – Supply Chain Integration
SCR – Supply Chain Responsiveness
MC - Mass Customisation
AHP - Analytical Hierarchy Processing
DSM - Design Structure Matrix
TBL - Triple Bottom Line
3DCE - Three Dimensional Concurrent Engineering
OEM - Original Equipment Manufacturer
ECM - Environmentally Conscious Manufacturing
DFE - Design for Environment
DFR - Design for Recycling
DFD - Design for Disassembly
DFSC - Design for Supply Chain
CLSCM - Close Loop Supply Chain Management
RL - Reverse Logistics
LCA - Life Cycle Assessment
CSR - Corporate Social Responsibility
SME - Small Medium Enterprises
MBMP - Modularity Based Manufacturing Practices
BOM – Bill of Material
MRP – Material Requirement Planning
CR- Consistency Ratio
CI – Consistency Index
RI – Random Index

Academic Biography

- El-Said, A.T. and Tipi, N. (2014). *An Approach for Improving Supply Chain Sustainability Using Product Design Modularity*. Paper presented at Logistics Research Network, University of Huddersfield, United Kingdom.

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Chapter 1 Introduction

1.1 Motivation

Sustainability has emerged since the beginning of the 1980's as a critical topic towards the continuation of supply chains (Hassini, Surti, and Searcy, 2012; Kumar and Rahman, 2017). Non-renewable natural resources (Taticchi, Tonelli, and Pasqualino, 2013), green supply chain management (Winter and Knemeyer, 2013) standard of living (Lei, 2009), a narrow focus on financial performance (Hoffman and Bazerman, 2005), corporate social responsibility (Hildebrand, Sen, and Bhattacharya, 2011) are some of the major drivers for an increase in research aiming to provide solutions and alternatives for supply chains to become more sustainable. Accordingly, supply chains are now required to integrate economic, environmental, and social considerations in their decision making to ensure the survival and competitiveness of their operations (Carter and Rogers, 2008; Seuring and Muller, 2008).

The process of integrating sustainability into supply chains however can be quite a daunting experience for many reasons. The first reason relates to the concept of sustainability itself, where for a supply chain to become sustainable it would have to ensure economic profitability, while reducing environmental harm, and improving social wellbeing for all involved stakeholders simultaneously (Pagell and Shevchenko 2014; Reefke and Sundaram 2016). Therefore, supply chains are faced with a complex maze of decisions with multiple objectives for multiple criteria. Hoffman and Bazerman (2005) discussed that for supply chains to become sustainable, decision makers need to realise that in some cases environmental and social improvements will not go hand in hand with economic objectives.

The second reason is attributed to the difficulty in assigning quantifiable criteria to measure the effect supply chain operations have on the environment and society (Taticchi, et al., 2013). This is usually because environmental and social effects cannot be represented in monetary terms, which leads to an absence of a common denominator supply chains can use to monitor their environmental and social performance. This further complicates the integration of sustainability in supply chains, because without quantifiable criteria it becomes difficult for supply chains to identify the processes that have the most influential impact on their environmental and social performance.

The third reason is that supply chains usually consist of separate entities, each with specific roles and responsibilities in the value creating process within a supply chain. Therefore, sustainability is only achievable if all supply chain members coordinated their operations with the objective of improving economic, environmental and social sustainability (Gupta, Abidi, and Bandyopadhayay, 2013). Hence, the decentralised nature of supply chains further adds to the complexity of integrating sustainability in supply chain management.

The fourth reason is that supply chains usually operate through a set of standard operating procedures that take care of the day-to-day processes. Long-term decisions, such as facility location, strategic alliances, and asset capital investments are quite difficult to alter once made (Chopra and Meindl, 2007). Therefore, a supply chain, which is already operational, becomes quite inflexible. Decisions related to the structure of the supply chain in terms of material sourcing, transportation networks, inventory management, product offerings, labour and machine hours for production, maintenance, repair, product upgradability, disposal at end of life all have an effect of economic, environmental, and social performance of a supply chain. This inflexibility creates a problem when trying to change decisions to incorporate sustainability within supply chain operations.

Consequently, a supply chain is most flexible during the product design stage because a supply chain's design and planning phase are very much dependent on the product design the supply chain aims to produce (Aydinliyim and Murthy, 2016; Kristianto and Helo, 2015). A supply chain is considered as both a supply network connecting suppliers to producers to customers, and as a value chain where each supply chain member oversees adding value to the product as it passes through the supply chain. Product design as a process begins with researching and recognising customer requirements, which are translated into functional requirements to be included in the design parameters of the product. The design parameters specify the responsibility of each supply chain entity regarding what value they oversee creating (Tomiyama, et al., 2009). Krishnan and Ulrich (2001) argued that product design can be considered as the blue print for a supply chain's network structure signifying the roles and responsibilities of each member along the value creation process involved in the sourcing, manufacturing, and delivery of the product. Product design provides the basis for identifying material requirement, which in turn provides the basis for supplier selection; accordingly, transportation networks are developed to connect between supply chain members (Zhuo, San, and Seng, 2008).

The integration of product design and supply chain design has already been addressed in the literature through the concept of design for supply chain (DFSC) (Zhang, et al., 2017; Kremer, et al., 2016). Sharifi, Ismail, and Reid (2006) for example investigated the effect integration product design and supply chain design decisions had on the agility of a supply chain. Chiu and Okudan (2014) examined the effect product design decisions have on supplier selection and related this to overall supply chain performance. Others, such as Yan and Feng (2013) evaluated the effect product design decisions have on a supply chain's environmental sustainability in terms of a supply chain's ability to recover, recycle, remanufacture, and reuse its products. This provides a basis for the overreaching effect product design has on supply chain processes that affect economic and environmental performance.

Product design generally refers to the degree of how modular or integral a product's design is (Shutkin, 2007). Modularity in design focuses on the standardisation of inputs that can be mixed and matched in various combinations leading to product variety in the range of end items a supply chain can produce (Agrawal, et al., 2016; Yan and Feng, 2013; Shamsuzzoha, 2011; Salvador, 2007). Integrality in design, on the other hand, focuses on the standardisation of the end product design and the specific integration of a product's components to achieve optimum functionality (Aydinliyim and Murthy, 2016; Zhuo, San and Seng, 2008; Shutkin, 2007). Schilling (2000) argued that modularity and integrality could be considered as extremes on opposite ends of a product design spectrum. The degree of modularity or integrality of a product design depends on the separability, transferability, and combinability of the components that make up the product (Kristianto and Helo, 2015). For a modular design, the focus is on having a one to one relationship between each component and the function it provides (Ulrich, 1995). Meaning that if this component is separated from the product, the overall functionality of the product is not affected, and the product will remain functional if that module is replaced. However, for integral products the focus is on the synergies achieved between the components. An integral design's objective is to increase the overall functionality of the end item through designing the components in such a way where there is a one-to-many relationship between component and functionality (Ulrich, 1995). Meaning that one component can be responsible for multiple functions, which makes removing that component affect the overall functionality of the end item. A modular design versus an integral design will therefore lead to different supply chain designs. Material selection, supplier selection, inventory management, process design, production and scheduling, product offerings, customisation options, after sales services are amongst the main supply chain processes affected by the degree of modularity or integrality of a product design (Lau, et al., 2010).

Modularity in design in particular is seen to have an effect on the economic performance of a supply chain through affecting product offering, customisation options for products, inventory management, component selection, and supplier selection (Agrawal, et al., 2016); environmental performance through affecting recovery, recycling, remanufacturing, reuse, and redesign product options (Yan and Feng, 2013); and social performance through process design and work path simplification in assembly processes for line workers (Jacobs, et al., 2007).

Accordingly, research within this thesis will aim to provide a clear distinction between the effect different product design methodologies have on sustainable supply chain management. This research will also aim to present product design modularity (PDM) as an applicable initiative that can be implemented by supply chains to integrate sustainability in their supply chain operations. The motivation for such integration is supported by a number of reasons:

1. Product design decisions have overreaching effects on supply chain policies and practices across all supply chain members.
2. Allows for supply chains to be flexible enough to transform their operations to be more environmentally and socially responsible.
3. PDM in particular is seen to affect economic, environmental, and social performance in a supply chain, therefore can overcome the trade-off problem faced when trying to reduce environmental harm and improve social wellbeing.
4. Provides a focused view on sustainability from the point of view of the effect of PDM on sustainable supply chain management (SSCM).

1.2 Research questions, aims and objectives

Therefore, the research gap that this thesis aims to cover is whether the adoption of PDM can influence a supply chain into becoming more sustainable economically, environmentally and socially. The coordination between product design and supply chain design decisions will allow for the supply chain to be flexible enough to accommodate changes made with the purpose of improving supply chain sustainability. This led to the development of the research questions for this thesis:

1. How does PDM affect SSCM?
2. Does PDM lead to more sustainable economic, environmental, and social supply chain operations?

The purpose of the first question is to identify all areas and processes in the supply chain that are affected by changes in product design. Through identifying these processes, the nature of the effect of modularity in design on each process can be classified into economic, environmental, or social.

The second question will build on the findings of the first question by testing whether adopting modularity as a design method will result in: improving the economic performance of a supply chain through increasing profits and reducing supply chain operational costs; reduced environmental harm through less dependence on non-renewable natural resources; and improved social well-being through enhancing the standard of living for line workers.

Accordingly, the research aims and objectives for this thesis are:

Aims

1. To develop a conceptual framework integrating between product design, supply chain management, and sustainability.
2. To provide an analytical tool which can be used to evaluate the effect of product design on SSCM.

Objectives

1. To analyse and categorise all interconnecting relationships in the literature between product design and supply chain design that lead to economic, environmental, and social effects on sustainable supply chain operations.
2. To conduct a comparative study on the effects modularity in design versus integrality in design have on the sustainability of supply chain operations.
3. To provide evidence for all relationships, which link modularity in design to SSCM through obtaining empirical data from a case company.
4. To develop the relationships between product design and supply chain design into criteria that can be used to monitor the effect changes in product design have on the sustainability of supply chain operations.
5. To integrate all the criteria into an analytical tool that evaluates the economic, environmental, and social performance of the supply chain.

Table 1.1 below provides the connection between the research questions, its aims and the research objectives proposed.

Table 1.1: Research questions, aims and objectives

Research Questions	Aims	Objectives	Chapter
1.How does PDM affect SSCM?	1.To develop a conceptual framework integrating between product design, supply chain management, and sustainability.	1. To analyse and categorise all interconnecting relationships in the literature between product design and supply chain design that lead to economic, environmental, and social effects on sustainable supply chain operations.	Literature Review Chapter
2. Does PDM lead to more sustainable economic, environmental, and social supply chain operations?	2. To provide an analytical tool, which can be used to evaluate the effect of product design on SSCM.	2. To conduct a comparative study on the effect modularity in design versus integrality in design have on the sustainability of supply chain operations.	Research methodology chapter.
		3. To provide evidence for all relationships, which link modularity in design to SSCM through obtaining empirical data from a case company.	Findings Chapter
		4. To develop the relationships between product design and supply chain design into criteria that can be used to monitor the effect changes in product design have on the sustainability of supply chain operations.	AHP Analysis Chapter
		5. To integrate all the criteria into an analytical tool that evaluates the economic, environmental, and social performance of the supply chain.	

1.3 Proposed Methodology

Research within this thesis will follow a pragmatic philosophy. Abductive reasoning will be used to translate the conceptual framework into data requirements to be used for the justification of the interconnecting relationships between PDM and economic, environmental, and social supply chain processes. The research design for this thesis will follow a mixed methods approach to allow for quantitative and qualitative data inputs in order not to restrict the findings and provide a comprehensive answer to the research questions. A case study methodology will be adopted as the main research strategy with archival data and semi-structured interviews being integrated within the case study for data collection purposes. The case study itself will follow a comparative approach by comparing the particular design of one modular component to another integral component within the same product family. The case study will aim to collect empirical data from a case company working with modular products.

1.4 Originality

A supply chain's design is heavily dependent on the product being delivered at the end of the chain. Long term decisions regarding facility location, production capacity, transport networks, inventory management are all considered as supply chain decisions, but will be directly affected by a product's design (Chopra and Meindl, 2007). These decisions not only shape a supply chain's design, but also influence the sustainability of the supply chain. Therefore, the originality of research in this thesis stems from the perspective this research takes on the integration of product design and supply chain design decisions to assess the effect different product design methodologies (modular versus integral) have on the economic, environmental and social aspects of a supply chain's operations. To portray such a relation, this research will present a conceptual framework analysing and categorising the supply chain processes affected by product design decisions to assess the effect modular compared to integral designs have on economic, environmental and social supply chain performance. This research aims to develop a cause and effect relationship between product design decisions and the sustainability of supply chain operations. Through this cause and effect relationship supply chains can control the sustainability of their operations through product design decisions.

Furthermore, there are usually different design alternatives for new product developments or for product updates. To evaluate which of these design alternatives is considered more sustainable, an analytical tool is required to link between a specific design alternative and its effect on the sustainability of the supply chain. Therefore, this research aims to provide an analytical model that can compare between different product design alternatives and provide a weight for each alternative regarding their effect on the economic, environmental, and social performance of a supply chain.

Analytical hierarchy processing will be used for the model development to provide a systematic approach to the model, which can be adopted by supply chains for the purpose of identifying the effect changes in product design can have on the sustainability of their operations. The model development will act as a guide for supply chains to identify and design their own criteria depending on the nature of their supply chain operations. This research will demonstrate the steps and procedures for the model development in such a way so that it can be adopted by supply chain practitioners aiming to gain more control on the sustainability of their operations through product design decisions.

The research will follow a holistic approach to ensure all aspects of sustainability are included in the evaluation. The effect of PDM on supply chain operations is also evaluated based on empirical data to shift away from traditional theoretical approaches in the SSCM field.

1.5 Thesis Structure

This thesis is composed of six main chapters.

Chapter one: is the introduction chapter and presents the motivation and thought development that led to the research gaps. Based on the research gaps the main research questions, aims, and objectives are presented.

Chapter two: is the literature review chapter, which is divided into two sections. The first section provides the necessary background on PDM and SSCM as individual topics through a critical literature review method (Grant and Booth, 2009). The purpose of this section is to provide a state of the art review on product design methodologies, modular systems theory, product architecture, and sustainable supply chain management research to provide the base knowledge required for the next section of the review. The second section of the literature review focuses on identifying the overlapping areas between product design modularity and supply chain management and categorising interconnecting economic, environmental, and social supply chain operations. This section follows an integrative literature review methodology (Torraco, 2005), which provides a systematic approach towards the review of articles. Through the integrative literature review five main themes are identified, which integrate between PDM and SSCM. Based on these themes the researcher introduces propositions that assume PDM having a positive effect on SSCM. This chapter concludes with the development of the conceptual framework for this thesis.

Chapter three: is the research methodology chapter. This chapter will focus on presenting the research paradigm for this thesis. The chapter aims to present the research design development starting with the philosophical ontological and epistemological perspectives. The chapter then integrates the philosophical stance of the research design with the research approach, methods, strategy, case study design, and data collection methods then follow this.

Chapter four: is the findings chapter, which presents the data collected for each relationship identified within the conceptual framework. This chapter implements the research design that was set out in the research methodology chapter. Data collected for each relationship is discussed to provide justification for the effect of PDM on a particular supply chain process from an economic, environmental, or social point of view. Data for each relationship is then discussed to analyse how PDM affected specific supply chain processes to lead to economic, environmental, or social improvements. The purpose of this chapter is to validate the conceptual framework through presenting empirical evidence, which supports each relationship with data findings from the case study.

Chapter five: is the analysis chapter, which presents analytical hierarchy processing (AHP) as an analytical tool to be used for evaluating the effect of product design on SSCM. An AHP model hierarchy is designed to reflect the themes and relationships identified within the conceptual framework and all data findings from the previous chapter are input within this hierarchy. This chapter aims to integrate all data findings by combining all economic, environmental, and social relationships to obtain an aggregate singular value for the effect of PDM on SSCM.

Chapter six: is the conclusion chapter where research implications, limitations, recommendations and future work are presented. This chapter focuses on presenting the academic and practical contributions of this thesis. It also discusses future directions for improving sustainable supply chain operations through the integration of product design and supply chain design decisions.

This chapter presented the motivation and rationale, which led to identifying the research gaps. The chapter also introduces the main research questions, aims, and objectives to be covered linking them with the research gaps. Finally, this chapter acts as a guide for readers to easily associate where each aim and objective is covered within the thesis.

Chapter 2 Literature Review

2.1 Introduction

This chapter will focus on the first research question discussed in the introduction chapter, which is 'how does PDM affect SSCM?' To answer this question the literature review will be used to build a conceptual framework that integrates between product design modularity and supply chain areas and processes affected by adopting modularity in design. This chapter will therefore cover the first aim of the thesis, which is to develop the conceptual framework by analysing and categorising the interconnecting relationships between product design modularity and supply chain design that can affect a supply chain's economic, environmental and social sustainability.

This chapter will be divided into three main parts. Part A will present an in-depth critique of the different fields encompassed within this research, namely product design, modular systems theory, supply chain management and sustainability. The objective of Part A will be to identify and present the relationships and specific areas within each field dependent on product design.

Part B will present an integrative literature review (Torraco, 2005) on product design modularity and sustainable supply chain management. The objective of the integrative review is to provide a literature analysis for the identification of interconnecting themes between PDM and SSCM through a systematic evaluation of past literature, which has linked modularity in design to economic, environmental or social aspects within supply chain management.

Part C will summarise and organise the various themes and relationships identified through the integrative literature review into a conceptual framework. The framework will aim to present the areas in a supply chain that are affected by modularity. The framework will further classify these supply chain areas based on whether the resulting adoption of modularity in design affects economic, environmental, or social supply chain performance.

2.2 Literature Methodology

There are numerous articles on writing literature reviews that discuss the different methodologies for conducting literature reviews (Rocco and Plakhotnik, 2009; Carliner, 2011; Torraco, 2005; Tranfield et al., 2003; Whittemore & Knafl, 2005). Grant and Booth (2009) offer one of the most comprehensive reviews presenting 14 literature review types and associated methodologies categorising the literature reviews based on Search, Appraisal, Synthesis, and Analysis (SALSA). The critical literature review methodology (presented in Table 2.1) is deemed the most appropriate to be used in Part A of the literature since it is usually used in initial stages of a research to provide a in depth understanding of terms and theories; and in the identification and clarification of the research gap. The critical review offers the ability to synthesize themes and concepts by taking stock and evaluating what is of value from previous bodies of work (Saunders, et al., 2009). However, it lacks the systematic structure present in other types of literature reviews and there is no formal requirement to present methods of search, analysis, and synthesis (Grant and Booth, 2009). The emphasis is on the conceptual contribution of each item of included literature, not on the formal quality assessment. While such a review does serve to aggregate the literature on a topic, the interpretative elements are necessarily subjective, and the resulting product is the starting point for further evaluation, not an end. The research is therefore further developed using an integrative literature review methodology (Torraco, 2005) in Part B, which provides a systematic more objective review of the literature. This interpretative element, nevertheless, is in line with the inductive research nature at the beginning of this research. Saunders et al. (2009) described the inductive approach as being exploratory in nature where the aim is to develop theories from the data and subsequently relate them to the literature. The nature of an inductive approach is not to provide a summary of everything that has been written on the topic, but to review the most relevant and significant research related to the chosen research area. Hence, new findings and theories can emerge (Strauss and Corbin, 1998).

Table 2.1: Critical Review Methodology based on SALSA

Label	Description	Search	Appraisal	Synthesis	Analysis
Critical Review	Aims to demonstrate writer has extensively researched literature and critically evaluated its quality. Goes beyond mere description to include degree of analysis and conceptual innovation. Typically results in hypothesis or model	Seeks to identify most significant items in the field	No formal quality assessment. Attempts to evaluate according to contribution	Typically narrative, perhaps conceptual or chronological	Significant component: seeks to identify conceptual contribution to embody existing or derive new theory

Adopted from: Grant and Booth, 2009.

2.3 Part A: The Critical Review

Writing a critical review methodology consists of a repetitive process as is illustrated in Figure 2.1. The process begins with a general search related to the research area. The results obtained are then evaluated and recorded. Through analysing and cross-referencing between articles in Part A, keywords are generated, and the research parameters are more defined. Therefore, the output from Part A of the literature review will be a clearer research focus and the keywords that will be used in the search strings for the integrative review in Part B . Finally, the literature review is updated and revised. This process is repetitive throughout the duration of the research period since new articles are continuously identified relevant to the research area (Saunders, et al., 2009).

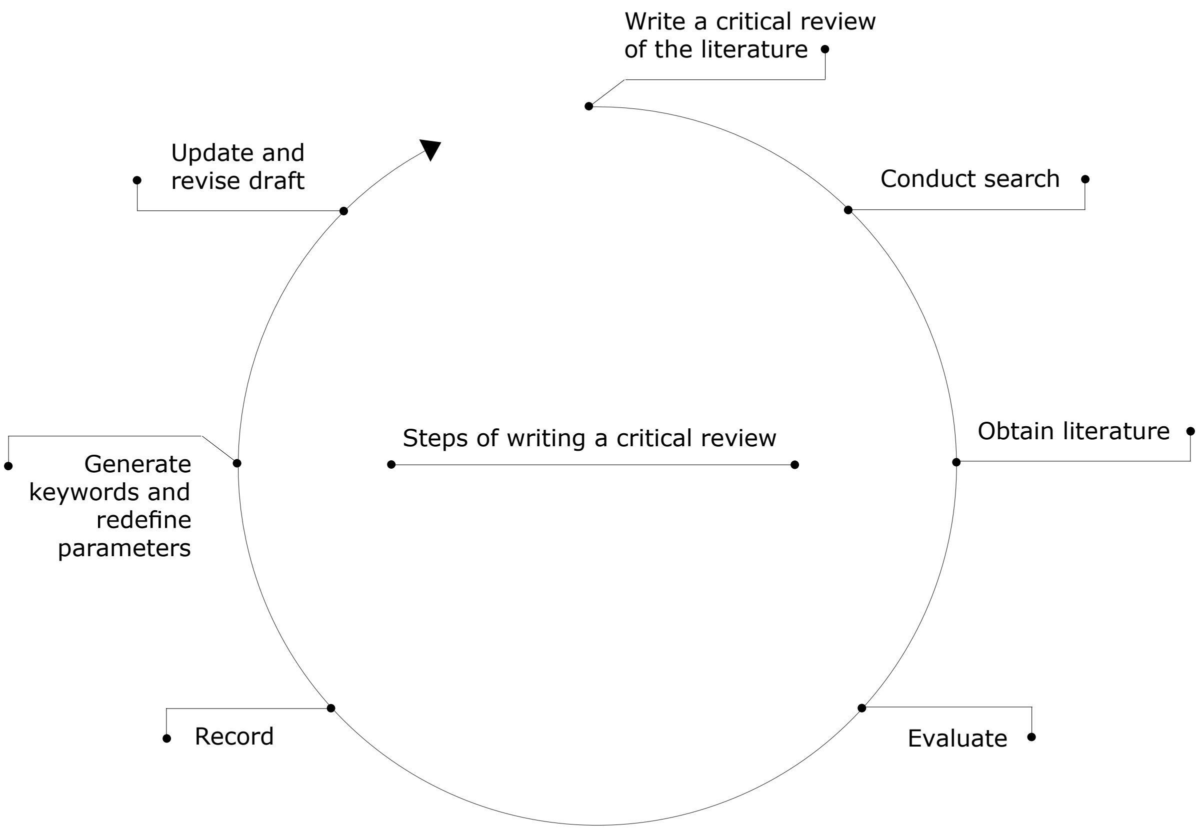


Figure 2.1 The Critical Literature Review Process (Adopted from Saunders, et al., 2009)

In Part A of the literature review the critical review is conducted to provide an understanding and critique on product design, modular systems theory, product design modularity, and sustainable supply chain management.

2.3.1 Drivers for Modularity

Research regarding modularity is considered quite established. Modularity was first introduced in the field of operations management through the seminal work of Simon (1962) and Starr (1965), whom presented some of the earliest definitions of modularity. Simon (1962) recognised modularity as an attribute within complex systems. The concept was that to manage complex systems, the system would be decomposed into independent blocks. The blocks would have standardised interfaces to easily integrate different blocks within the system and to identify the roles and responsibilities (function) of each block. This would facilitate decomposition of a complex system into a set of manageable blocks where decisions can be made for each block independently and then aggregated through the standardised interfaces. Starr (1965) proposed modularity in production to increase variety in product offerings without increasing production cost through the standardisation of components into independent interchangeable modules.

This definition of modularity was then taken and applied in different complex systems such as products (Jacobs, et al., 2011), organisations (Lau, et al., 2010) and services (Song, et al., 2015). For this thesis the focus will be on products as systems and supply chains as systems.

From a practical perspective modularity has been implemented as a design goal to solve several problems within supply chains. It has evolved from a concept used to solve the trade-off between product variety and production cost (Gershenson, Prasad and Zhang, 2004; Vickery, et al., 2016) for use in mass customisation (Zhang et al., 2008) and postponement in production (Nepal, et al., 2012) to having an effect on the total supply chain structure and the relationship between suppliers and manufacturers (Doran, 2003; Pashaei and Olhager, 2015).

To better understand the continued relevance of research on modularity in product design, it is important to analyse the drivers for modularity that have continued to push towards a modular product design until our current day. Bonvoisin, et al. (2016) argued that the method in which products' functions are divided onto its components, i.e. product design, could affect the efficiency and effectiveness of said product from an economic, ecological and social perspective. Kleindorfer, et al. (2005) also offered modularity in product design as a path towards sustainable product design.

It is common knowledge that a standardised product is cheaper to produce since through mass production, economies of scale can be achieved. However, customers' demand is volatile, and to maintain a competitive position in the market companies need to be able to quickly respond to changes in demand in terms of quantity and product offerings (Vickery, et al., 2016). Not only that, but products' life cycles are shortening rapidly, especially for technological products, where newer versions of mobile phones, laptops, tablets, televisions, just to mention a few, are being produced on a daily basis (Esfahbodi, Zhang, and Watson, 2016). The question of how to maintain a diversified product offering, while being responsive to volatile customer demand without a drastic increase in production costs? Also, due to shortening product life cycles, what is the best available method for disposing of products at end of life stage? Product design modularity offered the solution to both questions.

The traditional design practices already incorporate modularity in Design for Assembly (DFA) and Design for Manufacturing (DFMA) in which modularity is one of the major objectives to improve operational performance (Kasarda, et al., 2007; Kremer, et al., 2016). Considerable research effort has also been channelled into the area of Design for Disassembly (DFD), Design for the Environment (DFE) and Design for Recycling (DFR) where modularity also plays a major role in reducing environmental harm associated with the manufacturing, maintenance and disposal of products (Ijomah, et al., 2007; Tseng, et al., 2008; Jawahir and Bradley, 2016).

Modularity is also seen to influence supply chain organisational structure. Where in the pre-modularity era most operations were conducted under the umbrella of one company with vertical integration being dominant (Doran, 2003; Lau, et al., 2008; Augusto and Miguel, 2005); it is now common practice for each supply chain tier to become specific to the manufacture of one module instead of a complete product. This has changed the buyer supplier relationship within the supply chain and also led to a focus on horizontal integrations (Danese and Filippini, 2013; Ulku and Schmidt, 2011; Danese, et al., 2011).

The manufacturing process in most supply chains has seen significant changes as well since to offer a diversified product range, most manufacturing processes currently follow a postponement strategy where assembly of the final product occurs at the last stage of production to avoid obsolete inventory, which is made easier through modularity (Nepal, et al., 2012). Modularity is also integrated in the process design of cell manufacturing to increase production responsiveness, where each cell can focus on the manufacturing a certain module (Ernst and Kamrad, 2000). This facilitates the distribution of labour and machinery to produce different modules in response to changes in demand (Forza, Salvador and Rungtusanatham, 2005).

Modularity also plays an important role in a product's end of life (EOL), which has gained more attention due to increased environmental concerns related to how the product will be recycled or disposed at this stage. By combining the concepts of modularity in design with DFD, DFE and DFR products are designed to be disassembled into modules with similar material composition to allow for modules to be reused or recycled and the parts that are actually disposed of a product are drastically reduced (Ulku and Hsuan, 2017; Jawahir and Bradley, 2016; Kremer, et al., 2016; Das and Posinasetti, 2015; Gu and Sosale, 1999).

The drivers for modularity have stemmed from economic or environmental factors, where modularity is incorporated in product design to help reduce supply chain operational cost and allow for simplified recovery and disassembly of products to open channels for recycling, reuse and remanufacture processes. Table 2.2 summarises some of the main economic and environmental forces that have given rise to the incorporation of PDM in supply chains.

Table 2.2: Modular Driving Forces

Economic Driving Forces	Environmental Driving Forces
Product Variety (Shamsuzzoha, 2011) Demand Volatility (Vickery, et al., 2016) Postponement (Nepal, et al., 2012) Shortening Product Life Cycle (Esfahbodi, Zhang, and Watson, 2016)	End Of Life (Ulku and Hsuan, 2017) Design for Environment (Gu and Sosale, 1999; Kremer, et al., 2016) Design for Recycling (Jawahir and Bradley, 2016) Design For Disassembly (Kremer, et al., 2016; Ijomah, et al., 2007)

2.3.2 Modular Systems Theory

Even though modularity has been a significant topic in research over the past 60 some years, modularity has only relatively recently been presented as a general systems theory through the work of Baldwin and Clark (1997), Schilling (2000), Shutkin (2007). Since Simon (1962) presented modularity as an attribute that facilitates the management of complex systems by designing them to near decomposability, much research has investigated the role and applications of modularity in different systems (Bask, et al., 2010). However, the defining concepts of modularity as a theory remained relatively unexamined.

Schilling (2000) introduced the general theory of modularity to be based on three main concepts: coupling and re-combinability, synergetic specificity and heterogeneity of inputs and outputs.

Coupling and re-combinability is the basis for most definitions of modular systems (Ulrich, 1995; Schilling, 2000; Shutkin, 2007, Kamrad, Schmidt and Ulku, 2017). A system in general is defined as a solution within the context of a problem, where the context of the problem defines the scope of the system (Simon, 1962; Shutkin, 2007). For example, if the problem is to improve organisational performance, then the context of the problem is for that specific organisation and the system in question would be that specific organisation's system. The departments within the organisation are then considered the building blocks of that system. A modular system is defined by its ability to be decomposed into separate loosely dependent blocks (Sanchez and Mahoney, 1996; Langlois, 2002; Shutkin, 2007). Coupling refers to the level of dependence between the components of a system. If a system consists of components that are heavily dependent to perform its functions, separating these components will deteriorate the functionality of the entire system. Re-combinability in this context refers to a component's ability to be separated from one system and recombined with another or recombined with a different component than the one initially coupled with in a system. In other words, this can be translated to the ability to transfer one component either within the system or across systems. Schilling (2000) described this in terms of a balance between what a system loses through the separation of dependent components versus what a system gains in terms of increased flexibility when able to separate and recombine components to better fit the system's environment.

The coupling and re-combinability of a system's components is also considered one of the most commonly used concepts in the development of metrics to measure the degree of modularity within a system (Sosa, Eppinger and Rowles, 2003; Guo and Gershenson, 2003; Holtta-Otto, et al., 2012). What is lost when separating components, or in other terms the degree of synergy between two components is identified as the degree of synergetic specificity (Schilling, 2000; Lau, et al., 2007; Kamrad, et al., 2017). Some systems can achieve higher levels of functionality through a specific pairing of components (synergy), but by doing so these systems also forfeit a degree of component transferability within the system (Schilling, 2000). Other systems are seen to consist of more independent components that can be paired up in a variety of configurations with little or no loss in functionality (Langlois, 2002). Therefore, some systems are seen to migrate towards more dependency between their components, which is defined as an integrated system, while other systems shift towards more loosely coupled components i.e. modular systems. Lau et al. (2007) and Schilling (2000) developed a continuum describing the level of modularity within a system depending on the synergetic specificity of a system's components as an attribute of the degree of separability, transferability and specificity of a system's components. They defined separability as the degree of independence of a system's components allowing them to be separated from the system without loss of functionality. Transferability refers to the components ability to be recombined in different configurations within the same system and across different systems. Specificity is the degree to which a component has a clearly defined configuration that results in unique functionality with the system interface. The decomposition of systems into independent blocks can therefore be demonstrated as a continuum depending on the degree of synergetic specificity of the system's blocks. The degree of synergetic specificity would in turn have an inverse relationship with the degree of separability, transferability and re-combinability as is illustrated in figure (2.2) below.

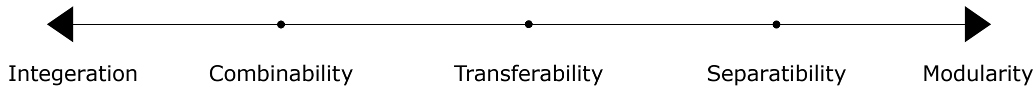


Figure 2.2 The Synergetic Specificity Continuum (Adapted from Schilling, 2000)

The last element in the general theory of system's modularity is the heterogeneity of inputs and outputs. The demand for heterogeneous output from any system is directly related to a need for increasing that system's modularity. To achieve heterogeneous output an increase in the heterogeneity of a system's inputs is also required (Kamrad, et al., 2017; Shutkin, 2007; Schilling, 2000; Ernst and Kamrad, 1997). For example, if we look at a product as a system, with the product's components acting as the building blocks, i.e. modules of the product, an increase in the heterogeneity of customer demand would directly lead to an increase in the product design modularity and the heterogeneity of the system's inputs. This can be seen in many supply chain models opting for modularity in design as a solution to balance out between producing variety in their product offerings and increased manufacturing costs.

Numerous examples of the integrality or modularity of systems can be found in different fields ranging from biology, chemistry, organisations, electric structures, software packages and product systems (Frandsen, 2017). With scientific and technological advancements paving the way for better understanding of the relation between a system and its function, more complex systems are now seen to shift towards a more modular structure to facilitate the management of such systems. One of the most demonstrative examples of how our understanding of science and technology has helped migrate a predominantly integrated system into a modular one is the human body. Currently, it is not uncommon to replace defective organs with those from another person or synthetically grown organs (Schilling, 2000).

Ever since modularity was first introduced as a concept and with the transition of modularity into a general systems theory it has increasingly been applied in a variety of managerial fields. Campagnolo and Camuffo (2010) for example constructed a review on modularity from a managerial scope portraying the effect modular systems theory have on organisational structure. Eissens-Van der Laan et al. (2016) investigated the role of modularity in the service industry, where services such as healthcare and insurance are packaged together as independent offerings. Pashaei and Olhager (2015) examined the effect of different product architectures (modular versus integral) on supply chain design decisions. Kamrad et al. (2017) developed a model based on the synergetic specificity continuum to identify a system's optimum state depending on the penalties resulting from having an integrated versus a modular system. Vickery et al. (2016) developed a model to measure product performance based on the modularity of product and process designs.

What this proves is that until this day modularity is still a relevant concept that has the potential to be integrated within a variety of fields to facilitate the decomposition of complex systems into smaller blocks that are easier to manage. This research will therefore investigate the effect of modularity in product design on sustainable supply chain management. To achieve this, this research will focus on identifying the main processes within the supply chain that are affected by modularity in product design and if modularity in product design is indeed a factor in enhancing the sustainability of a supply chain's operations.

The previous section mainly focused on modularity as a general systems theory defining the two extremes identified as modularity versus integrity of any system. The next section builds on this by applying modular systems theory on product systems.

2.3.3 Product Modularity Defined

Building on the discussion in the previous section of modular systems theory, it is important to note that this thesis will only focus on products and supply chains as the systems for analysis.

A product system consists of modules, which are defined as a component or group of components (subassemblies) that are designed in such a way to deliver a specific function for the product to operate as desired while being independent of other modules' functions (Pimmler and Eppinger, 1994). Sanchez and Mahoney (1996, pg. 65) explained independent modules as components, which 'do not exchange information, energy, or material to perform their function, nor do they require spatial coordination'.

Ulrich (1995) defined modularity in product design as a one to one relationship between a product's modules and the function the module performs, while integral products would in turn have a one to many relationship between module and function. Research on the theory of modularity in product systems originated from this concept of independence that Ulrich presented. Products with a modular design would consist of loosely coupled components that are independent of each other in the functions they are designed to perform, while integrated products would be heavily coupled in specific configurations in order to achieve improved functionality (synergy).

Suh (1998) introduced the theory of axiomatic design where there are two design axioms: an independence axiom and an information axiom. Modularity is achieved through the independence axiom by having the components achieve the required functions independently. Hence components can be separated and recombined while each component maintains its functionality. The information axiom focuses on the information required in developing the module. The argument is that the less information that is required to develop the module the more optimal this will be.

Tomiyama, et al. (2009) also built on Suh's axiomatic design theory arguing that there are four main domains in axiomatic design: the customer domain, the functional domain, the physical domain, and the process domain (Figure 2.3). The customer domain is the starting point, where market research is conducted in order to identify customer requirements. The functional domain comes after the customer domain, where customer requirements are translated into functional requirements to ensure the product's functions are in accordance with how the customer intends to use the product. Next is the physical domain or the product domain and here the functional requirements need to be translated into a product design, which is able to do the functions required by the customer. At this stage, where the functional requirements are translated into the product design, is where the product design methodology is decided. A modular design methodology would translate into the product being composed of independent components each able to perform the required function without being dependent on other components. However, if the design is based on tightly coupled components, which are dependent on each other in order to perform the required functions then this design would be integral.

The final domain that Tomiyama, et al. (2009) discussed is the process domain, which is where the product design is translated into the required processes for the manufacturing of the separate modules of the product system. The overlap between each domain and the next is usually developed in the form of design structure matrices (DSM), which are used to ensure that the requirements of each domain are translated into the next domain.

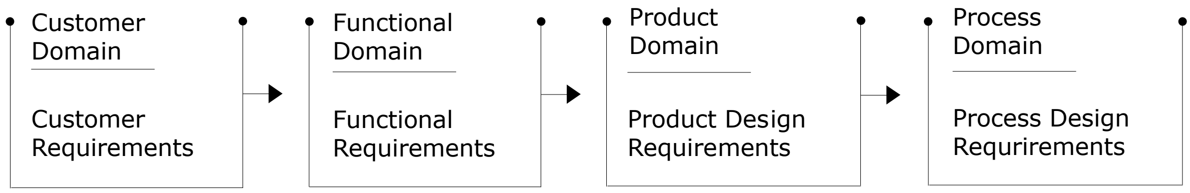


Figure 2.3 Product Design Domains (Adapted from Tomiyama, et al., 2009)

Kong, et al. (2010) presented product design modularity in the form of an evolutionary theory developing through five stages in history. The first stage which they named spontaneous modularity due to the absence of theoretical guidelines for modularity and this dates to prehistoric developments where modularity was used such as in building the Great Pyramids or the Great Wall of China. The second stage, pre-industrial modularity, started around 1776 where it started becoming common nature to separate industrial products into parts for manufacturing. Starting from the 1960's industrial modularity began, where developments in various industrial fields focused on gaining the benefits of modularity from a manufacturing perspective. The age of modularity began in the 1990's where it became a widely researched topic academically to record the benefits gained from modularity in the industry. The final stage, which they named the pan modularity time, began around 2004 where modularity has expanded into various fields including organisational modularity and service modularity.

Several authors have aimed to construct systematic literature reviews focusing on modularity in general and modular product designs in specific (Bonvoisin, et al., 2016; Frandsen, 2017; Campagnolo and Camuffo, 2010; Salvador, 2007). What these authors agree on is that even though the concept of modularity is well established there are still numerous opportunities for expanding the application of the concept and theory of modularity in more fields. Campagnolo and Camuffo (2010) for example conducted a literature review integrating modularity to organisational structure. Eissens-Van der Laan et al. (2016) evaluated how the service industry has begun developing independent service packages using the same principles in the general theory of modularity.

There is also a consensus that depending on the focus of the research the application of the concept of modularity in product design can change in scope. While there currently are differences in defining product modularity, this does not imply that some are correct while others are wrong. Such differences can be the result of the research being from different disciplinary areas or depending on the level of abstraction the researcher takes when considering product modularity. For example, engineering focused research usually focuses on the system structure decomposition of products, while managerial research usually investigates product modularity from the scope of the product's architecture (Salvador, 2007). Bonvoisin et al. (2016) also discussed the lack of consensus on a singular definition for product modularity due to the definition being based on the practice of modularity, which can be at different stages within a product's life cycle rather than a predefined method encompassing the definition of modularity.

Gershenson, et al. (2004) attempted to reduce the ambiguity in defining product modularity by distinguishing between two kinds of modules within a product: a production module and a functional module. In a production module, components are defined based on production considerations alone where each component is manufactured individually and then assembled to perform the function. An example for this would be a bicycle, where each module of the bicycle is produced individually, but the bicycle is only functional when all modules (wheels, gears, chasse) are assembled together. In production modules the components cannot function individually. In a functional module all components are manufactured together as part of the same module, however components can perform different functions independently. For example, a car radiator consists of a pump and fan, while each performs a separate function they are part of the same module.

Gershenson, et al. (1998) previously provided the definition of modularity to include a form-process relationship in addition to the already established from-function relationship. In the form-process relationship they introduced the aspect of similarity in the processes each module must undergo in its life cycle. In other terms components, which undergo the similar processes in their life cycle stages can be grouped together adding to the already existing definitions of modularity in product design.

Ulrich and Tung (1991, pg. 75) defined product modularity in terms of two characteristics of product design: '(1) similarity between the physical and functional architecture of the design and (2) minimization of incidental interactions between physical components'. They used these characteristics in distinguishing between six product modularity formats:

- Component Sharing Modularity: products are designed to consist of a base of common modules shared between end items of a particular product family. Example: elevators.
- Component Swapping Modularity: products are designed with a focus on customisation of final products through interchanging components that offer different grades of the same function. Example: personal computers.

- Cut to Fit Modularity: offers the ability to change the dimensions of a given module in terms of length, width, and height to fit in different end items. Example: furniture.
- Mix Modularity: modules can be mixed in different combinations to offer a range of functions, with each combination offering a unique function. Example: paint.
- Bus Modularity: Products are designed to accept additional modules for adding extra functions. Example: personal computers.
- Sectional Modularity: standardised components can be arranged in different configurations where each end item has a unique pattern. Example: Legos.

Salvador (2007) conducted a systematic literature review on the various papers defining product design modularity (PDM) and grouping the different definitions based on one of the following aspects of the definition of modularity: component commonality, component combinability, function binding, interface standardisation, loose coupling. He goes on to argue that these can be considered attributes of a modular product, where component commonality and combinability both need to be present for a product to have a modular design. Function binding, interface standardisation and loose coupling are all considered a result of a product having common and re-combinable components.

Piran et al. (2016) distinguished between three stages of modularity in product design depending on the stage of the product's life cycle: modularity in design, modularity in production and modularity in use. They then further explain that modularity in design is at the product design stage where the functional requirements are translated into design parameters. This stage addresses the boundaries between the components subsystems and their interfaces to be assembled into the final product. Modularity in production builds on modularity in design in that it refers to the management of the resources required for manufacturing the product. Production lines, labour, stock, equipment and processes are configured in such a way as to improve efficiency by decomposing the manufacturing process into independent stages. Finally, modularity in use refers to the ability of the customer to mix and match between different modules within the product to achieve different or improved functions. Modularity in use also includes the maintenance and repair of the product, which in turn influences environmental considerations in terms of material reuse and recycling to reduce dependence on non-renewable resources.

It becomes quite clear that even though modularity in product design is quite an established topic, there is still a level of ambiguity regarding its definition. There is however, a consensus on an abstract definition of product design modularity in that it entails a shift in focus from standardisation of the final product to standardisation of the components making up the final product. These standardised components should be designed in such a way to allow for mixing and matching allowing for variations in product offerings. Therefore, a product or a module on its own cannot be used to analyse modularity in product design. Jiao, Simpson and Siddique (2007), argued that to assess product design modularity, the correct unit of analysis should be a product family. With this design goal in mind, modularity in product design translates into attributes defining the components that make up the product family (system). These attributes are component commonality, component combinability and interface standardisation. Component commonality means that more end items share the same common module in their production. Component combinability, meaning that modules can be combined in different configurations allowing for variations in product offerings or variations in customisation options for the same product. To achieve component combinability a prerequisite in the design of the components is interface standardisation, where components are designed with standardised interfaces to allow for the transference of modules between different end items.

Accordingly, definitions for modularity in product design are mainly based on these two attributes. Component coupling definitions of modularity focused on functional modularity of the components loose coupling in terms of the modules having a one to one relationship with the function they are designed to accomplish allowing for modules to be independent of each other and for modules to be easily separated from the end item without affecting the overall functionality of the product. Component commonality on the other hand best describes modularity definitions focusing on physical modularity. In component commonality the physical structure of the component relating to the interfaces of the components allow for one component to be shared across different products within the product family.

It also becomes clear that the definition of modularity needs to be linked or integrated with a product’s life cycle due to each product life cycle stage entailing different processes. Accordingly, the concept of modularity becomes quite different depending on whether one is considering product design modularity at the design, manufacturing, or use stage of the product.

As discussed earlier, the definition of product design modularity is also dependent on the disciplinary field under which modularity is defined. Since the overall aim of this research is to investigate the nature of the effect of modularity in design on supply chain management, modularity in design will be examined from a product architecture perspective rather than a system decomposition perspective. Therefore, the next section will discuss the relationship between modularity in product design and its effect on the product architecture of a product family (system).

2.3.4 Product Architecture

Product architecture is the blue print for the product. It generally consists of three main elements: a set of functions that the product is responsible for achieving, a map that relates each function to a specific module or group of modules, and interface specifications that outline the relationship between the different module groups (Jung and Simpson, 2016; Bonvoisin, et al., 2016; Baldwin & Clark, 2000; Ulrich, 1995). The product architecture for a modular product would therefore exhibit a one to one mapping between functions and modules or as close to a one to one relationship as possible (Ulrich, 1995). Gershenson et al. (2004) argued that for a modular product the goal is to reduce dependencies between components that are part of different modular clusters by grouping components with similar functional impact together. They further discussed this by explaining that products can have varying degrees of modularity depending on the proportion of a product's components that are grouped into modules and the degree of independence these modules exhibit. Therefore, a product's architecture helps define a product's degree of modularity through outlining the components that make up the product, the distribution of functions on the components, and the relationship between the components in terms of the processes required in order to transform the components into the final product. A modular product would accordingly have a one to one relationship between function and component, have standardised interfaces between the components and standardised processes for the transformation of the components into final products.

Ye, et al. (2009) provide several methods, which can be used when representing modular product architectures:

- Matrix representation:

Focuses on portraying the relationships between the components of a product. The components would make up the rows and columns of the matrix to discern the categorisation of the components into function groups.

- Component trees:

Structures the product into its building blocks of components and subassemblies in a tree like manner with branches representing the level of details and subassembly interactions within a given product.

- Process graphs:

The product’s architecture, in terms of components and processes required for assembly or production, are detailed in order outlining the sequence of the processes.

- Product decomposition graphs:

Like the process graphs, however the processes are listed in reverse to outline the decomposition procedure for the product. This also gives focus to the dependence between the modules. Usually represented as a fish bone diagram.

Fixson (2005) provided one of the clearest definitions for product architecture as being the set of information that defines how many components a product is made up of, how these components interact together, the processes involved in order to build or assemble these components into the product, how they are used, and finally how the components are disassembled. Ulrich (1995, pg. 420) defined product architecture as ‘the scheme by which the function of a product is allocated to physical components’. The purpose of product architecture hence is to outline the physical components making up a product and define what they do and how they interact with the rest of product (Ulrich and Eppinger, 2000). Mikkola and Gassmann (2003) discussed this further by explaining that product configurations are rooted in product architecture designs, which may be integral or modular. In the case of a modular design a product’s architecture would hence portray components being independent of each other, with each module responsible for a certain function, simple assembly or disassembly of a product’s components. An integral design would accordingly have a product architecture with heavily coupled components, functions being integrated across a range of components and complicated disassembly that affects the overall functionality of the product. Changes to one component cannot be made without making changes to other components.

The next section will discuss the effect modularity in design has had on the reshaping of the supply chain structure.

2.3.5 Modularity and design for supply chain

Krishnan and Ulrich (2001) argued that a supply chain’s design should begin on a drawing board. They clarified this by explaining that a supply chain is usually in a position of balancing multiple objectives simultaneously. Therefore, product design decisions and supply chain design decisions should be considered concurrently to factor in issues such as component availability, supplier partnerships, make or buy decisions, supply chain network structure, pricing, and other capacity constraints. In other words, they emphasise that design encompasses more than just the functionality and appearance of products; product design can be considered the starting point of a supply chain, since various long and short term supply chain decisions are dependent on product design.

Sharifi et al. (2006) talk about two processes within supply chain management, which are supply chain design (SCD) and design for supply chain (DFSC). SCD focuses on developing the network's strategy as well as designing its processes, structure, operations and integrating the supply chain member's strategies together. According to Fxson (2005) SCD refers to whether the strategic focus within the supply chain will be towards achieving a responsive/agile or physically lean/efficient strategy. DFSC on the other hand is considered part of the new product development (NPD) process. It focuses on designing a product that integrates with the strategic vision of the supply chain. In other terms developing a product design while considering the impact on SCD (Pero et al., 2010, Sharifi et al., 2006, Mikkola and Gassmann, 2003). Pero et al. (2010) argued that SCM and NPD are related to each other, since the supply chain produces and distributes the product, which is the output of the NPD process. Through linking NPD and SCM supply chain constraints can be anticipated at an early stage (Pero et al., 2010, Mikkola and Gassmann, 2003). Decision support models linking NPD and SCM either consider bill of materials (BOM) or product architectures. However, trade-offs between process, product, and supply chain design only become clear when considering a product's architecture to understand the relationship between the components of the product (Krishnan and Ulrich, 2001). They explain that when considering product architecture, design decisions relevant to how modular or integral the product will be, and the effect of this on the supply chain is made clearer.

Hult and Swan (2003) argued that through linking product design with supply chain management three marketplace shifts usually happen. The first shift will be the entire supply chain moving towards a customer functionality focus instead of a product focus. Second, the mentality will change from thinking about product differentiation towards customised solutions. Third the relation between supply chain members will develop from transaction based into relation based intimacy.

A product's design is therefore seen to have a direct impact on supply chain processes from the sourcing of components to production to distribution all the way till how the finished product will be presented to consumers in retail outlets (Pero et al., 2010, Christopher and Peck, 2003). Van Hoek and Chapman (2007) argued that the alignment between product design and the supply chain must be enhanced to further develop supply chain capabilities. Abecassis (2006) also supported this by explaining that there is in fact a more strategic role for design, which impacts the total supply chain.

Vickery et al. (2016) argued that coordinating between manufacturing process and product design decisions (i.e., concurrent engineering); and integrating product design and supply chain design decisions (i.e., DFSC) is not considered sufficient enough to enable a supply chain to compete in today's market. This is mainly due to customers continuously demanding greater variety in product offerings and increasingly shorter product life cycles. Fine (1998) argued that these three domains (process, product and supply chain) all possess architecture; and the key for the success of the entire supply chain comes from matching these architectures. Fixson (2005) also supported this by arguing that a comprehensive product architecture assessment methodology could offer a solution where decisions from all three domains are linked together. Fine (1998) named the process of integrating all three-domain decisions as three dimensional concurrent engineering (3DCE). Even though the objectives and constraints for each domain add to the complexity of the overall decision making process; 3DCE reduces supply chain risks, improves performance and allows for critical long-term decisions to be made.

With firms increasingly striving to rationalise their product offerings to include more diversity at lower cost, shortening product life cycles, and increasing environmental awareness, it becomes clear that the product architecture (modular or integral) has a direct influence on supply chain design and process design. With modularity offering a solution for increasing product variety, reduced manufacturing costs and opportunities for reducing dependence on non-renewable material in production, numerous industries (automotive, electronics, furniture) are seen to shift towards increasingly modular product architectures.

From the literature it is clear that through the development of modularity, there is now an emergence of what can be called a modular supply chain; this is because modularity can be seen to have an effect on each of the supply chain generic processes hence affecting the decisions at each process and also affecting the internal and external supply chain relationships (Bonvoisin, et al., 2016; Khan et al., 2012, Doran, 2003, Lau, et al., 2009, Rungtusanatham and Forza, 2005, Nepal, et al. 2012).

Nevertheless, the effect modularity has on the entire supply chain is more complex to associate (Hoetker, 2006). The reason for this is that supply chains are becoming more decentralised with globalisation being the norm in several major industries (automotive, electronics, furniture). Therefore, companies must balance between being responsive while managing risks associated with global supply chains. Such risks are directly amplified if changes in product design or production processes become necessary (Holmstrom, et al., 2006). However, what is clear is that modularity in product design reduces complexity in terms of managing such risks. Having a bill of material representing a modular product architecture, which is designed in alignment with a supply chain's strategy can mitigate supply chain risks as well as offer increased supply chain responsiveness (Hvam, et al., 2017). Doran et al. (2007) argued that by structuring a product family to have standardised components, supply chain complexity is significantly reduced.

Ro et al. (2007) explained that modularity in product design reduces complexity in supply chains due to several reasons: First is that it allows companies to concentrate on their core competencies and by doing so outsource their less strategic activities to suppliers. Second, it redefines the roles of first tier suppliers who can now be responsible for producing entire modules or systems and coordinate the network of suppliers in earlier tiers. Modularity in product design leads to interface standardisation, which in turn allows for the reallocation of tasks so that a brand name firm develops the process and design for the product while the manufacturing process itself is outsourced to a contract manufacturer (Doran, et al., 2007; Sturgeon, 2003). Modularity in design also leads to extensive co-development in terms of a product's architecture between the original equipment manufacturer (OEM) and suppliers (Lau and Yam, 2005). Once the complete product design is defined, developments on a modular level become the responsibility of that particular module's supplier (Ro, et al., 2007).

The value transfer theory, which is a stream of literature in supply chain management develops that for a firm to concentrate on its core businesses, a manufacturer transfers non-core value adding activities further up the stream to its suppliers (Schaltegger and Burritt, 2014; Porter and Kramer, 2011). This creates a sort of chain reaction where the first tier supplier re-organises its business structure to accommodate for the increased responsibilities in terms of production and management, and then in turn also pass down other value adding activities, which have become non-core activities for the first tier supplier, to the second tier supplier. Doran et al. (2007) argued that, modular product design leads to the redistribution of value adding activities from being centralised within a single organisation to being shared across the overall modular supply chain as modules become outsourced to suppliers with the technical competence for modular development. This allows each link in the supply chain to focus on its core value adding activities enhancing the overall competitiveness of the chain.

Sako and Murray (1999) suggested a different view on the concept of modularity where they developed two different roles within the supply chain: the 'integrator' and the 'modulariser'. In the integrator role, module control remains with the OEM. In the modulariser role, the OEM looks to transfer module control by outsourcing entire modules to first-tier suppliers with the capabilities required to provide modular solutions.

Hvam et al. (2017) discussed the relation between modularity and the supply chain as well arguing that there is a direct relation between modularisation and outsourcing. They explained that increased modularity leads to simplifying the process of outsourcing the manufacturing of product parts, since the decomposition of product system can be done in such a way that the interfaces of the building blocks (modules) are specified and standardised. In addition, it also facilitates the creation of partnerships and inter-firm learning between the supplier tiers within the supply chain (Mikkola and Gassmann, 2003; Hult and Swan, 2003). By shifting the responsibility of building entire modules to suppliers, the OEM also shifts the cost of innovation on the supplier. By allowing different suppliers to compete for the module leads to a more efficient and effective module design (Doran, 2003). Doran and Roome (2003) also argued that modularity in design develops relation based intimacy between OEMs and suppliers of strategic modules. Danese et al. (2011) also supported this by arguing that modularity in product design is linked with significant performance improvements as a result of enhanced supplier integration.

Several authors support Doran's theory emphasizing that modularisation develops stronger supplier relationships, which further stimulates the formation of a modular supply organisation. Stephan et al. (2008) discussed that a modular supply organisation is characterised by a relational and physical structure that mirrors that of the product's modules. The supply chain structure itself is altered as a result leading to reducing the number of suppliers, who in turn become responsible for the production of entire modules. Modularity in design is also attributed to the creation of standardised decoupled interfaces between the modules, which leads to improved communication within the supply chain where the module becomes a common unit across the entire chain. This also preserves the manufacturer's intellectual property rights due to the segmentation of the product into separated independent (Schilling, 2000; Danese and Romano, 2004). By limiting the discussion between the OEM and the supplier to a specific module, the OEM in this case can control and segment what information to relay to the supplier and what information can lead to the replication of the entire product design (Dube, Muyengwa and Battle, 2013).

Modularity in product design also affects assembly operations in the supply chain, allowing for delaying the assembly of the end item till the last stage in the supply chain before delivery to the final customer (Nepal, et al., 2012). This is better known as postponement, which allows the supply chain to consider direct customer input on the product specifications they require. Postponement is also associated with mass customisation, which is defined by

Piller (2005, pg. 314) as a ‘customer co-design process of products and services that meet the needs of each individual customer regarding certain product features’. The benefits of postponement can also be seen in improving supply chain responsiveness through a reduction of finished goods inventory levels, which in turn reduces the possibility of obsolete products, and allowing for the quick assembly of end items as per customer specification.

A modular design also means that a certain module can be interchanged without affecting the functionality of the product. For example, a computer can run on an Intel processor or on an AMD processor without losing functionality. From a supply chain perspective this offers more security because the supply chain will not stop due to a missing module when most modules are interchangeable, hence lower supply chain risk (Qrunfleh and Tarafdar, 2013).

Another major effect a modular design can have on supply chain is found in product recycling or in product returns. A product with a modular design can be taken apart and the modules which are still functional refurbished and reused again with major benefits for the environment and the resources that would have been needed to build the product again from scratch. This opens a path for closed loop supply chain management and green supply chain management (Qiang, 2015).

Nepal et al. (2012, pg. 322) sum up the effects that can be seen on a supply chain network as a result of modularisation:

- Simplified outsourcing process where there is a shift in the value creation process, where suppliers become responsible for the production of entire modules
- Reducing the number of first tier suppliers and increased dependency and coordination in the design and development of more components as modules.
- Decentralisation of the manufacturing process, where modularity leads to a shift in the manufacturing process to first tier suppliers who in turn transfer non-core value adding processes to 2nd tier suppliers.
- Strategic partnerships between OEMs and module suppliers.

The next section will discuss the incorporation of sustainability within supply chain management and identify the most common issues and problems supply chains face when shifting towards more sustainable operations.

2.3.6 Sustainable Supply Chain Management

This section aims to offer a critical state of the art review on the most influential literature on SSCM with a view to define SSCM. This section will also present the requirements and major obstacles faced by supply chains in order to integrate sustainability in their operations.

Chopra and Meindl (2007) discussed the trade-off between responsiveness and efficiency within the supply chain. They explained that responsiveness means increasing the supply chain's ability to respond to customer demand. In most circumstances increasing responsiveness is costly to achieve and is usually targeted towards a differentiated competitive strategy where the customer's focus is usually on service level, customization, and fast delivery. Efficiency on the other hand means being able to add value from limited resources and to reduce waste along the supply chain. Efficiency focuses on reducing cost as a main target. Supply chains usually aim to target a balance between responsiveness and efficiency depending on numerous conditions such as which market segment they target, type of product, competition, etc. Discussions regarding sustainability have just recently begun to arise. Wakeland, Cholette and Venkat (2012) discussed that in order for a supply chain strategy to be effective it must also explicitly address sustainability.

Sustainability has become a widely researched topic academically and widely sought after practically. The rise in research regarding sustainability can be dated back to the 1980's where the Burtland Commission defined sustainability as 'development that meets the needs of the present without compromising the ability of future generations to meet their needs' (World Commission on Environment and Development, 1987, p.8). This is considered the most adopted and often quoted definition of sustainability (Carter and Rogers, 2008). However, sustainability means a number of different things depending on the perspective in question. Taticchi et al. (2013) Defined that a sustainable firm is characterised by currently and for the foreseeable future being able to produce and deliver its goods and services without causing depletion or degradation to people, planet or profit. This definition was based in part on De Steiguer (1995) environmental economic theory, particularly that the rate of consumption of any resource should not exceed the rate of replenishment. Also, that the external effects and costs the operations of a firm have on its surroundings should be considered in a firm's decision making process.

The rise in research regarding sustainability developed from a number of drivers which will be further discussed in detail in this section, however, these drivers can be summarised into an understanding that economic and profit focuses of a firm are no longer sufficient and that a firm is required to take environmental and social responsibilities into account in order to remain competitive and survive in today's market. Sustainability still remains in its developmental stage; therefore, it is quite expected not to have a single definition encompassing all facets of the term (Carter and Rogers, 2008). Linton et al. (2007) presented that sustainability has been defined differently depending on the scope and the field of the research, where divergent definitions have been presented in operations management, social science and engineering science. Table 2.3 presents some of the most acknowledged definitions for sustainability.

Table 2.3 Summary of most commonly used sustainability definitions

Author	Definition
Carter and Rogers (2008, pg. 363)	Defined sustainability as 'the ability of one or more entities, either individually or collectively, to exist and flourish (either unchanged or in evolved terms) for lengthy timeframes, in such a manner that the existence and flourishing of other collectivities of entities is permitted at related levels and in related systems.'
Shrivastava (1995, pg. 955)	Defined sustainability as 'offering the potential for reducing long-term risks associated with resource depletion, fluctuations in energy costs, product liabilities, and pollution and waste management.'
Hassini, Surti, and Searcy (2012, pg. 70)	Defined business sustainability 'as the ability to conduct business with a long-term goal of maintaining the wellbeing of the economy, environment and society.'

All sustainability definitions presented have a common principle, which is that in order to achieve sustainability an integration of the economic, environmental, and social aspects of the organisation have to be taken into account simultaneously. The debate presented in the literature currently is based around the trade-offs required to reach sustainability. Hoffman and Bazerman (2005) argued that the most common trade-offs in sustainability generally revolve around the fact that social and environmental investments do not necessarily have to result in economic improvement. They also presented that as soon as this becomes accepted between supply chain members the easier it will become to adopt a sustainable approach towards managing the supply chain.

Meckenstock, Povoa and Carvalho (2016) discussed that sustainability should be viewed as a wicked problem, which are a unique category of problems with specific characteristics. Wicked problems lack an agreed problem definition and have no clear solution approaches

(Rittel and Webber, 1973). They argued that due to the converging objectives of the economy versus the environment versus society there are no easy win-win situations in sustainable management.

Markman and Krause (2016) aimed to provide a stricter definition for sustainability by arguing that sustainable management should not be equated with reducing environmental harm, unethical conduct, trade-offs, or corporate social responsibility. They provided that in order to truly become sustainable firms needed to re-assess the relationships between the three pillars of sustainability. They therefore argued that the definition of sustainability should not equate between the three pillars of sustainability and instead the environmental pillar should receive more weight than the social pillar, which in turn should receive more weight than the economic pillar.

Nevertheless, some supply chain activities do improve all three aspects (economic, environmental and social) simultaneously and are therefore defined as sustainable. Figure 2.4 provides a graphical presentation for the definition of sustainability as presented by Carter and Rogers (2008). They developed this model based on the integration of Elkington's (1994) triple bottom line accounting (TBL) system, where sustainability is offered as an integration of the three P's (people, profit, planet) translated into economic, environmental, and social aspects. This accounting methodology was presented as an alternative to the singular profit focus to incorporate the environmental and social aspects of the organisation within its performance measures. It went further than the traditional accounting methods that focus solely on shareholder value or return on investment and integrated environmental and social aspects (Slaper and Hall, 2011).

The development of the sustainability definition is based on not looking at the environmental or social aspects as standalone processes but integrating them along the economic aspect in order for an organisation to maintain its operations without harming the environment, benefiting the society where it operates, and maintaining competitiveness and profits economically. Pagell and Shevchenko (2014) in their definition of sustainability provided that true sustainability cannot be equated to maintaining or simply reducing harm. True sustainability needs to work on reversing or improving sustainable operations. Genovese et al. (2017) discussed the overlapping of the definitions of sustainability and circular economy. They argued that sustainability is a prerequisite in order to achieve a circular economy, which they defined as the circular passage of material and energy through our planetary system.

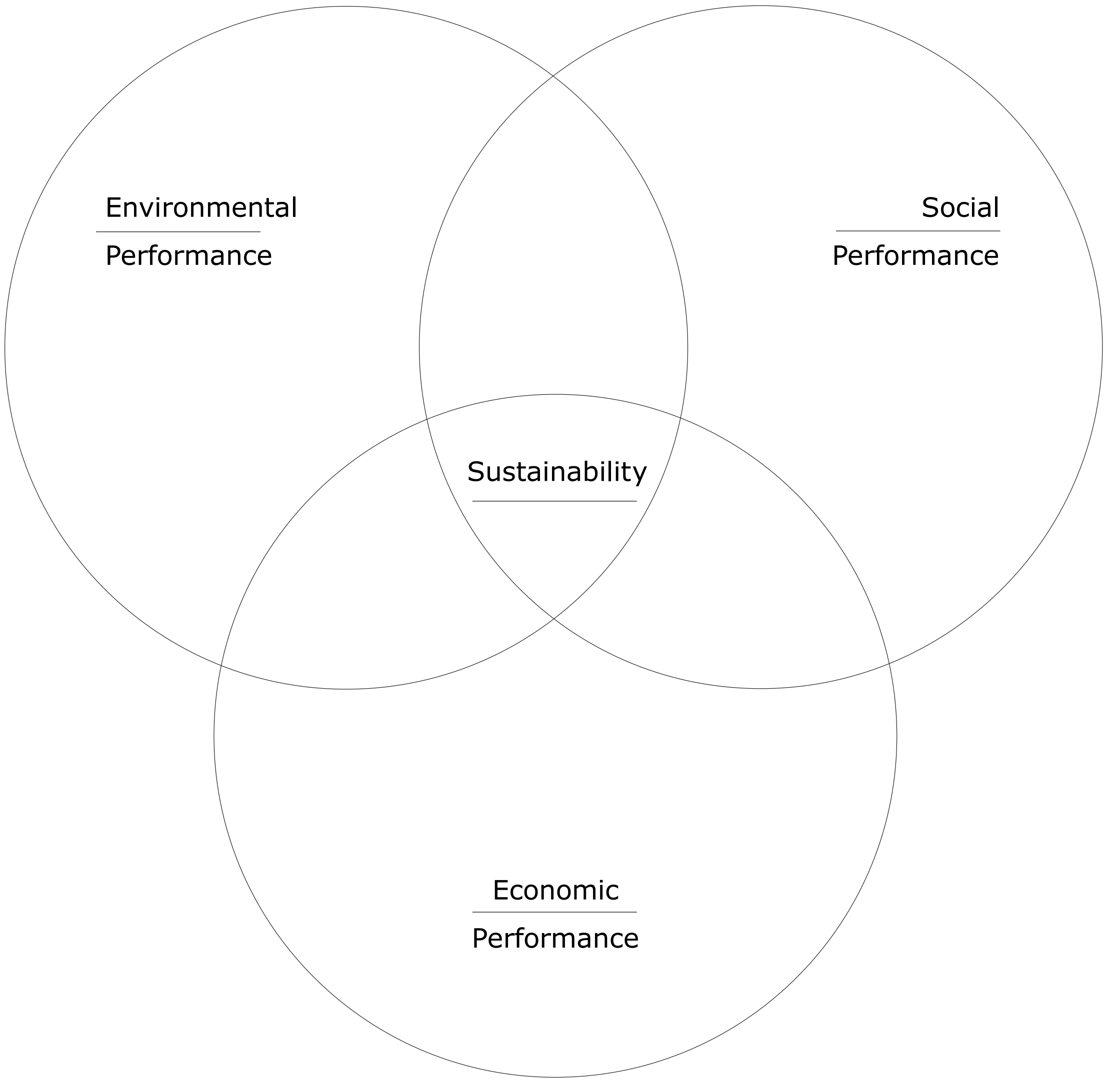


Figure 2.4 Aspects of Sustainability (Adapted from Carter and Rogers, 2008)

The direction of research that followed was based around how to integrate this definition of sustainability with supply chain management. This opened the door for research regarding supply chain sustainability. Tate et al. (2010) proposed that the natural path towards implementing sustainable initiatives in business is through the integration of sustainability and supply chain management. This is due to the fact that in order for sustainability to be truly effective it will require all supply chain members to take part in the implementation of sustainable practices and cannot be limited to one company alone.

Supply chain sustainability has been defined through numerous papers. Table 2.4 presents some of the most widely agreed upon definitions, which are most commonly repeated through papers on supply chain sustainability.

Table 2.4 Summary of most commonly used definitions for sustainable supply chain management

Author	Definition
Carter and Rogers (2008, pg. 368)	Defined Sustainable Supply Chain Management (SSCM) as 'the strategic, transparent integration and achievement of an organisation's social, environmental, and economic goals in the systemic coordination of key inter-organisational business processes for improving the long-term economic performance of the individual company and its supply chains.'
Seuring and Muller (2008, pg. 1700)	Defined SSCM as 'the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements.'
Hassini, Surti, and Searcy (2012, pg. 70)	Defined SSCM as 'the management of supply chain operations, resources, information, and funds in order to maximize the supply chain profitability while at the same time minimizing the environmental impacts and maximizing the social wellbeing.'

Research motivation towards the incorporation of sustainability within supply chain management began with research into green supply chain management (Murphy and Poist, 2000). Winter and Knemeyer (2013) conducted a systematic review on the link between supply chain management and environmental sustainability outlining several key areas where both fields overlap such as: carbon footprint, green purchasing, remanufacturing, supplier certification, purchasing ethics, safety management and reverse logistics Focus on the environmental aspect of sustainability can be attributed to a shift in legislative direction of governments. For example, the (WEEE) directive 2002/96/EC on waste electrical and electronic equipment together with the (RoHS) Directive 2002/95/EC on restriction of hazardous substances in Europe (European Union, 2003) are both legislative initiatives within the European Union, which obligate supply chains to the safe disposal of products at end of life. These initiatives apply the waste hierarchy, employing the 3Rs: reduce, reuse and recycle. This has created a need for both manufacturers and researchers to investigate options on how to transform traditional operations into sustainable ones not just for one entity, but also across all supply chain members (Brandenburg, et al., 2014).

According to Seuring and Muller (2008) the literature showed that the term sustainable supply chain management has been inconsistently defined and applied in research. Investigations from the logistics and supply chain management research perspectives into issues such as the environment, human rights, safety have been made separately without considering the potential integrating these topics together can produce (Carter and Jennings, 2002). Brandenburg and Rebs (2015) further argued that most definitions on SSCM focus primarily on the downstream or forward material flow within the supply chain, which presents a gap in most definitions that neglect the reverse material flow and closed loop supply chain management effect on sustainability.

Carter and Rogers (2008) presented a systematic review on the term sustainability from the perspective of supply chain management. From the literature they reviewed, they were able to sum up that the term sustainability increasingly refers to an integration of social, environmental, and economic supply chain responsibilities. Taticchi et al. (2013) also support this through their definition of sustainable supply chains. From their point of view a single entity cannot truly become sustainable due to the decentralisation and interdependence of firms today in the development of a product or service. Therefore, the supply chain including all its entities need to work together and implement sustainable policies that include environmental and social criteria in addition to the traditional economic criteria in order to transform traditional supply chain management to SSCM. What this further implies is that supply chains aiming to become sustainable would have to meet multiple and conflicting objectives, namely being able to maximise profit, while reducing environmental harm and improving social wellbeing in their surrounding environment.

In their research Taticchi et al. (2013) identify 30 papers approaching sustainable supply chain performance management considering all the three dimensions of the TBL. However, the question that arises is how to measure the TBL. Economic, environmental and social criteria cannot be represented in monetary terms and therefore lack a common denominator. Profit is measured in dollars; however, social capital and environmental or ecological dimensions have effects that cannot be equated to numerical representations, which makes it difficult to come up with a common unit of measurement. Hence, a number of authors advocate calculating the TBL in terms of an index (Slaper and Hall, 2011; Hassan, et al., 2012). In this way, the incompatibility of the measures is eliminated. However, in place of measures, the development of the indices should follow a systematic methodology, which would allow for comparisons on a supply chain, company, product, project, or city level.

Slaper and Hall (2011) considered the absence of a standardised accounting system for sustainability as a strength at this stage of research development on the topic. They argued that this in turn provides the user with the flexibility in adapting the framework to the different needs of the entities (businesses or non-profits), different projects or policies (infrastructure investment or educational programs), or different geographic boundaries (a city, region or country), or different scope (project or case specific).

Not all authors were proponents of the TBL however; Norman and MacDonald (2004) argued that numerous companies claimed to be implementing the TBL to improve their companies' brand image. They further claimed that reporting systems, which focus on transparency such as the Global Reporting Initiative (GRI), do not provide tangible solutions to measuring social or environmental impacts. While such developments are still to be applauded, more effort is required in developing a unified methodology for reporting social and environmental operational impacts.

In summary, there are three major issues, which become apparent when conducting research on sustainable supply chain management. The first issue is the broad scope of sustainable supply chain management. In their review, Winter and Knemeyer (2013) presented some of the overlapping areas between sustainability and supply chain management and summarised the following set of topics: purchasing ethics, remanufacturing, green purchasing, safety management, carbon footprint, supplier certification, and reverse logistics. This gives an indication towards how broad the topic of sustainable supply chain management truly is. Therefore, most studies conducted so far have usually taken a narrower scope of sustainability focusing only on one of the aspects of sustainability instead of attempting to incorporate all three simultaneously (Pagell and Shevchenko 2014; Reefke and Sundaram 2016; Ansari and Kant, 2017).

The second issue is the lack of practical initiatives towards integrating sustainability within supply chain management. Dubey et al. (2017) argued that there has been a considerable increase in research towards integrating sustainability and supply chain management. However, most of this research focused on developing theoretical models, which portray the effect sustainable management can have on supply chain management. Papers which provide practical initiatives in terms of transforming a supply chain from a traditional managerial perspective into sustainable supply chain management perspective are still quite rare (Carter and Rogers 2008; Seuring and Muller 2008; Carter and Easton 2011; Dubey et al. 2017). This issue can still be attributed to sustainability being in its early stages of development and requiring more focus on the development of theory at this current stage.

The third issue is the lack of a standard system accounting for the level of sustainability within a supply chain. Even though there have been numerous attempts, offering frameworks, developing metrics to measure the performance of sustainable supply chain management (Taticchi, Tonelli and Pasqualino, 2013; Hassini, Surti & Searcy, 2012; Schaltegger and Burritt 2014; Reefke and Sundaram, 2016; Formentini and Taticchi, 2016) there is yet to be a standard system. The problem remains in the nature of sustainability itself being difficult to find a common denominator across economic, environmental and social aspects. Most of the research conducted in this area however uses Elkington's (1998) triple bottom line accounting philosophy as a basic guideline with people, planet and profit as the three main pillars for the development of the metrics.

2.4 Part B: The Integrative Review

Part B will present the integrative literature review as a systematic approach towards identifying supply chain areas and processes that are affected by modularity in product design.

The integrative literature review is a form of research that reviews, critiques, and synthesizes representative literature on a topic in an integrated way such that new frameworks and perspectives on the topic are generated (Carliner, 2011). Grant and Booth (2009) discussed the integrative literature review under their SALSA classification scheme (Table 2.5). Since the focus of an integrative literature review is not quantitative or qualitative in nature, but on the research questions, it is labelled as a mixed review method. What this means is that the integrative review does not solely focus on identifying the number of papers, which discuss PDM and SSCM, but also on critically assessing the arguments within these papers with the objective of developing new research themes.

Table 2.5: Mixed Studies Review (Integrative Review)

Label	Description	Search	Appraisal	Synthesis	Analysis
Mixed studies review/mixed methods review	Refers to any combination of methods where one significant component is a literature review (usually systematic). Within a review context it refers to a combination of review approaches for example combining quantitative with qualitative research or outcome with process studies	Requires either very sensitive search to retrieve all studies or separately conceived quantitative and qualitative strategies	Requires either a generic appraisal instrument or separate appraisal processes with corresponding checklists	Typically both components will be presented as narrative and in tables. May also employ graphical means of integrating quantitative and qualitative studies	Analysis may characterise both literatures and look for correlations between characteristics or use gap analysis to identify aspects absent in one literature but missing in the other

Adapted from Grant and Booth (2009)

Most integrative literature reviews are intended to address two general kinds of topics: mature topics, or new emerging topics (Torraco, 2005). Due to SSCM being in its introductory stages, this research follows the latter of the kinds of integrative literature reviews that Torraco (2005) discussed. From the literature (Winter and Knemeyer, 2011; Carter and Rogers, 2008; Seuring and Muller, 2008), it is recognised that there is a lack of research for applicable initiatives in supply chain management that would lead to SSCM. De Brito and Laan (2010), discuss the procrastination between the integration of supply chain management and sustainability. Hence, it can be argued that presenting product design modularity as a means towards a more sustainable supply chain can be considered a new or emerging topic. The result of an integrative literature review on new and emerging topics is usually an initial conceptualization of the topic (Bailey and Kurland, 2002). Integrative reviews have been previously used in a number supply chain management related fields with a focus on reaching new conceptual frameworks in both emerging topics such as incorporating modularity concepts in the service industry (Bask, et al., 2010); the effect of modularity on product offerings and customer satisfaction (Bask, et al., 2013); the transition from traditional supply chain management into a three dimensional management system integrating economic, environmental and social constraints in the decisions making process (Gupta, et al., 2013); and in mature topics such as the use of demand management to achieve improved supply chain agility (Gligor, 2014).

Torraco (2005) presented the integrative literature review writing process in the form of a cycle, which begins with conceptual structuring of the review, followed by a discussion of a detailed explanation of how the review was conducted, and finally the writing focus of the integrative review is on critical analysis and conceptual reasoning in order to reach new theories and concepts, as illustrated in Figure 2.5 below.

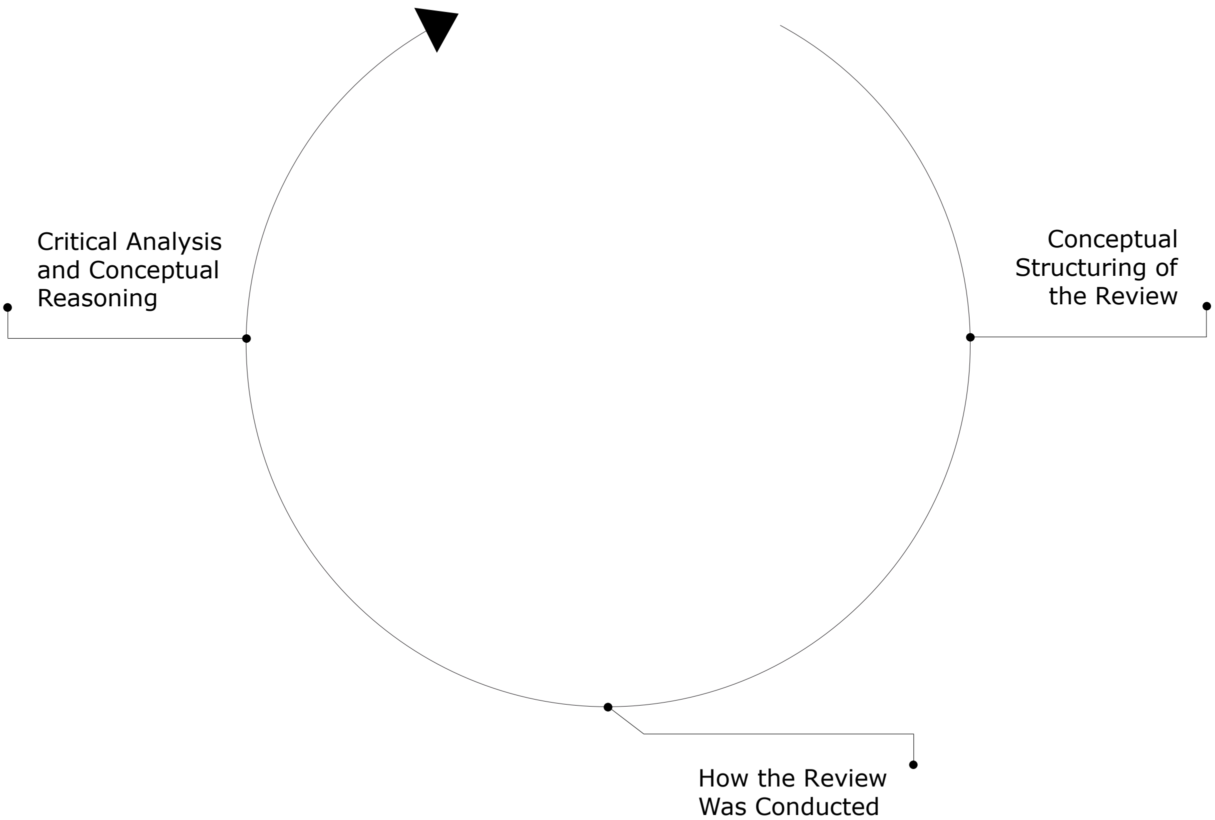


Figure 2.5 The Integrative Literature Review Process (Adapted from Torraco, 2005)

2.4.1 The Conceptual Structuring of the Review

Building on the previously discussed definitions of SSCM and PDM provided in Part A, the conceptual structure for this thesis will be to integrate between PDM and SSCM across the three aspects of sustainability (economic, environmental, social). This is illustrated in Figure 2.6 below. The concept is divided into two stages: First, to identify the operations and processes within the supply chain, which are affected by a modular product design. Second, is to identify whether these operations and processes, when under a modular design, impact economic, environmental, or social supply chain performance. This leads to the development of three questions:

1. How does PDM improve economic supply chain performance?
2. How does PDM improve environmental supply chain performance?
3. How does PDM improve social supply chain performance?

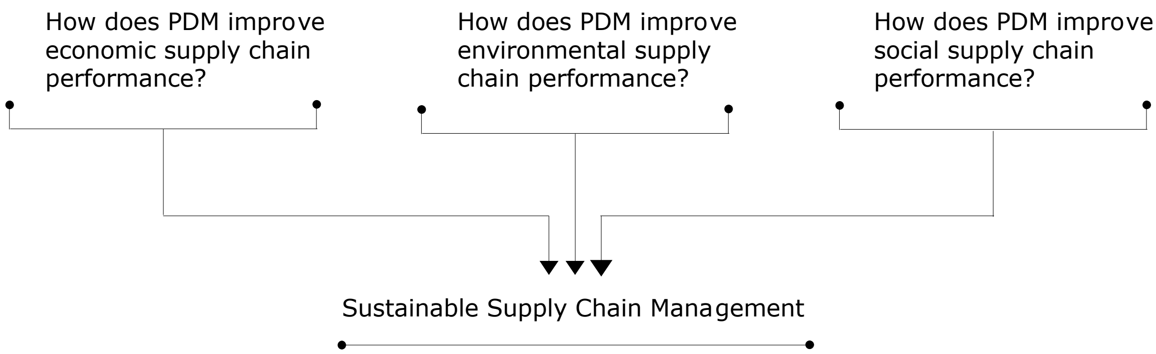


Figure 2.6 The Conceptual Structuring of the Review

2.4.2 How the review was conducted

This relates to the methodology of writing an integrative literature review. This section explains how the literature was identified, analysed, synthesized, and reported. This section focuses on the replicability of the research. Torraco (2005) presents a four-step guide outlining how an integrative review is to be conducted illustrated in Figure 2.7 below.

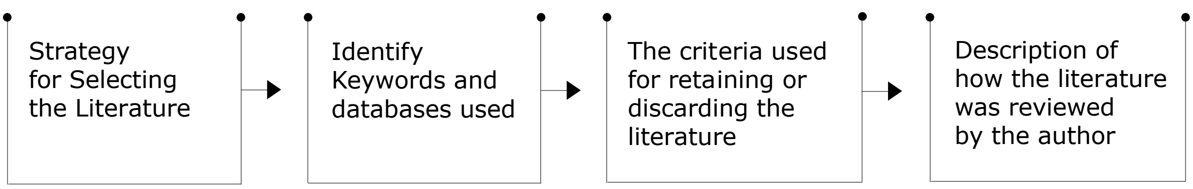


Figure 2.7: Methodology for Conducting the Review

The strategy for selecting the literature followed the conceptual structure for writing the review. The focus was to identify literature where PDM has an influential role in improving the performance of the supply chain. However, this was not easy to conduct due to the nature of the topic articles were dispersed between journals with an engineering focus, and others with a managerial focus, and others with a focus purely on sustainability. Therefore, having a clear conceptual structure to begin with helped focus the search strategy for relevant articles.

The main keywords used were:

- Product design modularity
- Supply chain management
- Sustainability

The main databases used were:

- Science Direct (www.sciencedirect.com)
- Scopus (www.scopus.com)
- Emerald Insights (www.emeraldinsights.com)

These databases were selected on the merit of the availability of management related articles as well as engineering related articles, which was vital to obtain wider range of results from both fields to present the integration between PDM and SSCM.
Given that literature on sustainability began to emerge in the 1980's, the search was limited to articles from the 1980's until March 2018 and attempted to include the most current literature. The search began by first trying all three keywords simultaneously which returned with no articles containing all three keywords.

The search was then conducted using the first two keywords together (Product design modularity and supply chain management), which returned with a total of 229 articles in total from the respective databases.

The search was conducted again using (product design modularity and sustainability), which returned 34 articles in total from the respective databases.
The inclusion criteria for using the articles in the review were:

- The article's focus must be on product design
- The article must have a managerial focus
- The article must have a relationship between PDM and SCM (this relationship is then further classified as to whether being economic, environmental, or social)

The exclusion criteria for not using the papers in the review:

- If the article has a purely engineering focus
- If the articles focus was on organisational modularity
- If the articles focus was on service modularity
- Conferences and dissertations were also excluded

All articles were reviewed through two screening stages. The first stage consisted of a review of the abstracts and keywords of all search results. The second stage consisted of thorough reading of full articles which were to be included in the review. A total of 194 articles out of the sum of 263 (229 the results from the first search string + 34 the results from the second search string) were found to be out of the scope of this research; leaving a total of 69 articles to be included.

The articles were then further classified according to whether the focus of the article was on relating PDM to the economic, environmental, or social aspects of the supply chain. 43 of the articles focused on linking PDM to operational improvements within the supply chain, which can be linked to economic improvements in terms of cost reduction or profit enhancement. 21 articles presented a link between PDM and environmental elements. 5 articles attempted to present a simultaneous view presenting two or three aspects simultaneously, however from these five papers only three papers discuss effects, which can be linked to the social aspect. Appendix I presents the articles included in this review. The articles were classified according to whether the focus of the article was on relating PDM to the economic, environmental, or social aspects supply chain management.

2.4.3 Findings

This section will present the findings of the integrative literature review in the form of the thematic development recognised through the collation of articles. The themes development process was based on analysing the articles to identify which supply chain areas were affected by modularity in design. The researcher used Nvivo and Excel to identify the common relationships and develop the themes. The Excel sheets used in the structuring of the thematic framework are provided in Appendix I. Articles discussing similar supply chain areas were grouped together and are represented by a singular theme. The section follows the conceptual structuring of the review. Themes affecting economic performance of the supply chain are grouped and presented together, while themes for the environmental and social aspects are also presented in a similar manner respectively.

2.4.3.1 PDM and Supply Chain Design Economic Aspect

In regard to PDM and the economic aspect of the supply chain, the first theme in the literature focused on the dependence of mass customisation on PDM (refer to Table 2.6 for a full list of references linking PDM to mass customization). Kumar (2005) defined mass customization from two perspectives. The first being the focus on offering customers with products, which are custom made to their requirements. The second, refers to the cost aspect, with mass customization operations strive to offer products at a competitive price. Through the division of final products into separate modules and components each with a specific function allows for products offering different functions meeting differing customer requirements. At the same time the eternal trade-off between increasing manufacturing costs and increasing product variety is solved. PDM allows for the standardization of the components, which allows for economies of scale in the manufacturing process.

Table 2.6 Articles linking PDM to economic supply chain aspects

Literature Theme		Authors
Theme 1: Mass Customisation	Economies of Scale	Zhang, et al. (2017); Chiu and Okudan (2014); Danese and Filippini (2013); Nepal, Monplaisir and Famuyiwa (2012); Bush, Tiwana, and Rai (2010); Lau, Yam and Tang (2010); Kong, et al. (2010);Brun and Zorzini (2009); Zhou, San and Seng (2008); Zhang, Huang and Rungtusnatham (2008); Ro, Liker and Fixson (2007); Huang, Zhang and Liang (2005); Jose and Tollenaere (2005);Kumar (2005); Mikkola and Gassmann (2003); Doran (2003); Cantamessa and Rafele (2002); Kusiak (2002); Salvador, Forza and Rungtusanatham (2002); Novak and Eppinger (2001); Ernst and Kamrad (2000); Duray, et al. (2000); Hsuan (1999); Hoek and Weken (1998);Gershenson and Prasad (1997); Ulrich (1995)
	Product Variety	Danese and Filippini (2013); Pero, et al. (2010); Zhang, Huang and Rungtusnatham (2008); Ro, Liker and Fixson (2007); Huang, Zhang and Liang (2005); Jose and Tollenaere (2005); Kumar (2005); Kusiak (2002); Salvador, Forza and Rungtusanatham (2002); Ernst and Kamrad (2000); Duray, et al. (2000); Hoek and Weken (1998); Gershenson and Prasad (1997); Ulrich (1995)
	Inventory Cost Saving	Lau, Yam and Tang (2010); Brun and Zorzini (2009); Zhang, Huang and Rungtusnatham (2008); Jacobs, Vickery and Droge (2007); Huang, Zhang and Liang (2005); Jose and Tollenaere (2005); Kumar (2005); Mikkola and Gassmann (2003); Doran (2003); Cantamessa and Rafele (2002); Kusiak (2002); Salvador, Forza and Rungtusanatham (2002); Novak and Eppinger (2001); Ernst and Kamrad (2000); Duray, et al. (2000); Hsuan (1999); Hoek and Weken (1998); Gershenson and Prasad (1997); Ulrich (1995)
Theme 2: Supply Chain Integration	• Supplier Integration • Manufacturing Integration • Information Integration • Design Integration	Zhang, et al. (2017); Danese and Filippini (2013); Nepal, Monplaisir and Famuyiwa (2012); Danese, Romano, and Bartolotti (2011); Ulku and Schmidt (2011); Lau, et al. (2010); Bush, Tiwana, and Rai (2010); Lau, Yam and Tang (2010); Pero, et al. (2010); Antonio, Richard and Tang (2009); Lau, Yam and Tang (2007) a; Howard and Squire (2007); Jiao, Simpson and Siddique (2007); Doran, et al. (2007); Ro, Liker and Fixson (2007); Voordijk, Meijboom and Haan (2006); Lau and Yam (2005); Doran and Roome (2005); Huang, Zhang and Liang (2005); Mikkola and Gassmann (2003); Doran (2003); Cantamessa and Rafele (2002); Salvador, Forza and Rungtusanatham (2002); Novak and Eppinger (2001); Ernst and Kamrad (2000); Hsuan (1999); Hoek and Weken (1998)
Theme 3: Supply Chain Responsiveness	Simplified Production and Scheduling	Lau, Yam and Tang (2010); Pero, et al. (2010); Khan and Creazza (2009); Jose and Tollenaere (2005); Mikkola and Gassmann (2003); Doran (2003); Kusiak (2002); Ernst and Kamrad (2000); Duray, et al. (2000); Hoek and Weken (1998); Gershenson and Prasad (1997)
	Reduced Cycle Lead Time	Danese and Filippini (2013); Lau, Yam and Tang (2007) a; Lau, Yam and Tang (2007) b; Ro, Liker and Fixson (2007); Fixson (2005); Huang, Zhang and Liang (2005); Kusiak (2002); Salvador, Forza and Rungtusanatham (2002); Duray, et al. (2000); Hsuan (1999); Gershenson and Prasad (1997)

This link becomes quite apparent when reviewing the literature, where PDM is directly linked to achieving mass customization, which is directly linked increasing product variety. PDM also allows OEM's to offer customised end products. This is different than increasing offerings within their product range. PDM is linked to allowing supply chains to increase product variety through mass customisation, however this only means the supply chain will increase products with pre-set options (Kumar, 2005; Zhang, et al., 2017). A customised end product means the original equipment manufacturer (OEM) will be able to employ assemble to order manufacturing based on individual customer order, which is also linked to improving sales and increasing supply chain profit (Piller, 2005). This answers the first perspective of the definition presented by Kumar (2005). Through PDM mass customization can be achieved offering a wider range of diversified products for the customers to choose from and allowing for customization options. Several mobile phone manufacturers have currently capitalized on this, offering separate modules for cameras or batteries or additional memory modules for their phones that can be easily configured to the original mobile set (Shutkin, 2007; Kumar, 2005; Mikkola and Gassmann, 2003).

PDM also standardizes the modules, and since standardization is directly linked to economies of scale in the manufacturing process, this answers the second perspective of the definition. Furthermore, PDM reduces inventory costs through the inventory pooling risk effect (Jacobs, Vickrey and Dorge, 2007; Brun and Zorzini, 2009). In addition, PDM leads to a reduced number of components per final product, which directly reduces inventory requirements. Another aspect is that since end items can share the modules this allows for one pool of inventory for a number of end items, which improves inventory availability and reduces risks of stock out. This allows companies to solve the trade-off between increasing their product variety while maintaining competitive prices for their product offerings. Figure 2.8 presents a model for the identified relationships between PDM and mass customisation.

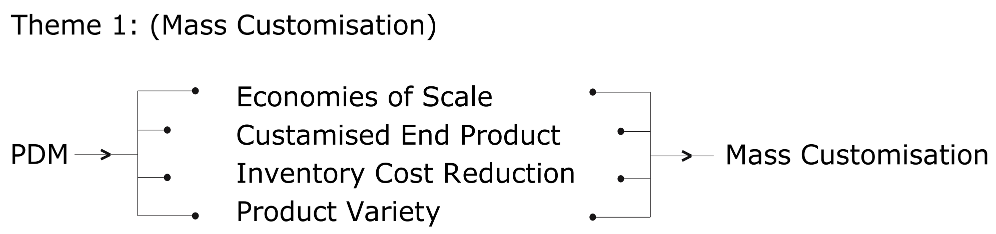


Figure 2.8 PDM and Mass Customisation

The second major theme (refer to Figure 2.9) within the literature examined PDM and its effect on supply chain integration (refer to Table 2.6 or full list of references linking PDM to supply chain integration). Zhang et al. (2017) defined supply chain integration as the process of integrating suppliers, customers and internal functional units in a supply chain with the objective of optimizing the overall performance of the supply chain. Through PDM the manufacturing process no longer needs be conducted under the umbrella of one company. PDM allows for the manufacturing process to be divided on a number of suppliers which can be in different supply chain up stream tiers. Doran (2003) presented the relationship between PDM and its effect on the idea of value transfer in the supply chain. There is a current trend for firms to focus on their core competencies and outsourcing any processes or components not considered core to their competitiveness. By dividing the manufacturing process into the development of separate modules, OEM's transfer all operations, which are not considered core, to upstream suppliers within their supply chain. Meaning they transfer part of the value creation processes with their suppliers. Jacobs, Droge and Vickery (2011) argued that PDM facilitates information sharing between supply chain entities through having a common language of communication, which is the module itself. They also discussed enhanced manufacturing integration, where the production and scheduling of the various supply chain tiers have to be coordinated simultaneously to ensure the right levels of production and inventory are maintained across the entire supply chain.

Through improving information and manufacturing integration across the supply chain, PDM also directly affects the integration between supply tiers in the development of new products. Through having separate modules in the production process, new products can be developed without requiring an overhaul of the entire design of the product. Through changing a limited number of modules, a new product design can be achieved. Hence, a considerable amount of literature also relates PDM to new product development (Lau, et al., 2010; Pero, et al., 2010; Danese and Filippini, 2013; Zhang et al. 2017).

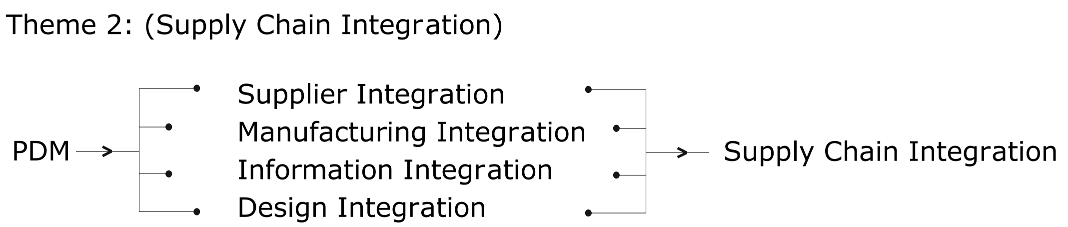


Figure 2.9 PDM and Supply Chain Integration

The third theme (refer to Figure 2.10) within the literature discussed the effect PDM has on supply chain responsiveness (refer to Table 2.6 for full list of references). Bush, et al. (2010) linked PDM to improved supply chain responsiveness through arguing that PDM reduces production cycle lead times. When implementing PDM in manufacturing processes a postponement strategy is usually applied as well. This allows for moving the decoupling point in the supply chain as close as possible to the customer, where most elements (components/modules) of the product have already been manufactured and usually only the assembly of the product remains. PDM also greatly reduces the number of components required in the manufacturing of a product, which leads to simplified scheduling and planning in the supply chain. Reduced production cycle lead times and simplified production and scheduling are seen to have a direct positive relationship with supply chain responsiveness (Sharifi et al. 2006; Danese and Filippini 2013).

Theme 3: (Supply Chain Responsiveness)

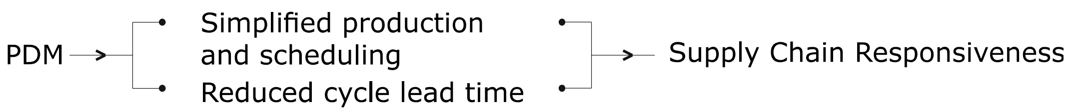


Figure 2.10 PDM and Supply Chain Responsiveness

The previous literature discussion led to the development of two propositions, which present the relationship between PDM and the economic aspect of the supply chain.

Proposition 1 (P1): PDM allows for cost savings in the supply chain.

Proposition 2 (P2): PDM allows for increasing supply chain profit.

PDM can be directly linked to economies of scale, and inventory cost savings in the supply chain, which directly lead to cost savings.

PDM is also directly linked to mass customization and increasing product variety offerings in a supply chain, which is directly linked to improved sales and increased profit (Gershenson, et al., 2004). Table 2.7 presents a summary of PDM effects on supply chain operations that have an economic nature.

Table 2.7 Relationship framework between product design modularity and the supply chain economic aspect

Economic	1. Increase in sales due to product variety based on modular design. 2. Increase in sales due to the availability of a customized end product based on modular design. 3. The ability to pool modules used for different products which leads to inventory cost savings. 4. Mass production or mass purchase of modules, which leads to savings due to economies of scale. 5. Cost savings allowed from the outsourcing of modular products. 6. Reduction of supplier lead-time uncertainty also leading to lower inventory and out of stock costs. 7. Lower set up and holding costs. 8. Simplified planning and scheduling leading to lower inventory and out of stock costs.

2.4.3.2 Product Design Modularity and Supply Chain Design Environmental Aspect

Several literature streams (refer to Table 2.8 for full list of references) have linked between PDM and environmental aspects of the supply chain across several themes (refer to Figure 2.11). Product design is quite essential when implementing supply chain strategies aimed at reducing environmental harm. Beginning with choosing the raw material for the product, to green sourcing options, and product disposal considerations. A major driver for this stream of research can be attributed to proposals in legislation such as the WEEE directive 2002/96/EC on waste electrical and electronic equipment together with the RoHS (reduction of hazardous waste) Directive 2002/95/EC in Europe (European Union, 2003). Within these proposals the waste hierarchy was applied, employing the 3Rs: reduce, reuse and recycle, which forced both manufacturers and researchers to explore options on how to improve the sustainability of operations across the entire supply chain (Ijomah, et al. 2007). Yan and Feng (2013) also investigated the difficulties of extending the supply chain to include issues such as remanufacturing, recycling and refurbishing, which added complexity to supply chain design together with a set of potential strategic and operational issues.

Another major environmental driver for modularity in design is the ‘polluter pays’ principle, which makes original equipment manufacturers (OEMs) and other forward supply chain actors responsible for take-back and recovery of their products once discarded by their last users (Toffel, 2003). Through a modular design the process of recovery and disposal of the product is simplified due to the ability to break down the product into components and the possibility of being able to reuse, refurbish, and recycle more components of the product. A modular design method for achieving components reuse and recycle in inverse manufacturing is proposed to reduce environmental burden (Kimura, et al. 2001), which performs commonality analysis to identify the modules shared by different product. A multi-viewpoint modular design method for engineering design reuse is developed to respond to market and new regulation requirements quickly to allow for the OEMs to gain the maximum benefits from the disposed products (Meehan, et al. 2007; Kristianto and Helo, 2015; Aydinliyim and Murthy, 2016).

Table 2.8 Articles linking PDM to environmental supply chain aspect

Literature Theme		Authors
Theme 4: The 6R Concept	DFE/DFR/ECM	Kristianto and Helo (2015); Yan and Feng (2013); Yu et al., (2011); Kuik, Nagalingam, and Amer (2010); Jayal, et al. (2010); Qian and Zhang (2009); Tseng, Chang and Li (2008); Umeda et al. (2008); Kasarda et al. (2007); Meehan et al. (2007); Ijomah et al. (2007); Newcomb, Rosen and Bras (2003); Gershenson, Prasad and Allamneni (1999); Gu and Sosale (1999)
	LCA	Beske and Seuring (2014); Seuring (2013); Yu et al. (2011); Tseng, Chang, and Cheng (2010); Umeda et al. (2008); Kasarda, et al. (2007); Newcomb, Rosen and Bras (2003); Gershenson, Prasad and Allamneni (1999); Gu and Sosale (1999)
	CLSC/RL	Aydinliyim and Murthy (2016); Bask, et al. (2013); Seuring (2013); Taticchi, Tonelli and Pasqualino (2013); Huang, et al. (2012); Ilgin and Gupta (2010); Tseng, Chang and Li (2008)

Gu and Sosale (1999) presented one of the earliest literature streams linking PDM to environmental sustainability. They discussed specific design strategies such as design for environment (DFE), design for recycling (DFR) for environmentally conscious manufacturing (ECM). PDM naturally assists in these strategies. By having a product's design composed of modules, which can be easily separated and interchanged, the focus changed from recycling an entire product to recycling one module. Meaning that only one module would need to be replaced for the product to continue to remain functional, which reduces the bulk of the material that needs to be recycled. Another aspect is through modular design it becomes easier to change the modules, and to choose greener modules without necessarily changing the entire design of the product with the change being concentrated to one module only (Yu, et al., 2011).

DFE and DFR have also been closely linked with product life cycle assessment (LCA) (Qian and Zhang, 2009). Umeda et al. (2008) defined LCA as a design methodology, where a designer develops a life cycle scenario for the product by assigning life cycle options, such as maintenance, upgrading, recycling, and reused for different stages through a product's life.

From the literature, it becomes apparent in the arguments presented, the changing nature in the design process from a focus on product life cycle to a focus on modular life cycle (Yu et al., 2011; Ijomah et al., 2007). Where the life expectancy of a product can be greatly extended through a modular design. Chopra and Meindl (2007) presented the case of Xerox copiers and how they were able to answer a lifelong customer complaint through elongating their products' life cycle by changing to a modular product design. Kasarda, et al. (2007) argued that through PDM products are generally composed of independent components, which can be easily separated and changed without affecting the overall functionality of the product. Hence, the maintenance and repair operations of products become easier. This has also assisted in changing the customer mentality to focus on changing the damaged module instead of a focus on changing an entire product.

Another stream of literature (refer to Table 2.8) presented the relationship between PDM and closed loop supply chains (CLSC) and reverse logistics (RL) (Ilgin and Gupta, 2010; Seuring, 2013; Bask, et al., 2013). Where they defined CLSC as supply chains, which manage and integrate the forward and reverse flows for material. They argued that through a modular design the processes of recycling and reusing components of a product are greatly improved, which naturally assists in the integration between the forward and reverse material flows within a supply chain (Krikke et al., 2003).

More recent literature (refer to Table 2.8) has attempted to integrate all of the previously mentioned themes (DFE, DFR, ECM, LCA, CLSC) with the 6R concept. Joshi et al. (2006) first presented the 6R concept as a transformation from the tradition 3R model, which only focused on reduce, reuse and recycle to also include recover, redesign and remanufacture. Yan and Feng (2013) discuss the relation between modularity and the 6R's. They defined reuse as the means that a product or its components could be reused in the similar product. Recycle mainly focuses on the process of converting material such as metal to improve the reuse of potentially useful materials (USEPA 2008). Recover involves the process of collecting used products at the end of life, and then disassembly, sorting, and cleaning for utilization (Joshi et al., 2006). Reduce is to use less of any non-renewable resource through focus on reuse, recycling, and recovering activities. Redesign is to improve next generation products through innovative techniques to make them more sustainable, while remanufacture involves the reprocessing of used products or components through innovative techniques without loss of functionality (Joshi et al., 2006).

Theme 4: (6R Concept)

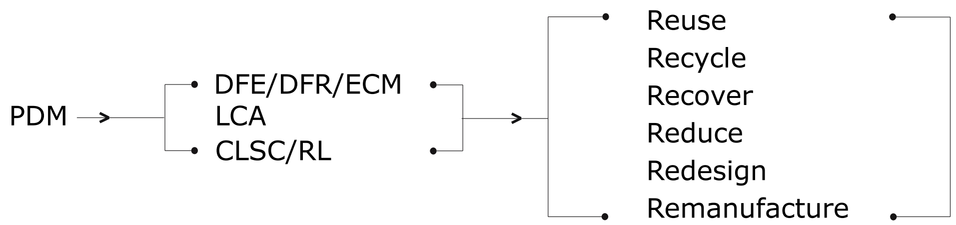


Figure 2.11 PDM and the 6R Concept

The previous literature discussion led to the development of the third proposition for this thesis, which links PDM to a supply chain’s environmental aspect.

Proposition 3 (P3): PDM can be used to reduce environmental harm within supply chains.

A considerable amount of the literature presented the effect PDM has on improving a combination of, or all of the 6Rs processes within a supply chain. This effect is then further linked to one of the previously mentioned themes (DFE/DFR, LCA, CLSC/RL) to argue the positive relationship between PDM and a supply chain’s environmental aspect. Table 2.9 presents a summary of the effects PDM has on supply chain operations where there is potential for reducing environmental harm.

Table 2.9 Relationship framework between product design modularity and the supply chain's environmental aspect

Environmental	1. Reuse of returned modules in the production process. 2. Reduction in the purchase of new non-renewable resources. (Due to the pooling effect) 3. Remanufacturing and refurbishing of modules from returned products. 4. Recycle 5. Recover 6. Redesign

2.4.3.3 Product design modularity and social supply chain aspects

The integrative literature review provided no direct link between PDM and the social aspect of sustainability, with most of the literature focusing mainly on the effect modularity has on operational or environmental enhancements. The literature did not attribute modularity as a factor that affects any social measures of a supply chain's performance directly. However, a number of papers do hint towards certain effects product design can have indirectly on certain social aspects that are generally linked to economic aspects, such as employee productivity for example. A summary of such articles is presented in table 2.10.

Nevertheless, a relationship can be induced linking modularity to social performance through modularity's effect on supply chain design and process design. Evidence that supply chain design and process design are both affected by product design is grounded in the concept of three-dimensional concurrent engineering (3DCE) (Fine, Golany and Naseraldin, 2005; Gan and Grunow, 2013; Kremer, et al., 2016). 3DCE as a concept proposes the integration of the decision making process for product design, process design, and supply chain design, so that all three decisions are made simultaneously (Ellram, Tate and Carter, 2007). Opting for a modular product design will therefore have an effect on decisions for process design and supply chain design (Fine, 1998; Fixson, 2005; Fine, Golany and Naseraldin, 2005). The next section will discuss 3DCE in more detail providing a brief discussion regarding concurrent engineering and the development of 3DCE. A section that discusses the effect of PDM on supply chain design focusing on how the social aspect of the supply chain's performance is affected will follow this. Finally, a section discussing the effect of PDM on process design, also focusing on the social aspect of a supply chain's performance will follow.

Three Dimensional Concurrent Engineering

Zhang et al., (2008) discussed how that the common order for the decision making process used to be the development of product design, followed by process design and then reaching supply chain design sequentially in a linear approach. However, this method is no longer effective and cannot keep up with shortening product life cycles and increasing consumer demand for variety (Daie and Li, 2016). Fine, Golany and Naseraldin (2005) discussed how this serial sequencing created design constraints for each following design stage. They explained that once the product design was set its parameters were used as constraints for the process design and once both product and process design were set they were considered constraints for the supply chain design. This sequential process led to suboptimal design solutions and a long lead-time. Hence, the need for integrating the decision process became apparent (Fine, 1998; Rungtusanatham and Forza, 2004). This began with concurrent engineering, which is identified in the literature as the integration of product design and process design so that decisions concerning product and process might be made simultaneously (Ellram, et al., 2007). The main objective of concurrent engineering in combining the design decisions is to foresee problems and take advantage of processing opportunities (Gan and Grunow, 2013; Fine, Golany and Naseraldin, 2005; Forza, et al., 2005).

Numerous papers also discuss the integration of product design and supply chain design decisions presenting the concept of design for supply chain (DFSC) (Sharifi, et al., 2006; Gan and Grunow, 2013; Gokhan, et al., 2010; Kremer, et al., 2016). Rungtusanatham and Forza (2005) argued that when planning for the supply chain, merely coordinating manufacturing process design decisions with product design decisions (i.e., concurrent engineering) or coordinating supply chain design decisions with product design decision is not enough (i.e., DFSC).

Fine (1998) argued that all three domains (product, process and supply chain) possess architecture; and matching these architectures is key to the success of three-dimensional concurrent engineering. Fixson (2005) argues that a comprehensive product architecture assessment methodology can serve as a base that links decisions from all three domains together.

However, a major trade-off does exist when implementing 3DCE. The benefit of integrating the decision making process of all three domains presents itself in the form of improved time to market, reduction of re-design and re-work, and increases the chances of smoother production. This is mainly due to the flexibility of the decision making process since no design is yet fixed making changes possible to any of the three domains. The downside, however, comes in the form of the complexity of the process, which will require joint optimisation of multiple objectives with the added constraints from each domain (Blackhurst, et al., 2005; Gan and Grunow, 2013).

Having a modular product design goal will therefore directly influence the supply chain design and on the process design objectives and constraints. The next two sections will discuss this in more detail focusing on how modularity affects supply chain design and process design to induce the effect PDM has on the social performance of a supply chain.

Table 2.10 Articles linking PDM to social supply chain aspect

Literature Theme		Authors
Theme 5: Concurrent Engineering	Modular Clusters/ Employee Learning Curve	Brandenburg, et al. (2014); Gan and Grunow (2013); Liao, Tu and Marsillac (2010); Shamsuzzoha (2011); Fixson and Park (2008); Jacobs, Vickery and Droge (2007); Ellram, Tate and Carter (2006); Fine, Golany and Naseraldin (2005); Forza, Salvador and Rungtusanatham (2005); Gershenson, Prasad and Zhang (2004); Fine (1998)

PDM and Supply Chain Design

It has become very rare in our current age to find a company that produces the entirety of its product offerings. Instead of spreading their resources on developing an entire product, companies today focus instead on their core competencies and outsource the remainder of the processes (Daie and Li, 2016). Product modularity facilitates the concentration on core competencies, and the outsourcing of less strategic activities to suppliers. Modularity also triggers a re-definition of the role of the first-tier suppliers (Doran et al., 2007, Ro et al., 2007), who can produce entire modules and systems, while coordinating the network of component suppliers.

Sturgeon (2003) also supported this discussing how product modularity and interface standardisation enable reallocation of tasks, in a way that the brand name firm conducts the development process whereas the contract manufacturer carries out production. Modularity can also lead to extensive co-development efforts between the OEM and suppliers to define the product architecture (Lau and Yam, 2005). Once it is defined, modules' suppliers make the detailed module development (Ro et al., 2007).

The ability to outsource entire modules to suppliers further upstream also resulted in a major change to supply chain networks. Manufacturing operations of a product no longer needed to be centralised in one location. The flexibility in locating the manufacturing process has been the main cause towards the restructure of supply chain networks (Sturgeon, 2003). In order to achieve further optimisation and efficiency in their supply chains many product producers opted to locate their manufacturing facilities to areas with cheaper resources (natural resources, labour) (Lei, 2009). Each module can be produced in a different location and assembly can take place in an entirely different location. Even though modularity presents numerous benefits in terms of supply chain efficiency, the decentralisation of the manufacturing process translated into more complex inventory calculations and transportation modelling. In turn this noticeably added to supply chain complexity.

Daie and Li (2016) presented a supply chain hierarchy model to compute supply chains with least complexity based on two main variables: 1. The number of different product offerings. 2. The demand for each product offering. They argued that modular product design has become common practice for many automotive and electronics supply chains where there is increased demand for product variety and shortening product life cycles. However, they also discussed how modular design adds to the complexity of supply chain structures through the spatial dispersion of the manufacturing process. At the same time, modularity also helps define the role of suppliers since each module will have a standardised interface fit within a greater scheme, which is the product architecture (Nepal, Monplaisir and Famuyiwa, 2012). This enabled the division of the manufacturing process to pre-set modules, which makes the outsourcing process of shifting the manufacturing process to a supplier less complex.

Wang, Aydin and Hu (2009) also proposed a complexity measure for assembly supply chains where they compare between the supply chains network complexity in relation to the cost saving potential of that particular network. They argued that modularity in product design led to the development of modular assembly supply chains.

Through solving supply chain models with an objective of reducing complexity resulted in what is known as modular (industrial) clusters. Baldwin and Clark (2000) defined modular clusters as a group of firms and markets for (goods, labour, and capital) which emerged in direct relation to the adaptation of product design modularity. Lei (2009) presented the same concept, however, giving modular clusters the name industrial clusters instead. The clustering of firms assisted in the emergence of well-developed transportation routes for inbound and outbound material as well as a pool of skilled labour. Porter and Kramer (2011) defined industrial clusters as ‘geographically proximate group of inter-connected companies and associated institutions in a particular field, linked by commonalities and complementarities’.

The restructure of supply chain networks and the development of industrial clusters due to modular product design is where certain social aspects of a supply chain are affected. Thomsen and Pillay (2012) examined literature on the relation between corporate social responsibility (CSR) and industrial clusters. They argued that the effect of industrial clusters on promoting corporate social responsibility remains an under investigated area of research. They explained that this is due to a lack of systematic studies that empirically assess the

links between CSR initiatives and broader economic, social, and environmental effects in developing countries. They discussed that the initial debate started in the 1990s.
Porter (1998) investigated the role of the clustering of small and medium sized enterprises (SMEs) into geographically proximate and interconnected enterprises on poverty reduction concerns in developing countries. This co-location of SMEs would thus lead to enhance flow of knowledge between enterprises, sharing of ideas and innovation in products and business processes, trained workers, service providers, transportation companies, and specialised suppliers. This would lead to reducing transaction costs for individual firms as they form part of the cluster allowing SMEs a better opportunity to compete locally and globally (Schmitz and Nadvi, 1999). However, attempts towards assessing the social impacts of such industrial clusters in developing countries are very fragmented and often more related to economic aspects.

Thomson and Pillay (2012) presented a number of social benefits, which can be attributed to industrial clusters, dividing them into passive and active benefits. They argued that the passive benefits included: availability of a trained pool of workers, transportation companies, specialised input suppliers, local training institutes, and consultants to help guide the SMEs towards running a more competitive business. The active benefits were mainly associated in the ability of SMEs to band together to address external threats. Schmitz and Nadvi (1999) also argued that SMEs would be more able to engage in joint action through their industry associations and/or in cooperation with national or international support agencies that would allow SMEs mitigate numerous risks challenging their future survival.

From a social perspective this is beneficial for developing countries because a factory opening there means work opportunities and skills development programs for the populous. Hence, an important factor comes into play here, which is the stage of development of a country. If a country is considered a developed country this usually means that it has high standards of living and usually have a high minimum hourly wage to support this standard of living. On the other hand, if a country is considered a developing country this is usually quite the opposite with the minimum hourly wage being considerably lower (Thomsen and Pillay, 2012).

Nadvi and Barrientos (2004) conducted a study in collaboration with UNIDO (United Nations Industrial Development Organisation) to address the relationship between industrial clusters and poverty in developing countries. They combine a value chain mapping and capabilities approach as their methodology to develop a poverty and social impact assessment for cluster development programs. They provided that there is substantial evidence that clusters generate employment and incomes for the poor in the developing world. However, they also discussed that clusters have a varying effect where certain types of clusters have a more direct effect on poverty. These include clusters in rural areas and in the urban informal economy, clusters that have a preponderance of SMEs, micro-enterprises and homeworkers, clusters in labour intensive sectors and clusters that employ women, migrants and unskilled labour.

Through a critical assessment of literature on the effect of industrial clusters on social development resulted in another insight. It appears that there is a division of labour where the higher value adding part of the global manufacturing chain (branding, marketing, and supply chain management functions) are controlled by western buyers and developing country clusters are mainly in charge of lower value adding activities related to labour intensive manufacturing of industrial products (Schmitz and Nadvi, 1999; Nadvi and Barrientos, 2004; Lei, 2009; Thomsen and Pillay, 2012).

Therefore, it can be argued that PDM affects the structure of a supply chain through the decentralisation of the manufacturing process and the formation of industrial clusters. This restructure can result in improving certain social aspects in terms of unemployment, standard of living, and skill learning (Nadvi and Schmitz, 1994; Nadvi and Barrientos, 2004; Thomsen and Pillay, 2012). However, this is only true if certain criteria (cheap resources, supply chain processes) are met.

PDM and Process Design

A main element in supply chain design is capacity allocation (Chopra and Meindl, 2007). The human element in terms of skills required and labour hours required to complete a certain task are critical parts in terms of capacity planning. Fixson (2005) discussed how organisational structures for product development are found to mirror the product structures for products they develop. As Fixson explained this is due to the task structure being dependent on the product structure. A major part of decisions within the process design domain include the selection of the number and type of processes that will be used to manufacture the product. The number of components, the complexity of individual components, the extent components can be used across different products within a product family or across different product families, the number of product variables, are all major design decisions within the product domain that will directly have an effect on the process design domain (Gan and Grunow, 2013; Zhang, Huang and Rungtusanatham, 2008; Fixson, 2005).

The integration of product and process design decisions, even though quite established in regard to the economic and operational benefits, neglects to examine the social benefits of such integration. However, some literature does hint to some extent on certain socio-economic benefits of combining product and process decisions specifically when modularity in product design is present.

Jacobs, Vickery and Droge (2007) discussed the effect of PDM on improvements in employee skill learning curves. They explained that through module specialisation and standardisation process times, errors, and the product reworks are greatly reduced. Their discussion was mainly from an operational point of view, nevertheless it did present some insight into the effect modularity in design has over process design through the skill learning curve of employees.

Fixson (2005) also argued that since modularity in production is based on the use of common modules and a manufacturing process that is composed of a hierarchy of assembly steps, this will then lead to a simplified work path and gives the firm flexibility in meeting demand uncertainty. This work paths simplification is generally linked to increasing production efficiency due to decreasing human error and reducing the number of product reworks.

Liao, Tu and Marsillac (2010) examined the effect of modularity based manufacturing practices (MBMP) on organisational learning. They explained that a firm’s ability to gain knowledge and technology depends on the firm’s absorptive capacity, which results from continuous learning. Absorptive capacity is influenced by organisational communication, which is greatly improved through MBMP. MBMP standardise business processes allowing a much accelerated learning curve and easier integration between different inter-organisational departments. This also allows for simple change over processes that allow different product modules to be made simultaneously with assembly occurring at later stages in the manufacturing process. The simultaneous production of modules provides wider learning opportunities where employees acquire knowledge and skills pertaining to an entire product family instead of being specific to a limited number of products. Figure 2.12 presents the relational effect of PDM on supply chain design and process design from a social perspective

Theme 5: (Concurrent Engineering)

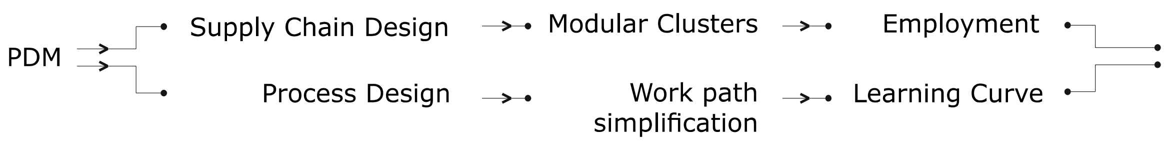


Figure 2.12 PDM and Three Dimensional Concurrent Engineering

Sturgeon (2003) presented a different perspective on the relation between modularity product design and process design. Sturgeon discussed how modularity in design is used as the basis for manufacturing automation. This is due to modularity in design clearly dividing the final product into standardised components. Thus, the process design for manufacturing such components can also be standardised. From a social perspective this would lead to loss of jobs and higher unemployment rates since automated manufacturing results in more efficient production. However, the output of the company needs to be high enough to justify the capital investment required for automation.

Therefore, to critically examine the role modularity in product design has on the social performance of a supply chain it is clear that there is no obvious answer and certain criteria need to be taken into consideration before reaching an answer. On the one hand modular clusters reduce the unemployment rate of their surrounding areas since the skills learned in one organisation can easily be transferred to another within the same cluster or a similar cluster. So, by learning one skill set a worker is hence eligible to work in more than one organization. Also, the learning time required by the worker to learn more skill sets is hugely reduced. At the same time employees can master different skill sets easier due to the work path simplification, which leads to more efficient employees resulting in reduced worker release and provides the opportunity to work more hours leading to higher incomes and an improved standard of living. On the other hand, modularity is also considered a stepping stone towards reaching automated manufacturing, which results in unemployment due to machines replacing human labour.

So, even though the main incentive for implementing a modular design is based on economic motives to reduce operational cost, certain social aspects of the supply chain are also affected (Lei, 2009). There is quite a fine line where modularity is actually beneficial in terms of the social aspect of a supply chain's performance. If the company is not yet producing at high enough levels to justify automation and if the company chooses to locate its manufacturing processes to a developing country, then this would result in social benefits for that country in terms of job opportunities and skills gained by the workers. Nevertheless, locations that meet such criteria (having low labour cost and skilled labour) become prime locations for companies to outsource their manufacturing processes to. Such locations develop into modular clusters or industrial clusters, which results in more job opportunities, and employees' ability to enhance and develop their skills and standard of living (Nadvi, 2007; Baldwin and Clark, 2000; Thomsen and Pillay, 2012). Table 2.11 presents a summary of the effects of PDM on social supply chain sustainability. Therefore, there are three main criteria that need to be met for PDM to have a positive effect on social performance in supply chain management:

- Production output (automation VS manual labour)
- Country development (high minimum wage VS low minimum wage)
- SC process (labour intensive)

Accordingly, the fourth proposition for this thesis is:

Proposition 4 (P4): PDM improves social wellbeing of supply chain employees.

Table 2.11 Relationship framework between product design modularity and the supply chain's social aspect

Social	1. Employee skills acquired from process modularity 2. Increased Job Opportunities

2.5 Part C: The Conceptual Framework

This framework (Figure 2.13) has been developed through evaluating current literature relating product design modularity with various elements within a supply chain. The integrative literature review allowed for the development of the thematic design of the conceptual framework. Each of the themes was identified based on a string of literature that connects PDM to supply chain processes through certain relationships. The mass customisation theme links PDM to improved economic performance in a supply chain through enhancing a supply chain's ability to offer a varied range of products, enabling a supply chain to offer customised end items (Jacobs, et al., 2011; Danese and Filippini, 2013; Zhang, et al., 2017). Both these relationships present opportunities for the supply chain to increase its profits through increasing product sales. Literature on mass customisation also provided that standardising modules within a product family leads to economies of scale and reducing inventory costs. Both these relationships are linked with reducing a supply chain's operational costs (Lau, Yam and Tang, 2010; Chiu and Okudan, 2014; Zhang, et al., 2017).

The supply chain integration theme collates the literature linking PDM and supply chain integration and classifies the specific areas where PDM enhances supply chain integration. The literature provided that PDM improves integration between supply chain members based on enhanced supplier, manufacturing, design, and information integration (Nepal, Monplaisir and Famuyiwa, 2012; Danese, Romano, and Bartolotti, 2011; Ulku and Schmidt, 2011). The literature here also supported that improved supply chain integration leads to reducing operational costs and increases a supply chain's potential for generating profit (Pero, et al., 2010; Antonio, Richard and Tang, 2009).

The supply chain responsiveness theme was identified through recognising PDM's effect on simplifying production and scheduling operations within a supply chain entity and between supply chain members (Lau, Yam and Tang, 2010; Pero, et al., 2010; Khan and Creazza, 2009). PDM was also linked to reducing production cycle lead time, where both these relationships are seen to increase a supply chain's ability to react to market changes (Jacobs, Vickery and Droge, 2007). Accordingly, improving a supply chain's responsiveness is linked to a supply chains' ability to mitigate risks and capitalise on opportunities arising from changing market demands.

The 6R concept theme was derived from three strings of literature. The first one discussed the adoption of PDM to alter normal manufacturing strategies to become more environmentally conscious through increasing the recycling, reuse, and remanufacture processes within a supply chain (Kristianto and Helo, 2015; Yan and Feng, 2013; Yu et al., 2011). The second string of literature discussed how designers integrate modularity in design to help them in planning a product's life cycle options for upgradability, maintenance and repair, and end of life stages (Beske and Seuring, 2014; Seuring, 2013). The purpose of this was also to increase the recycling, reuse, remanufacture, redesign, and operations within a supply chain by shifting the focus from considering a product's life cycle to considering a module's life cycle instead. The third string of literature discussed the role of PDM in enhancing closed loop supply chain management and reverse logistics through simplifying the recover, recycle, reuse, and remanufacture processes within a supply chain (Aydinliyim and Murthy, 2016). A common element between all three strings of literature was the adoption of PDM in order to reduce a supply chain's dependence on non-renewable natural resources and energy consumption during manufacturing through increasing these six operations: recycle, reuse, reduce, recover, redesign, and remanufacture within a supply chain.

The three dimensional concurrent engineering theme was based on the collation of literature that looked at how PDM affects supply chain design and process design (Fine, Golany and Naseraldin, 2005). PDM was seen to affect supply chain design through allowing for the development of industrial clusters (Navidi and Barrientos, 2004; Lei, 2009; Thomsen and Pillay, 2012). Supply chain entities working on separate modules for the same industry usually operate in the same geographic locations called industrial clusters. The development of industrial clusters is further associated with increasing job opportunities and improving the standard of living for people living in proximity to the clusters. PDM was also seen to affect process design through simplifying the work path for the manufacturing processes (Liao, Tu and Marsillac, 2010). This was in turn linked to enhancing employees' skills development, reducing the amount of product reworks, and overall was linked to increasing employee retention and work stability.

Based on the above themes the researcher developed four propositions, which aim to assess whether the effect of PDM on the supply chain leads to improve economic, environmental, and social performance.

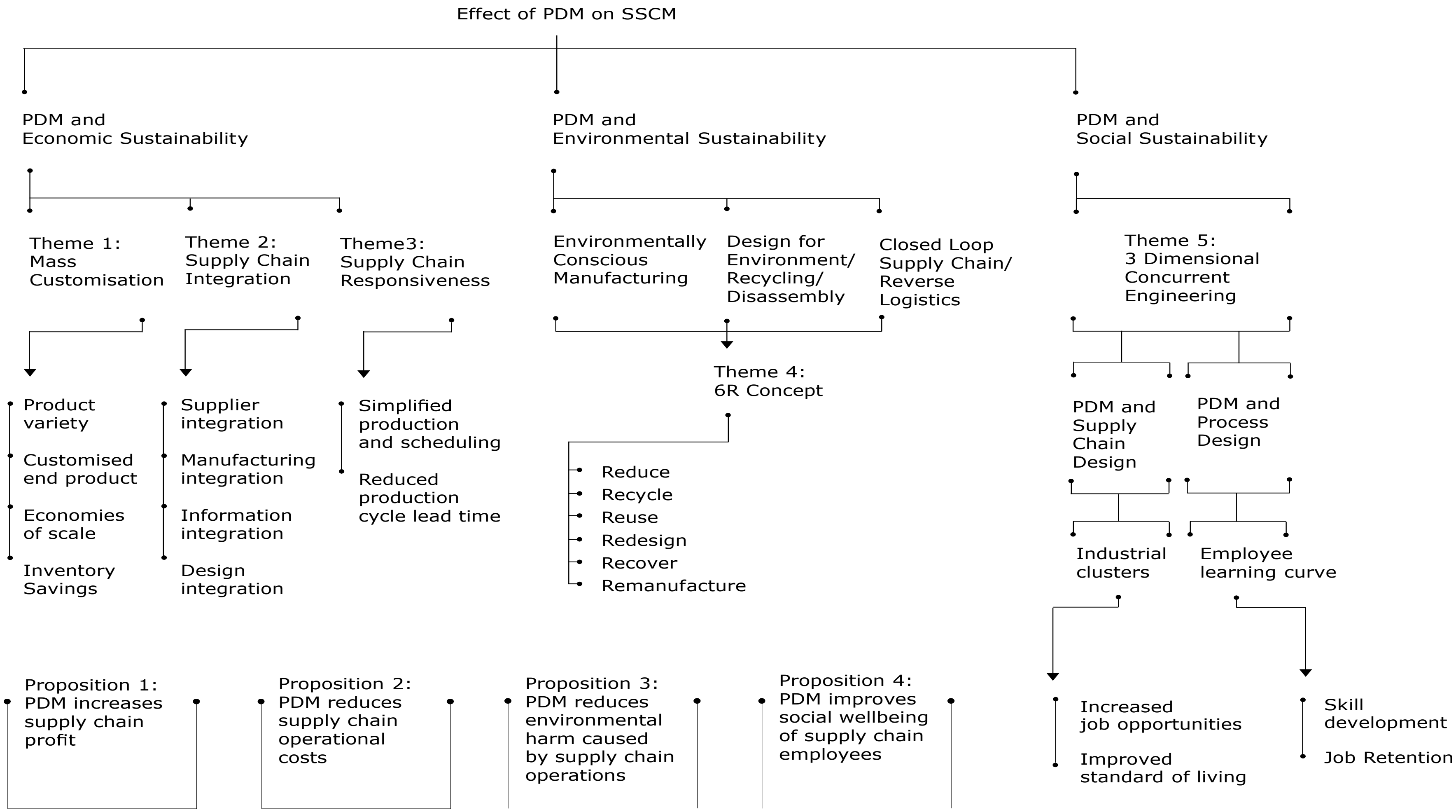


Figure 2.13 PDM and SSCM Conceptual Framework

2.6 Chapter Summary

This chapter was divided into three sections. Section A focused on presenting a critical review of the three separate fields of study (supply chain management, product design modularity and sustainability) within this thesis. This was done with a view to assess each of the fields separately. The findings of the critical review outline the research gaps that this thesis focuses on. The main research gap identified was in the literature on sustainability and sustainable supply chain management where there is agreement that supply chains are still facing a hard time transforming from traditional supply chains into sustainable supply chains. The main reasons for this can be summed up into the following four points.

- Conflicting objectives between economic, environmental and social aspects of sustainability make it quite difficult to develop a solution that improves all three dimensions simultaneously.
- Companies are focusing more on core value adding activities and transferring non value adding activities to suppliers further up the supply chain. This supply chain trend is causing supply chains to become more decentralised furthermore increasing the difficulty in implementing sustainable practices and policies across all supply chain entities.
- Inflexibility of supply chains once they are operational due to long term supply chain decisions such as facility locations, long term supplier agreements being difficult to change.
- Difficulty in assessing sustainability within supply chains due to the absence of a universally agreed upon sustainable supply chain management performance measurement system.

Literature on product design modularity addressed a number of these issues. Modularity in design helps in addressing economic and environmental supply chain issues. Integrating sustainability from the product design stage also helps overcome the problem of supply chain inflexibility. Modularity in design was also found to offer a common language for supply chain companies to have a unified unit that helps them integrate their supply chains. Therefore, it became clear to the researcher the need to identify all supply chain processes affected by modularity in design and further classify the effect modularity in design has on the supply chain into economic, environmental or social.

Section B presented the integrative literature review, which aimed at identifying all the overlapping areas in previous work where modularity in design was seen to have an effect on the economic, environmental or social performance of a supply chain. The purpose of the integrative review was to answer the first question for this thesis which is '*how does PDM affect SSCM?*'. The integrative review lead to the development five main literature themes linking PDM to SSCM. The development of the themes was through combining interrelated supply chain processes. Therefore, each theme is namely a combination of interconnected supply chain processes that are affected by modularity in design.

Section C presented the conceptual framework for this thesis, where all themes and processes are integrated into one framework. Accordingly based on the identified themes, four propositions are introduced (refer to figure 2.13). Testing these propositions would provide an answer to the second question within this thesis which is '*does PDM lead to more sustainable economic, environmental and social supply chain operations?'.*

Therefore, the next chapter will present the research methodology which will be developed based on the conceptual framework identified within this chapter in order to test each of the specific relationships under each of the five themes. The objective of the next chapter is to provide a systematic methodology for testing each of these relationships to be able to assess whether modularity in design had a positive or negative impact on the sustainability of supply chain operations.

Chapter 3 Research Methodology

3.1 Introduction

In the following chapter the research methodology will be presented. The objective of this chapter is to give an overview about research methodology as a process and apply this process on the research questions asked in the introduction chapter to present a methodology for how to answer these questions through systematic means.

The previous chapter (Chapter Two) evaluated the link between PDM and the economic, environmental and social aspects of sustainability from a supply chain perspective. The chapter concluded with the development of five main themes that were identified in the literature linking PDM to the economic, environmental and social aspects of sustainability from a supply chain perspective. The themes were then used in the development of four main propositions that aim to link PDM to enhancements in supply chain operations across the three aspects of sustainability. The themes and propositions are used in this chapter as the main structure for the development of the research framework. Please see Figure (3.1).

This chapter will first begin by presenting the research questions and link them to the themes and propositions developed in Chapter Two. This chapter will then present the research process in the form of five stages, which leads up to the research design developed for answering the research question. For each of the stages the different research choices are analysed and justification for the chosen research path is provided.

The first stage is the research philosophy, which will discuss the researcher's ontological and epistemological perspectives for this research. The second stage will analyse the most suitable approach for this research and provide an analysis of deductive versus inductive versus abductive reasoning. The third stage will discuss and provide justification for the chosen research method. The fourth stage will present the different research strategies available and the chosen research strategy for this dissertation. Finally, the research design and data collection methods are presented. The last section will discuss the ethical considerations for the data collection process. Therefore, the structure for this chapter is as follows:

3.2 Research Questions
3.3 Research Philosophy
3.4 Research Approach

3.2 Research Questions

Ghauri and Grønhaug (2005) discussed research to be composed out of two essential elements. The first element being an objective to increase knowledge, which they further explain suggests that you have a clear purpose that you want to find out. The second element is that in order for the process of increasing knowledge to be considered research, it has to be conducted in a systematic way. Systematic suggests that research is based on logical relationships and not just beliefs. As part of this, the research will involve an explanation of the methods used to collect the data, will argue why the results obtained are meaningful, and will explain any limitations that are associated with them (Saunders, Lewis and Thornhill, 2009). The term methodology refers to the theory of how research should be done (Vandeven and Johnson, 2006). The objective of this chapter is to present the logical relationships between the choices the researcher has made at each stage during the research process. Starting with the research question all the way to the research design and data collection to ascertain that the research will be conducted in a systematic way.

This research aims to identify all areas in a supply chain that are affected by modularity in design and answer whether product design modularity enhances supply chain sustainability. The first question for this thesis 'How does PDM affect SSCM?' The purpose of this question was to identify the economic, environmental, and social implications modularity in design has on supply chain operations. This has been answered through the development of the conceptual framework at the end of Chapter Two. From the literature discussed in Chapter Two, it is understood that to achieve a sustainable supply chain, improvements in the economic, environmental, and social aspects of the supply chain must be accomplished simultaneously in order to improve the overall TBL. Hence the second research question for this thesis, which is 'Does PDM lead to more sustainable supply chain operations?' is divided accordingly:

- How does PDM affect the economic performance of a supply chain?
- How does PDM affect environmental performance of a supply chain?
- How does PDM affect social performance of a supply chain?

In regard to the economic aspect, the integrative literature review conducted in Chapter Two provided three main themes in the literature that link PDM to economic performance of a supply chain: mass customisation, supply chain integration, supply chain responsiveness. These themes are then used as the basis for the development of two propositions linking PDM to economic performance enhancement in a supply chain.

Proposition 1 (P1): PDM can increase supply chain profit.

Proposition 2 (P2): PDM can reduce supply chain operational costs.

The environmental aspect had a singular theme, which is the 6R concept, with literature streams being divided between life cycle assessment, design for environment/recycling, and closed loop supply chain management/reverse logistics. This has led to the development of the third proposition linking PDM to environmental performance enhancement in the supply chain.

Proposition 3 (P3): PDM can reduce environmental harm resulting from supply chain operations.

As for the social aspect, the literature presented the link between PDM and social performance in the supply chain through the concurrent engineering theme. PDM is seen to influence supply chain design through the development of modular clusters. PDM is also seen to affect process design, influencing skills learning curve for employees. This has led to the development of the fourth proposition.

Proposition 4 (P4): PDM improves social wellbeing of supply chain employees.

The themes and propositions development from the literature analysis have been integral in the development of the research framework (Figure 3.1). It has been the aim of the researcher from the beginning to provide a complete picture regarding the integration of PDM and SSCM. The literature analysis provided the basis for the relationship between PDM and each of the aspects of sustainability from a supply chain perspective. The next stage for this dissertation will be to provide empirical evidence as to the practical applicability of PDM in enhancing SSCM. The term empirical means 'evidence drawn from concrete situations' as opposed to arguments developed either from purely theoretical bases or from experiments (Mutch, 2004:74). Where a major gap in previous researches conducted has been the lack of practical initiatives towards the operationalistaion of sustainability in the supply chain, research conducted for this dissertation aims to empirically assess if PDM enhances supply chain sustainability. Another major gap viewed in the literature is a narrow focus, where research usually only considers a singular aspect of sustainability at a time (Brandenburg, et al., 2014; Taticchi, et al., 2013). The research conducted for this dissertation will therefore also aim to provide empirical evidence as to whether PDM enhances sustainability in the supply chain across all three aspects (economic, environmental and social) simultaneously.

The research conducted for this dissertation is applied/explanatory in nature. This is because the objective of the research is to offer PDM as a practical solution towards achieving higher levels of sustainability within a supply chain. Hence, giving the research an applied nature. The research also aims to analyse whether there is a positive relationship between PDM and sustainability through examining relationships between PDM and a supply chain's economic, environmental, and social aspects. The relationships have been previously identified in the literature as presented in Chapter Two, currently there is very limited research answering whether PDM influences overall sustainable performance in a supply chain. Therefore, this research will have an explanatory nature by testing these relationships through an empirical research to identify whether PDM helps achieve improved economic, environmental, and social performance from a supply chain perspective.

This chapter aims to present the methodology followed to obtain the data required to test these relationships.

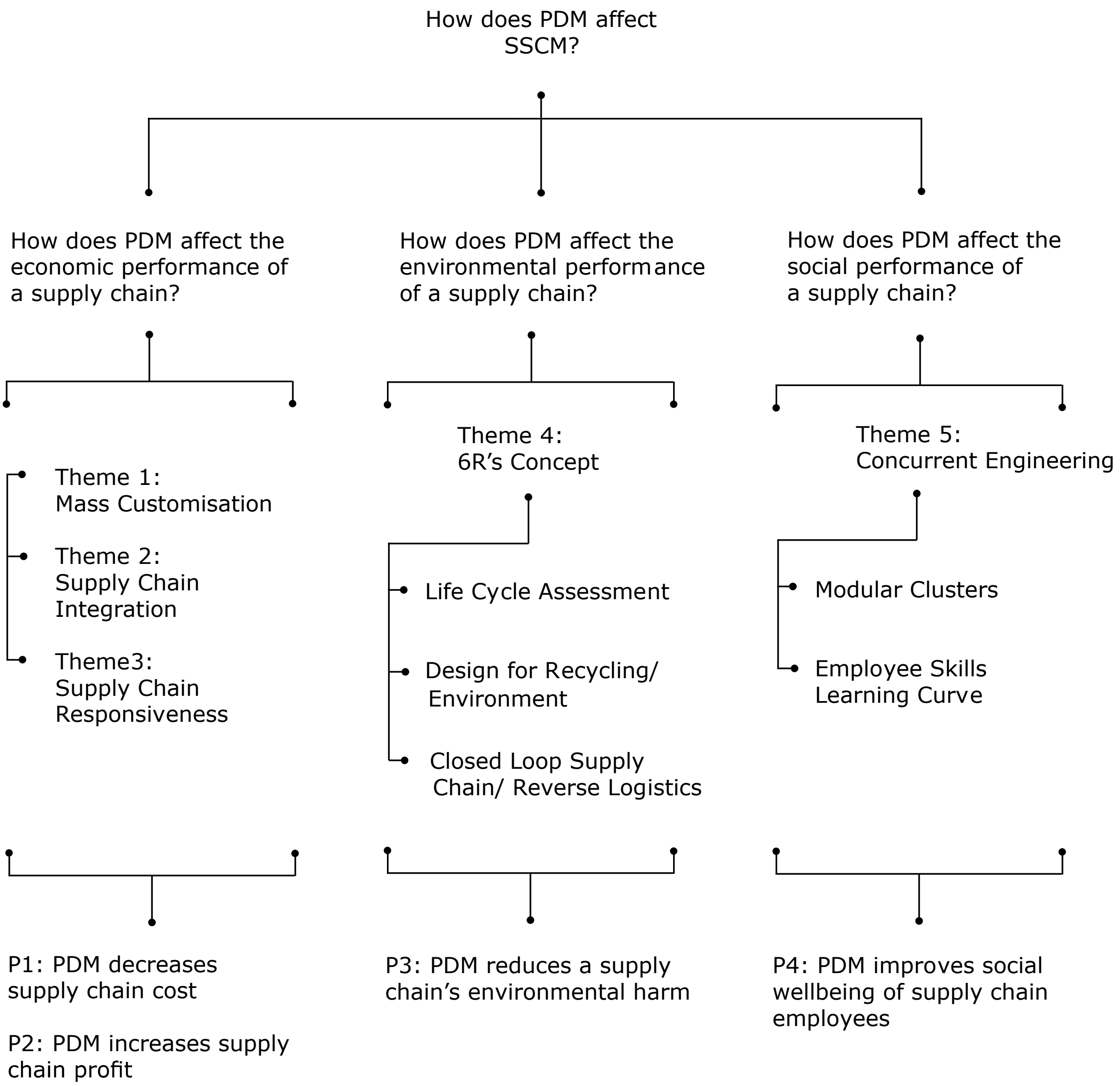


Figure 3.1 Research Framework

3.3 Research Philosophy

Research philosophy is considered the first phase in the research process. This phase focuses on the values of the researcher. Blaikie (2000) presented the research philosophy stage as the foundation of the research process, where the philosophical views of the researcher will influence all the methodological choices to be made at later stages in the research process. Creswell (2009) argued that researchers must think through the philosophical worldview assumptions that they bring to the study. What Creswell recognised as worldviews are more commonly known as research paradigms (Lincoln and Guba, 2000) or as ontology, epistemology and axiology of the research (Crotty, 1998). Ontology is mainly concerned with the researcher's view on reality (Hatch and Cunliffe, 2006). While epistemology is concerned with the researcher's point of view on how knowledge is created (Eriksson and Kovalainen, 2008). Axiology is concerned with the values of the researcher (Saunders, Lewis and Thornhil, 2009). Gill and Johnson (2010) argued that a researcher's pre-understanding of the research question being asked holds answers to the research design the researcher will develop.

There have been numerous classifications and categorisation of research philosophies and paradigms over the years (Saunders et al., 2009; Ritchie and Lewis, 2003). Even though this non-uniformity does present quite a maze to researchers, there seems to be agreements towards the broad concepts (Knox, 2004; Flowers, 2009; Mkansi and Acheampong, 2012). An objective ontological stance is usually accompanied by a positivist epistemological paradigm, where the researcher would view the reality of the world as being independent of any social actors and would only rely on hard facts obtained through natural science to create knowledge. While a subjective ontological stance is usually accompanied by an interpretivist epistemological paradigm, where the researcher views the world as being created through interactions with social actors within it and knowledge can be created through social sciences. These two philosophical stances present the extremes, with many authors being proponents to one or the other while arguing towards the advantages of following a positivist philosophy versus an interpretivist philosophy and vice versa (Morgan, 2007; Kelemen and Rumens, 2012).

A third paradigm is also presented known as pragmatism (Morgan, 2007; Bertilsson, 2004). The pragmatic view takes a different perspective than both the positivist and interpretivist views in that the focus of the researcher is on the research questions asked. Instead of narrowing the scope of the research to an objective or subjective view of reality, the pragmatic view is flexible to use both depending on the research question asked (Kelemen and Rumens, 2012). Tashakkori and Teddlie (1998) argued that it is more appropriate for a researcher to consider the positivism and interpretivism as a continuum rather than opposite positions. In their view one should not be limited to conducting research in one way. Guba and Lincoln (1994) also supported this argument explaining that a top down approach, where a researcher begins through setting one epistemological belief can in turn limit knowledge generation through fixating on a certain approach or certain methods for data collection in the following stages. Sinclair (2011) argued that scientific truths on their own do not provide a clear picture in making judgemental decisions. Sinclair goes on to explain that moral arguments require more than just scientific questioning and are best answered by an interpretivist philosophy accompanied by a more subjective view of knowledge creation.

However, a pragmatic view does pose a risk for the researcher, where the researcher needs to be quite acquainted with both quantitative and qualitative data collection and analysis methods (Knox, 2004; Mkansi and Acheampong, 2012). Morgan (2007) also argued that the actual research process is never as neat as to fit within the positivist or interpretivist views, with the actual research process usually going back and forth between both on a regular basis.

This is also the belief of the researcher, where the researcher will adopt a pragmatic view throughout the research. The research question developed for this dissertation is considered a complex question, which in order to answer was divided into three sub questions. Each sub question aims at relating PDM to one of the aspects of sustainability. It is the researcher's belief that in order to answer such questions following a singular view would limit the knowledge that can be generated and that through viewing the world from both perspectives (as a reality independent from social actors and as social actors shaping reality) simultaneously can provide much richer data to help in answering the questions. This research will view the product design process, supply chain management related processes, and reverse logistics related processes objectively. However, the human element very much affects a number of critical elements within this research from customer's influence to changing product design and customer demand behaviour to the product designers view of the product and the employees building the product. Therefore, this study will also focus on the human element and develop a research design to obtain both objective and subjective data.

3.4 Research Approach

The research approach is dependent on the order of the theory development for a given topic of research. If the research begins with the theory and follows through developing hypotheses and a structured methodology to test these hypotheses this would be considered a deductive approach. An inductive approach, on the other hand, would begin with the data collection and develop the theory as a result of analysing the data (Saudners, Lewis and Thornhill, 2009). The deductive approach will generally follow a positivist/objectivist worldview with an overall aim to be able to test the theory and reach generalisable results. An inductive approach would naturally lend itself to the interpretivist/subjectivist worldview where the focus of the research would be on gathering data from social actors to develop relationships and theories between their interactions and the reality of the world from their perspective (Bryman and Bell, 2015; Saunders, Lewis and Thornhill, 2009).

The third approach, which integrates with the pragmatic view, is the abductive approach. Morgan (2007) explained that the abductive approach is flexible to move back and forth between induction and deduction. Where the researcher can first convert observations into theories and then analyse the theories through action. Or theories can be tested at first and depending on the assessment further theories can be inferred (Bertilsson, 2004). Both options to the reasoning would depend solely on the research question and how the approach fits best in answering the research question and the knowledge development process (Servillo and Schreurs, 2013).

This research will follow an abductive approach to allow the researcher to be able to use both deductive and inductive reasoning. The research originally began through inductive reasoning with a view to develop a theory regarding the effect PDM has on SSCM, which was the first research question. The next stage in the research will follow a more abductive approach in testing this theory through empirically assessing the identified relationships between PDM and the economic, environmental, and social aspects within the supply chain through obtaining both quantitative and qualitative data to best answer the research question.

3.5 Research Method

Newman and Benz (1998) describe quantitative and qualitative approaches as different ends on a continuum. A study would then tend to be more qualitative than quantitative or vice versa. Mixed methods research resides in the middle of this continuum because it incorporates elements of both qualitative and quantitative approaches (Bazeley, 2015).

Qualitative research: is characteristically consistent with an interpretivist philosophy along with an inductive approach to research. Qualitative research's focus is on exploring and understanding individuals or groups within the context of a social or human problem. Research relies on inductively building and analysing data from particulars to general themes based on the researcher's interpretations of meaning from the collected data. The final written report has a flexible structure. Those who choose this form of research usually aim to produce in depth understandings that result in theory development rather than numerical generalisation (Creswell and Creswell, 2017).

Quantitative research: portrays the other end of the research continuum, which focuses on testing of objective theories. This is done by evaluating relationships between specific variables. These variables are measurable, so that numbered data can be analysed using statistical procedures. The final written report has a set structure consisting of introduction, literature and theory, methods, results, and discussion (Creswell, 2009). Quantitative research is consistent with a positivist or realist philosophy and a deductive research approach. The objective here is to be able to generalise and replicate findings through numerical and statistical proof.

This research will incorporate a mixed methods approach to inquiry that combines or associates both qualitative and quantitative forms. It will involve the use of both qualitative and quantitative approaches and the mixing of both approaches within this study. A mixed method approach naturally follows the abductive approach as a logical continuation to the pragmatic philosophy (Cameron, 2011). Thus, it is more than simply collecting and analysing both kinds of data; it also involves the use of both approaches simultaneously so that the overall strength of a study is greater than either qualitative or quantitative research (Creswell and Creswell, 2017).

Johnson et al. (2007:123) defined mixed methods research as ‘the type of research in which a researcher or team of researchers combines elements of qualitative and quantitative research approaches (e.g., use of qualitative and quantitative viewpoints, data collection, analysis, inference techniques) for the purposes of breadth and depth of understanding and corroboration’.

Molina-Azorín and Cameron (2015) outlined four ways in which using mixed methods can benefit business research: preliminary qualitative data can provide a deeper understanding of context to inform context-specific studies; attention to both process and outcome through mixed methods benefit theory-building; study of complex organizations would benefit from analyses that are integrated across micro and macro levels; and use of mixed methods helps to bridge the academic-practitioner divide through enhancing the interpretation and communication of results.

It became clear to the researcher at an early point in the research that the complexity of the research question will require both quantitative and qualitative data. To investigate sustainability within the context of supply chain management, data relating to economic, environmental and social supply chain performance criteria would be required.

For the economic aspect, the data requirements will be mainly to support the propositions P1 and P2. The data to be collected should reflect the effect of PDM on a supply chain’s economic performance. The data will need to focus on the three themes identified in the literature (Figure 3.1). For the economic aspect, data such as sales records, inventory records, purchase orders, production cycle times and production schedules will be required.

This data will mainly be quantitative in nature. However, data regarding customer preferences in product design and manager's operational perspectives will also be required. This data is qualitative in nature and would need to be collected through qualitative methods.

For the environmental aspect, the data requirements will be to support P3. The data to be collected should reflect the effect of PDM on a supply chain's environmental performance. The data will need to provide evidence as to whether PDM enhances the 6R's Concept. Data such as the maintenance and repair operations and any records for recycling and refurbishing would be required. This data is mainly quantitative in nature. However, data regarding the product designer's views on the effect of PDM on life cycle assessment and the integration of PDM in design for recycling/environment will also be required. This data is mainly qualitative in nature and would need to be collected through qualitative methods.

For the social aspect, the data requirements will be to support P4. The data to be collected should reflect the effect of PDM on a supply chain's social performance. The data will need to provide evidence linking PDM to the development of modular clusters and skills development in employees. This data will be part qualitative and part quantitative. The skills development in employees can be obtained through obtaining the opinions of the employees (qualitative) or through obtaining records of line product errors or cycle productions times (quantitative). As for modular clusters the data can also be obtained through official governmental records of the number of companies operating in the same field open in a certain area (quantitative) or through records from employees as to their working history and whether they worked in related fields before in neighbouring companies (qualitative).

3.6 Research Strategy

'Every type of empirical research has an implicit, if not explicit, research strategy, in the most elementary sense, the strategy is the logical sequence that connects the empirical data to a study's initial research questions and, ultimately, to its conclusion' (Gill and Johnson, 2010:144).

For this research a multi case study methodology will be used. Case study research requires the researcher to study a phenomenon without affecting the study subject at all (Bengtsson, 1999). Gerring (2008) discussed some of the major advantages of case study research:

- can be used for both quantitative and qualitative researches.

- usually requires cross-case analysis. Meaning the researcher would have had to conduct several evaluations prior to choosing a case best fit for his/her research. This cross-case analysis provides a more focused research and deeper level of evaluation and analysis.
- is quasi-experimental in nature. This is because the experimental ideal is often better approximated within a small number of cases that are closely related, rather than by a large sample of heterogeneous units.

Bengtsson (1999) identified there are three kinds of case studies: descriptive, explorative and confirmative studies. First, a descriptive study is when a phenomenon is studied to make the description available to others. Second, an explorative study is when we want to study a phenomenon to gain understanding about its nature and the problems related to the particular phenomenon. Finally, a confirmatory study is when we have one or more hypothesis to investigate in the context of the phenomenon we think it is applicable. This research will be based on a confirmative/explorative study as to assess the nature of the relationship between product design modularity and sustainability in supply chain management.

However, the strength of conclusions from the case studies is not very high, and it is claimed that the use of multiple cases yields more robustness to the conclusions from the study (Yin, 1994). Therefore, to overcome this, the researcher opted for using a multi case study strategy. The multi case study strategy enhances the validity of the research and overcomes some of the disadvantages associated with the single case study research (Gerring, 2008; Bengtsson, 1999).

Bengtsson (1999) also discusses that the selection of the cases for multiple case study is categorized into two types of selection. The literal replication means that the cases selected are similar and the predicted results are similar too. The theoretical replication means that the cases are selected based on the assumption that they will produce contradictory results.

For this research the aim is to achieve a literal replication in order to achieve a basis for the relationship between product design and sustainability in supply chain management. According to Robson (1993) the goal is not statistical generalization, but analytical generalisation instead.

The case itself, or what Gill and Johnson (2010) identified as the unit of analysis, will focus on two modules within the same product family with varying degrees of modularity.

Sandelowski (2011) also explained this process as 'casing the research case study', where a point of focus is provided for the research.

One module will be at the modular end, while the other will be at the integral end of the design spectrum. The degree of modularity will be based on Ulrich's (1995) definition of modular design where a module with a one to one relationship between physical and functional attributes is considered more modular than a module with a one to many relationship. Ulrich's definition is considered a prerequisite for the main characteristics of modularity including combinability, transferability, and separability of the components. This definition therefore considers the effect one module has on the entire design of the product.

After the first case study will be carried out comparing the first two modules to each other, the study itself will be repeated on another set of two modules. The researcher will then attempt to analyse the results to obtain analytical generalization. The analysis process will be structured to assess the four propositions that were made at the end of Chapter Two. Through this analysis the researcher can then develop an answer to each of the sub questions, which in turn will answer the main question for this research.

Therefore, the logical path for the research process leading to the research design for this dissertation will follow a pragmatic philosophy that will develop knowledge through answering the research questions following an abductive approach and mixed research methods (Figure 3.2).

Figure 3.2 The Research Process

3.7 Research Design and Data Collection

For this research a multi case study methodology will be used as the main strategy to be supported by interviews and archival research. The interviews are to be conducted at the preliminary stage of the research to assess the availability of the data and the willingness of the firm to cooperate in sharing their data. Once approval is gained from a firm, archival research will be conducted to gain records for the firm's sourcing process, ordering process, stock control process (inventory records), maintenance and repair process; as well as identifying the reports associated with these processes. Finally, a focus on two modules within the firm's product family will be the main case for analysis and comparison to identify how modularity in design can affect the economic, environmental, and social performance of the firm.

The first stage of the research strategy will entail conducting one on one interviews with supply chain personnel in relevant industries (industries known to have modular product design such as automotive or electronic). With a focus on procurement specialists, inventory specialists, production planners, and supply chain managers, because based on the relationships gathered from the literature these positions will be the most suited to have the data required in assessing the relationship between PDM and SSCM. An interview is a purposeful discussion between two or more people (Kahn and Cannell, 1957). The use of interviews will help the researcher to gather valid and reliable data relevant to the proposed research questions and objectives (Saunders, et al., 2009). The interviews are to be semi-structured in nature to give the interviewee an opportunity to elaborate on the nature of operations within their firms yet have a structure to confirm with answering the objectives of the research.

Huberman and Miles (2002) discussed four types of questions used in qualitative interviews depending on the objective of the research:

'Contextual: identifying the form and nature of what exists
Diagnostic: examining the reasons for, or causes of, what exits
Evaluative: appraising the effectiveness of what exists
Strategic: identifying new theories, policies, plans or actions'

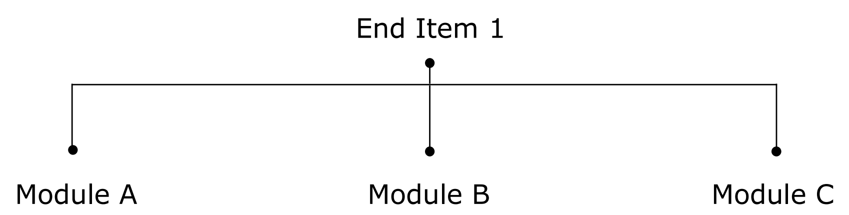
For this research, the questions lie within the evaluative and contextual questions. This research aims to evaluate the effect of PDM on sustainability within a supply chain context. Therefore, the questions aim to evaluate the effectiveness of modularity in design in terms of achieving sustainability through assessing the current operations of the case company.

The objective of these interviews is to:

1. Accurately identify the availability of the data required and the willingness of the company to participate in the research.
2. Gain an understanding of their sourcing process, ordering process, stock control process, maintenance and repair process; as well as identifying the reports associated with these processes; and how modularity plays a role in all of these.
3. Gain an understanding of their process design and production process.

Archival research makes use of administrative records and documents as the principal source of data. Archival research gathers data to answer research questions, which focus upon the past and changes over time to be answered, be they exploratory, descriptive or explanatory (Saunders, et al., 2009). Archival research will be used to gain data regarding the firm's product architecture (list of modules included in each product), ordering records, inventory records, sales records, maintenance and repair operations, returns and recycling, refurbishing records.

The second stage in the research design process will be to develop a multi-case study. The case itself will focus on two modules within the same product family as illustrated in Figure 3.3. Jiao, Simpson and Siddique (2007) discussed that in order to view the effect of modular product design the focus of the research cannot be limited to a single product or a comparison between two products, however the research must encompass a product family. By considering the range of product offerings within a product family the effect of modularity is more significant by viewing the transferability, combinability, and separability of the modules across the range of product offerings within that product family. However, one module will have a more modular design than the other. The degree of modularity will be based on Ulrich's (1995) definition of modular design which he explains the degree of modularity being based on the functionality of the module where a one to one module to function relation presents a more modular design vs. a one to many module to function relation offers a less modular design. Accordingly, a module that is shared or is common between more end items within the same product family can be identified as more modular. The commonality of the module signifies the component's ability to be transferred, combined, and separated within the product family. It would also comply with the definition presented by Ulrich (1995), where a common module in a product family would have a low component to function ratio. This means that since the component has a limited number of functions it can be separated from the end item without affecting overall functionality of the end item and furthermore can be transferred and combined with other end items.



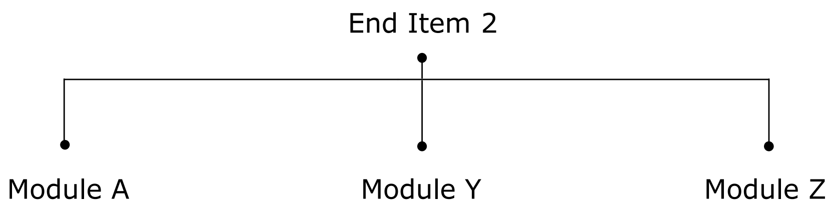


Figure 3.3 Product Architecture with Modules

The objective will be to see how these two modules (for example Module A versus any of the other modules, since Module A is the common module) are shared across the different products within this product family with a view to:

- Understand the procedure in which these modules are reordered or remanufactured to gain an understanding of the economies of scale obtained through quantity discounts, reduced setup costs, inventory pooling, and reduced inventory levels.
- Observe the different product varieties achievable through modular design by obtaining records of the number of end items sharing these same modules.
- Identify whether the modules are outsourced to get a view of the relationship with the supplier. This can also lead to an understanding of how the modular design affects supply chain integration between the supply chain members.
- Observe the modular life cycle of the particular modules taken within the case to record the percentage of returns recycles, refurbishes, reuses.
- Understand the process design required for those particular modules. If there are certain skills required or a particular process, which the workers need to learn and if that skill can be transferred or reused in other industries which can lead to increasing the workers' employability.

3.8 Data Collection

The data collection process will begin as the second stage in the research design process after preliminary interviews with prospective case companies. This stage will begin after finding a case company developing products with a level of modularity in design that would be willing to cooperate with the researcher and agree to participate in the research.

The literature review analysed in Chapter Two presented a set of relationships between PDM and each of the three aspects of sustainability from a supply chain perspective. This section will develop the data collection requirements to test these relationships within the case study research strategy. Therefore, each of the said relationships will be presented separately along with the data required to test each of the relationships. The data collection process is divided into two stages. The first stage will be to identify the case modules (unit of analysis) for comparison. The second stage will be to collect the data required to test the relationship between PDM and the aspects of sustainability through the comparing the effect each of the case modules has on the relationships identified in the literature.

Stage 1: Identifying the case modules (unit of analysis) for comparison

The research design developed in this dissertation will follow a case study strategy. The study will compare between two modules within the same product family. The modules themselves will be chosen based on the element of commonality, where one module will be shared and common between many end items and the second module will be shared across a limited number of end items. The study will be comparative in nature focusing on identifying the difference in operations between the effects Module A (M1) (which will be considered more modular, being shared across more end items) has on the supply chain in comparison to Module B (M2) (which will be considered less modular, being shared across a limited number of end items).

Therefore, after reaching a company willing to agree to take part in the study, the first stage in the development of the case study will be to identify the modules for comparison. The data required for this stage is the bill of material (BOM) for a product family currently being produced and sold by the company. This will generally be available in the company's database and considered as archival data of secondary nature. The BOM of a product family will show the number of end items offered by the company. The BOM will also present the modules and components required for the assembly of each end item displaying the common element of the modules, where it will be easy to assess which modules are more commonly shared across the end items within that product family.

After identifying a few probable modules that can be used as the case modules, an interview will be conducted with the product design engineer in charge of the design process for products within that product family. The interview will focus on developing a deeper understanding of the design process through semi-structured questions to give the interviewee the freedom to express his/her experience in the product design process. The interview will also provide further validation for the choice of the two case modules for comparison. The interview will also focus on identifying if there is a relationship between product and process design, and to what degree are both integrated with supply chain design.

Interview questions for the product design engineer:

- Can you please describe in as much detail as possible the product design process for (the end item products in the product family)?
- From your experience, which two modules would you choose in order to portray the effect modularity in design has on supply chain operations? Why these two modules?
- From your experience, what is the relationship between product design, process design and supply chain design?

Stage 2: The comparison process

After identifying the two case modules for comparison the next stage will be to compare between both modules across each of the relationships identified in the literature. The next part of the data collection process is divided into three sections. Each section will discuss the data required to test each of the relationships identified in the literature across the economic, environmental, and social aspects respectively.

3.8.1 PDM and the economic supply chain aspect

Table 3.1 below provides the full list of relationships between PDM and the economic aspect of supply chain management.

Table 3.1 Effect of PDM on a supply chain's economic sustainability

Economic	Theme 1: Mass Customisation	1. Increase in sales due to product variety based on modular design. 2. Increase in sales due to the availability of a customized end product based on modular design. 3. The ability to pool modules used for different products which leads to inventory cost savings. 4. Mass production or mass purchase of modules, which leads to savings due to economies of scale.
	Theme 2: Supply Chain Integration	1. Supplier Integration 2. Manufacturing Integration 3. Information Integration 4. Design Integration
	Theme 3: Supply Chain Responsiveness	1. Simplified production and scheduling 2. Reduced production lead time

3.8.1.1 Theme 1: Mass Customisation

- Product Variety

The first relationship presented in the literature focused on the relation between PDM and product variety where modularity in design can lead to increase in the range of product offerings to meet more customer demand (Zhang, et al., 2017; Chiu and Okudan, 2014; Danese and Filippini, 2013). Through this relationship there is an implicit understanding that modularity in design would lead to an increase in sales affecting the profit of the company positively. The data required for this relationship will be mainly secondary in nature. The data will most likely be available in the case company's database. Therefore, the data requirements to test this relationship will be mainly archival data.

- The bill of material (BOM) for a product family, which would show the number of end items offered by the company. The BOM will also present the two case modules (M1, M2) and the number of end items M1 VS M2 is a part of.

- Sales records for the product family for a minimum period of 12 months to be able to conduct the comparative study to assess the effect each of the two case modules had on the sales of the end items respectively.

- Customised End Product

Mass customisation is also directly linked to PDM in the literature through arguments that it is easier to customise a product by changing certain modules instead of changing the complete product design with every new customer order (Pero, et al., 2010; Zhang, Huang and Rungtusnatham, 2008; Ro, Liker and Fixson, 2007). Mass customisation can also be linked to improved sales and enhancing profit from one perspective as well as reducing operational cost through production economies of scale from another perspective (Nepal, Monplaisir and Famuyiwa, 2012; Bush, Tiwana, and Rai, 2010). The economies of scale relationship, however, will be discussed as a separate relationship. Therefore, for this relationship, the focus is on linking mass customisation to company sales and identifying if there is a positive relationship between them and whether this positive effect is caused by PDM. The data requirements for this relationship will be dependent on interviews with the case company's supply chain manager, therefore the data will be considered primary data. The supply chain manager is considered the most appropriate candidate to answer the questions required at this stage due to his/her understanding of the concepts in question, as well as having the authority to provide the data required and offer practical insights from previous experience. The interview questions asked will focus on identifying whether the company offers customized product offerings or not. If yes, then archival data can be obtained with records of sales of end items that have been customised displaying a relationship between the case modules and their effect on the sales levels. Therefore, if available, the archival data will be of a secondary nature. If not, however, the data will be gathered through interview questions to the supply chain manager focusing on interpreting his/her experience regarding the relationship between PDM, mass customisation and sales.

- Interview questions:
    - Does your company provide an option to customise end products?
    - From your experience how would you describe the relationship between PDM and mass customisation?
    - If PDM can be considered a main driver for mass customisation, then would you consider there being a relationship between PDM, mass customisation and sales levels?

- Inventory Cost Saving

Inventory is considerably one of the major costs in any supply chain (Brun and Zorzini, 2009). PDM allows for modules to be shared across different end items within the same product family (Zhang, et al., 2017). In other words, instead of requiring separate inventory for each end item and separate safety stock for each stock-keeping unit (SKU) in the inventory, modularity in design allows for inventory that is shared across different end items to be pooled together. The pooling effect would then lead to lower inventory holdings average per end item, which would lead to lower inventory costs (Lau, Yam and Tang, 2010; Brun and Zorzini, 2009; Zhang, Huang and Rungtusnatham, 2008; Jacobs, Vickery and Droge, 2007). The data required for this relationship will be mainly secondary in nature. The data will most likely be available in the case company's database and records. Therefore, the data requirements to test this relationship will be mainly archival data.

  - The BOM for the product family to identify the number of end items each module is a part of.
  - Inventory records of M1 VS M2 for a minimum period of 12 months. The total inventory of M1 will then be divided by the total number of end items M1 is a part of in order to calculate the average amount of inventory held of M1 per end item. The same process will then be repeated for M2 and a comparison between both averages can be conducted.

- Economies of Scale

PDM focuses on the development of modules that can easily be shared across different end items within the same product family. If the company produces its own modules this would lead to economies of scale in the production process leading to reducing overhead costs (Chiu and Okudan, 2014; Danese and Filippini, 2013; Nepal, Monplaisir and Famuyiwa, 2012). If the company purchases the modules from suppliers this would also lead to economies of scale since the module is shared across a range of end items (Doran, 2003). This would lead to the quantities purchased from the same module to increase usually leading to quantity discounts from suppliers. The data required for this relationship will be mainly secondary in nature. The data will most likely be available in the case company's database and records. Therefore, the data requirements to test this relationship will be mainly archival data.

- Purchase orders for M1 and M2 for a minimum period of 12 months. A comparison between the amounts ordered for M1 VS M2 will be conducted as well as a comparison between the unit prices of each.

3.8.1.2 Theme 2: Supply Chain Integration

- Supplier Integration

PDM allows companies to focus on their core competencies through dividing the end product into a set of modules, which can be easily outsourced. The process of outsourcing certain modules to upper tier suppliers in the supply chain requires close coordination between both supply chain members (Danese, Romano, and Bartolotti, 2011; Ulku and Schmidt, 2011). The advantages of the outsourcing process itself come from the opportunities the original equipment manufacturer (OEM) will have with the resources that are not tied up in the manufacturing of the outsourced module (Doran, 2003). The data required for this relationship will be gathered through semi-structured interviews with the supply chain manager of the case company. Therefore, the data will be primary in nature.

- Interview questions
    - How does PDM affect your make or buy decision?
    - Would you consider PDM advantageous for your company in focusing on its core competency? Why?
    - What is the nature of agreements you currently have with suppliers for the M1 and M2 modules; T1 and T2 modules?

- Manufacturing Integration

PDM requires companies to develop integrated production schedules (Jacobs, Vickery and Droge, 2007; Gershenson, Prasad and Zhang, 2004). The manufacturing of the end item as a process is developed through different stages at separate suppliers in the supply chain, which all require to work according to the same schedule for the manufacturing process to be complete. This process necessitates companies to share their production schedules together for an integrated and seamless manufacturing operation. This is required to achieve service levels promised to the customer and to reduce out of stock costs. The data required for this relationship will be gathered through semi-structured interviews with the supply chain manager of the case company. Therefore, the data will be primary in nature.

- Interview questions
    - How do you integrate your manufacturing process with your suppliers? What is the role of PDM in this process?
    - Do you share your yearly production schedule with your suppliers? Is this in part to achieve synchronised production with your module suppliers?
    - How often are there changes made to the yearly production schedule? Does modularity in design allow for such changes to be more accepted by your suppliers?
    - What are the cut off dates for changes on orders for M1 and M2; T1 and T2?

- Information Integration

PDM allows companies in the same supply chain to have a common language for communication. In this case the module itself becomes the common element where any company in the supply chain can identify (Doran, et al., 2007). This leads to easily integrating databases of different companies in the same supply chain using the same module name. These databases are usually uploaded on enterprise resource planning (ERP) systems, allowing for orders to be automated (Jacobs, Vickery and Droge, 2007). This reduces ordering cost in general and problems associated with the ordering process. The data required for this relationship will be gathered through semi-structured interviews with the supply chain manager of the case company. Therefore, the data will be primary in nature.

- Interview questions
    - What kind of effect would you say PDM has on information integration? Why?
    - Do you currently have an ERP system that is integrated with your suppliers? How would you say this affects your ordering process, production schedule and inventory control?

- Design Integration

PDM also requires a high level of integration between suppliers and the OEM for the development of new products (Voordijk, Meijboom and Haan, 2006;

Lau and Yam, 2005; Doran and Roome, 2005; Huang, Zhang and Liang, 2005; Mikkola and Gassmann, 2003; Doran, 2003). Product design becomes a collaborative process between the OEM and the suppliers to develop the new design, however, PDM provides a basis for communication. Where old modules can still be used in the new design or slight changes can be made to previous modules achieving new designs. This reduces the overall cost of new product design. This is due to PDM allowing for numerous variations of products to be developed through changes to a number of modules without requiring a complete change of the entire product design (Jiao, Simpson and Siddique, 2007). The data required for this relationship will be gathered through semi-structured interviews with the product design engineer of the case company. Therefore, the data will be primary in nature.

- Interview questions
  - ❖ How often are product designs changed within this product family? What is the effect of PDM on this process?
  - ❖ How often are new products introduced within this product family? What is the effect of PDM on this process?
  - ❖ How often are modules from old designs integrated into the new designs? Can you provide examples?

3.8.1.3 Theme 3: Supply Chain Responsiveness

- Simplified Production and Scheduling

PDM can help simplify the production and scheduling process through:

1. Reducing the overall number of suppliers (Danese and Filippini, 2013; Doran, et al., 2007; Doran, 2003)
2. Reducing the number of components per end item (Lau, Yam and Tang, 2010; Pero, et al., 2010; Khan and Creazza, 2009; Jose and Tollenaere, 2005).
3. Counterbalancing forecasting errors through the inventory risk pooling effect (Pero, et al., 2010; Khan and Creazza, 2009; Khan, Christopher and Creazza, 2012).

A focal characteristic of modularity is that end items would share modules. Instead of every end item requiring separate inventory, which either needs to be produced or outsourced for every component, PDM reduces the number of components managed in a product family. The data required for this relationship will be mainly secondary in nature. The data will most likely be available in the case company's database and records. Therefore, the data requirements to test this relationship will be mainly archival data.

- The BOM for the end items, which share M1 and M2 to obtain the total number of modules for the end items sharing M1 and M2. Calculate the average number of modules per end item for the group of end items sharing M1 VS the average number of modules per end item for the group of end items sharing M2.

- Reduced Production Cycle Lead Time

PDM can have a direct effect on the process design of a product. Through having standardised modules in production or in assembly this should make the process design for the end items more efficient. The standardisation process in the manufacturing or assembly of the modules can allow for opportunities of automation as well as more efficient employees able to provide higher production volumes due to decreased production cycle lead times (Danese and Filippini, 2013; Lau, Yam and Tang, 2007 a; Lau, Yam and Tang, 2007 b; Ro, Liker and Fixson, 2007; Fixson, 2005). The data will most likely be available in the case company's database and records. Therefore, the data requirements to test this relationship will be mainly archival data.

- The data required for this relationship will be the production man minutes for each end item that shares either M1 or M2. A calculation of the average man minutes required for the production of end items sharing M1 VS the average man minutes required for the production of end items sharing M2 can be conducted.

3.8.2 PDM and the environmental supply chain aspect

The relationship between PDM and environmental aspect of supply chain management focused on a main theme in the literature. This is presented as the fourth theme titled the 6R concept through the literature analysis conducted in chapter two of the literature review. This is due to the literature revolving around the effect modularity in design has on the supply chain's ability to manage its reuse, recycle, recover, reduce, redesign and remanufacture processes. PDM is seen to have a positive effect on these six processes, which leads to enhancing the environmental position of a supply chain. This is due the supply chain requiring less material for production and reducing the energy requirements for product development. The literature provided this relationship across three main points. The first point being the options PDM provides for environmentally conscious manufacturing (ECM) where modularity is seen as a key element in design for the environment (DFE) and design for recycling (DFR) (Kristianto and Helo, 2015; Yan and Feng, 2013; Yu, et al., 2011). The second point discussed how PDM is seen to influence the 6R concept through improving a product's life cycle. Where a product's life cycle can be further elongated through modularity by replacing certain modules instead of replacing the entire product (Beske and Seuring, 2014; Seuring, 2013; Yu, et al., 2011; Umeda, et al., 2008). The third point discussed in the literature focused on how modularity in design can lead to closing the loop in supply chain management and improving reverse logistics operations (Aydinliyim and Murthy, 2016; Bask, et al., 2013; Seuring, 2013; Taticchi, Tonelli and Pasqualino, 2013).

Table 3.2 below provides the full list of relationships between PDM and the environmental aspect of supply chain management.

Table 3.2 Effect of PDM on a supply chain's environmental sustainability

Environmental	Theme 4: 6R Concept	1. DFE/DFR/ECM 2. LCA 3. CLSC/RL

3.8.2.1 Theme 4: 6R Concept

- DFE/DFR/ECM

PDM is seen as a design strategy, which can be used to enhance environmentally conscious manufacturing (Gu and Sosale, 1999; Ilgin and Gupta, 2010). This is mainly due to modularity being a main element in DFE and DFR (Yan and Feng, 2013; Jayal, et al., 2010). Through environmentally conscious manufacturing, DFE and DFR, PDM can then be further linked to improving a supply chain's reuse, recycle, recover, reduce, redesign and remanufacture processes. This generally leads to supply chains requiring less material for production and reducing the energy requirements for product development. The data requirements for this relationship will be gathered through semi-structured interviews with the case company's product design engineer. As well as any records available in the case company's database relating to its reuse, recycle, recover, reduce, redesign and remanufacture processes. Accordingly, a mix between primary and secondary data will be required.

    - Interview questions

- Do you consider PDM as a design strategy for ECM? If so, how can PDM enhance ECM?
- Have there been cases where you changed suppliers of module designs to achieve a greener product?
- Do you link between PDM, reducing the number of components in products, and reducing the amount of material required in production?
- Specific questions related to M1 and M2, T1 and T2?

- Life Cycle Assessment

PDM is one of the main considerations when developing a product's life cycle assessment (LCA) (Qian and Zhang, 2009). LCA is a design methodology where a designer develops a life cycle scenario for the product by assigning life cycle options, such as maintenance, upgrading, recycling, and reuse for different stages through a product's life cycle (Umeda, et al., 2008). Modularity in design is seen as a main contributor to enhancing all of these processes. Maintenance becomes easier where components can be separated and changed without affecting the overall functionality of the product (Yu, et al., 2011). The same argument can be developed for upgradability. Where products can be upgraded through changing outdated modules with new ones without requiring replacing the entire product (Beske and Seuring, 2014). The data requirements for this relationship will be gathered through semi-structured interviews with the case company's product design engineer. As well as any records available in the case company's database relating to its reuse, recycle, recover, reduce, redesign and remanufacture processes. Therefore, a mix between primary and secondary data will be required.

- Interview questions
  - What is the effect that PDM has on the life cycle assessment for the end items that share M1 and end items that share M2?
  - What is the effect that PDM has on the maintenance and repair operations for end items that share M1 and end items that share M2?
  - What is the effect that PDM has on the life expectancy of end items sharing M1 and end items that share M2?
  - What is the effect that PDM has on the upgradability of end items that share M1 and end items that share M2?

- ❖ Has there been a shift in focus from a product life cycle focus to a module life cycle focus within your company?

- Closed Loop Supply Chain /Reverse Logistics

PDM is also acknowledged to increasing opportunities for supply chains to close the loop through integrating forward and reverse material flows (Krikke, et al., 2003). The ability to break down a product into specific components without affecting the overall functionality of the end item allows for many of these components to be reused or refurbished. This means that after the module has gone through the normal forward flow in the supply chain, it returns through reverse flow and can then be refurbished or remanufactured as part of a similar or the same product type closing the supply chain (Bask, et al., 2013; Seuring, 2013). The data requirements for this relationship will be gathered through semi-structured interviews with the case company's supply chain manager. As well as any records available in the case company's database relating to its reuse, recycle, recover, reduce, redesign and remanufacture processes. Hence, a mix between primary and secondary data will be required.

- o Interview questions
  - ❖ How do you generally manage your returns?
  - ❖ What kind of after sale services do you offer?
  - ❖ What is the effect that PDM has on your reverse logistics operations?
  - ❖ Does PDM help you achieve a closed loop in your supply chain for end items that share M1 and end items that share M2?

For all three points discussed, archival data in the form of records of the case company's maintenance and repair operations (MRO) for the end items which share M1 as well as the MRO records for the end items which share M2 will be required. These records will be used to calculate the percentages for reuse, recycle, recover, reduce, redesign and remanufacture for each of M1 and M2.

3.8.3 PDM and the social supply chain aspect

Even though the literature did not provide a direct link between PDM and the social supply chain aspect, it did however provide a link between PDM, process design and supply chain design. The integration of product design with process design and supply chain design is more commonly identified as three-dimensional concurrent engineering (Fixson, 2005; Taticchi, 2013; Fine 1998; Rungtusanatham and Forza, 2004). PDM is seen to influence the development of more modular process design, where the design process is segmented following the same structure as the modules production (Fixson, 2005). The segmentation of the process design is further linked to the skills development of the workers. Therefore, the main stakeholders in the development of this relationship will be the line workers. The second aspect of concurrent engineering is the effect product design has on supply chain design (Rungtusanatham and Forza, 2004). PDM allows supply chain members to focus their resources on their core competencies shifting non-core processes to upstream members in their supply chains (Doran et al., 2007, Ro et al., 2007). This has led to the development of modular supply chain clusters (Baldwin and Clark, 2000). Where supply chain members dependent on each other's modules generally operate within the same regions in order to reduce associated logistics costs and also due to the availability of skilled work force within that region (Baldwin and Clark, 2000).

Table 3.3 below provides the full list of relationships between PDM and the social aspect of supply chain management.

Table 3.3 Effect of PDM on a supply chain's social sustainability

Social	Theme 5: Three Dimensional Concurrent Engineering	1.Employee skills acquired from process modularity 2.Increased Job Opportunities

3.8.3.1 Theme 5: Three Dimensional Concurrent Engineering

- Modular Clusters (increased job opportunities)

PDM allows supply chain members to focus on their core competencies and outsource all non-core processes to upstream supply chain members (Doran et al., 2007, Ro et al., 2007). This creates a level of dependency between supply chain members leading to what is known as modular clusters (Baldwin and Clark, 2000). Where dependent companies operating in the same field usually open their facilities in close proximity to each other. The main reasons for this is the availability of a skilled work force and reducing associated logistical costs. Modular clusters are generally associated for increasing job opportunities in their surrounding geographical locations. This would mean increasing income and living standards of workers in such clusters (Thomsen and Pillay, 2012). The data required for this relationship will be gathered through semi-structured interviews with the supply chain manager of the case company. Therefore, the data will be primary in nature.

- Interview questions
  - Has PDM helped in the development of modular clusters in your area?
  - Do you consider that there is a relationship between PDM and the number of facilities you have and the number of employees you hired and their standard of living?

- Employee Learning Curve (simplified work path)

PDM leads to a more modular process design, which is developed according to the modular structure of the product. The process itself becomes more structured with a simplified work path (Gershenson, Prasad and Zhang, 2004). This leads to employees being able to acquire the skill sets of more than one process. It also leads to lower errors and reworks in the production cycle (Jacobs, et al., 2007). The data required for this relationship will be gathered through semi-structured interviews with the Product Design Engineer of the case company. Therefore, the data will be primary in nature.

- Interview questions
  - Do you think PDM has an effect on employee learning curve?
  - How does the relationship between product and process design affect the skill set requirements for the line workers?

It was also deemed important to get insight from the line workers regarding their experience in dealing with the assembly process of modular products, since they are the focal stake holder regarding the effect of PDM on the social aspect of sustainability in supply chain management. Therefore, a focus group interview will also be conducted with the line workers. The main aim of focus group interviews is to understand, and provide explanation for the meanings, beliefs and cultures, which affect feelings, attitudes and behaviours of individuals (Rabiee, 2004). Thomas, et al. (1995) defined focus group interviews as 'a technique involving the use of in-depth group interviews in which participants are selected because they are a purposive, although not necessarily representative, sampling of a specific population, this group being 'focused' on a given topic'. It is ideally suited for exploring complexity within the context of lived experience and encourages the participants to engage positively with the process of research (Rabiee, 2004). Richardson and Rabiee (2001) discussed that participants in this type of research are selected based on their knowledge of the topic, or that they are in some way affected by the topic in question. So, even though the line workers might not know much about modularity in product design, it is assumed that they are affected by it through PDM's effect on process design. It is also important in order to present a complete picture to gain the perspectives of both the employers and employees. Therefore, the focus will be to identify:

- ❖ Their employment history to assess a pattern of work in related industries in related areas to give evidence to the presence of modular clusters (This question is divided into part relating to the nature of work and part relating to the location of the job).
- ❖ Their opinions on working on the development of modular products versus integral products in terms of the learning environment in one versus the other.
- ❖ On site trainings offered by the case company related to the production of products that share M1 and products that share M2.

Focus group questions:

Question 1: Please provide your employment history in the company in number of years and months?
Question 2: Please provide your total employment history working in a related assembly operation?
Question 3: Please state in yes or no response if your previous employment history was also in an industrial zone?
Question 4: How many training sessions has each of you received from the case company?
Question 5: Have these trainings assisted you in increasing your knowledge and skill set? (Yes/No)
Question 6: Do you think that the skill sets you have gained from working in the case company will assist you in further developing your future career? (Yes/No) (Why?)
Question 7: Which do you consider better to work on, products with modular components (M1, T1) or products with integral components (M2, T2)? (Why?)
Question 8: Do you consider that working in this industry has improved your standard of living? (Yes/No) (Why?)

3.9 Research Ethics

It was identified from the literature review that the nature of the data required to assess the effect of PDM on the aspects of sustainability within a supply chain would be of a sensitive nature. Data such as inventory records, purchase records, and supply chain partnerships, which are considered highly sensitive to the competitive position of the company would be required to give evidence towards how PDM affects SSCM. The most difficult part of this research was to obtain approval from a case company to provide the data required for the analysis due to the data's sensitive nature. The researcher focused on contacting companies that can be considered OEM's to be able to see the effect of modularity on supply chain design and its effect on supply chain integration where the OEM can be considered the focal point where the modules are gathered for final assembly operation and the output is a finalised end item. The researcher also focused on contacting companies where modularity in design is common practice such as automotive companies and electronic appliance companies. Overall the researcher attempted to contact twelve companies, five in the automotive field and seven in the electronics appliances field. An appointment and company visit were arranged with all twelve companies. Three of the visits were with the companies' operations manager, five of the visits were with the companies' supply chain manager, and four of the visits were with the companies' chief executive officer. Preparations for each visit included copies of the information sheet (Appendix II) in English and translated in Arabic, copies of organisational consent forms (Appendix III), and copies of personal consent forms (Appendix IV). All companies were clearly notified from the beginning that all data shared would be considered confidential and that they would have the freedom to withdraw any or all parts of the data at any point in time. From the twelve mentioned companies, only one company agreed to participate in the research. Therefore, any data obtained from the interviews conducted during the visits with the other eleven companies were not included as part of this research. The main decision for refusal was generally due to the nature and sensitivity of the data required. Three of the companies agreed in the beginning then withdrew their consent shortly after agreeing after reviewing the data requirements.

The company's chief executive officer signed the agreement on the 3rd of November 2016. The data itself would be stored in a password-protected folder on the researcher's laptop as well as backed up on a password-protected flash drive owned by the researcher. The interviews were conducted at the company's production facilities in each of the respective interviewee's office. The researcher was offered the opportunity to have a tour within the production facility as well as observe the manufacturing operations while at the facility. All interviews were recorded in notes by the researcher and later transferred to word files within the password-protected folder. Data from the company's database records was obtained from the procurement department and the planning department through the authority of the supply chain manager. Table 3.4 provides the interview schedule.

The focus group interview was conducted during the line worker's break. The interview questions were translated and asked in Arabic. The answers were also in Arabic and translated by the researcher to English.

Table 3.4 Interview Schedule

Date	Position
3/11/2016	Chief Executive Officer
10/11/2016	Supply Chain Manager
17/11/2016	Supply Chain Manager
20/11/2016	Product Design Engineer
25/11/2016	Supply Chain Manager
4/12/2016	Product Design Engineer

Accordingly, all research conducted within this dissertation complied and conformed to the ethical regulation of the University of Huddersfield. An Organisational consent form was obtained from the case company, as well as personal consent forms from the chief executive officer of the company, supply chain manager, product design engineer, and all employees within the focus group study. Through the negotiations with the case company a condition of confidentiality was agreed upon, where the researcher will not mention the name of the company, and all module names will be encoded for the purpose of this research. It was also agreed that the case company has the right to withdraw their consent and the information provided at any stage within the research.

3.10 Chapter Summary

The previous chapter discussed the research design for this thesis. It presented the researcher's logic and justification for answering the research question through systematic means. The researcher opted for a pragmatic philosophy with abductive reasoning to provide an answer combining both quantitative and qualitative data elements through a mixed approach. The researcher also chose a case study research strategy with the unit of analysis for the case as the module. The focus of the case study is on the depth and quality of the data required to provide justification for the multiple relationships identified under the 5 main themes identified within the literature. The logic for the case study will be to build a comparison between two modules where each module would have a different degree of modularity. This comparison will focus on specific supply chain processes and observe the performance of the supply chain within that particular process for the both modules. The module that provides improved performance for the supply chain process would then provide justification towards whether modularity or integrality in product design leads to a more sustainable supply chain. The same case study strategy will then be repeated again for two different modules also with differing degrees of modularity in order to achieve analytical generalisation and overcome some of the limitations of the case study strategy. The chapter also discussed the appropriate data required to answer the research question and the appropriate data collection method for each kind of data according to which supply chain processes this data will relate to. The next chapter will present the data findings as obtained from the company that agreed to participate in the research.

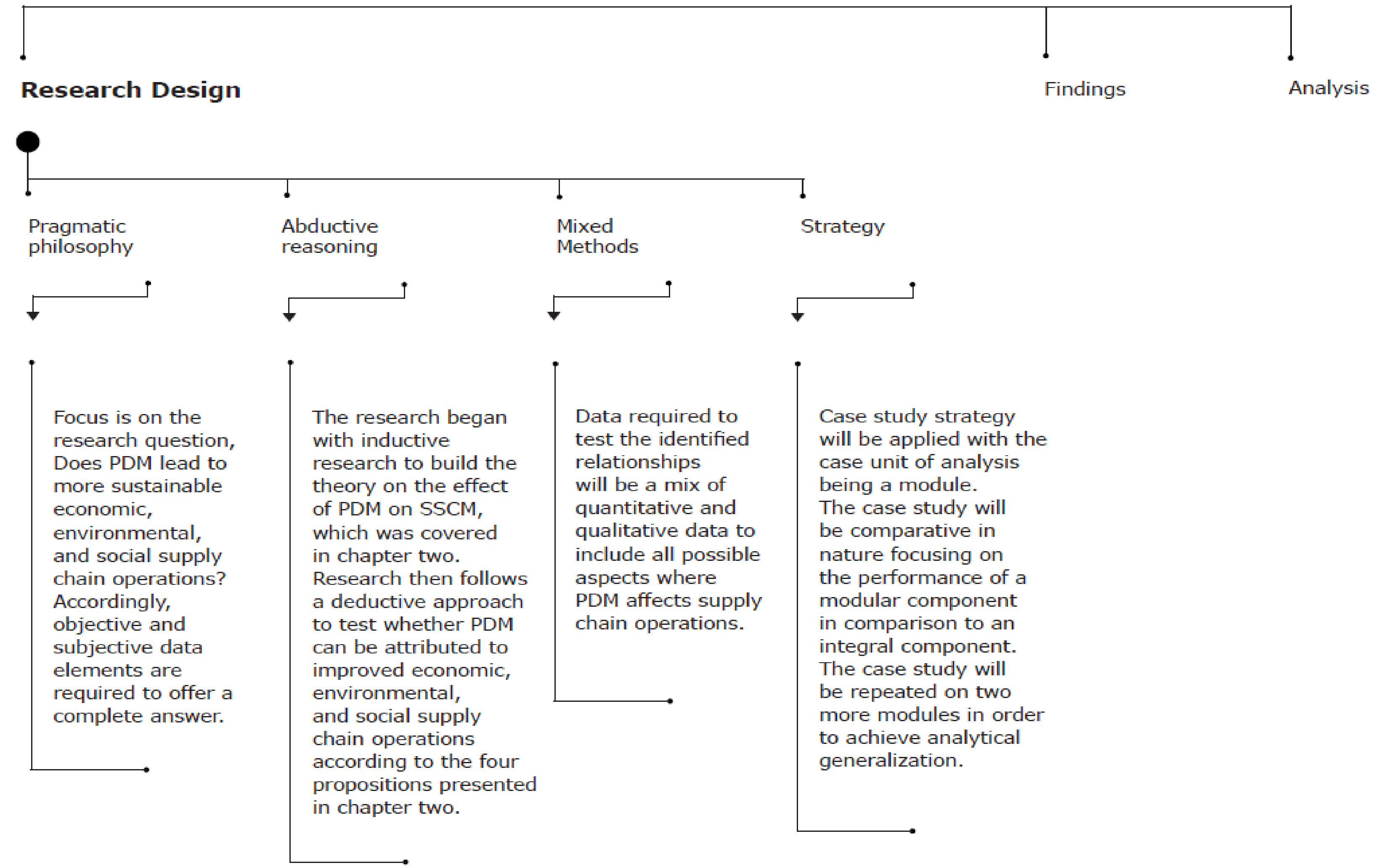


Figure 3.4 Methodology Chapter Summary

Chapter 4 Findings

4.1 Introduction

In this chapter the data collected will be presented and analysed to assess whether there is evidence to support the propositions made in Chapter Two. The chapter will follow the research design scheme presented in sections 3.7 and 3.8 in Chapter Three. This chapter will be divided into six main sections. The first section will present the case company providing the data. The second section will discuss how the modules (unit of analysis) for each of the two cases were chosen. The following sections will aim to answer one of the main sub-questions presented in Chapter One. Each of these sections will first provide the relationships as identified in the literature review conducted in Chapter Two and then present the data required for the analysis of that particular relationship. This will then be followed by the actual analysis, which will be conducted for both cases within this study. Therefore, the sections in this chapter are:

4.2 The case company
4.3 Identifying the case modules (unit of analysis)
4.4 The effect of PDM on the economic performance of a supply chain
4.5 The effect of PDM on the environmental performance of a supply chain
4.6 The effect of PDM on the social performance of a supply chain
4.7 Conclusion: The effect of PDM on SSCM

As discussed in Chapter Three, this research follows a pragmatic approach. Therefore, the focus of the research is on answering the research questions with some relationships linking PDM to SSCM requiring qualitative and others quantitative data. The data collected for each relationship depended on two main factors:

1. The nature of the relationship between PDM and the aspect of sustainability.
2. The availability of the data at the case company.

Quantitative data collected consisted generally of operational reports from the case company, while qualitative data consisted of interviews conducted with the case company's supply chain manager and product design engineer. A focus group interview is also conducted with the case company's line workers.

Due to the diversity of the nature of the collected data, the researcher was required to use a number of analytical tools to integrate all findings to answer the research questions.

For relationships that required quantitative data, the researcher presents the data sets of the operational reports as provided by the case company. This is followed by an interpretation and discussion of the significance of such data in relation to the effect of PDM on the respective aspect of sustainability and in relation to the research propositions.

For relationships that required qualitative data semi-structured interviews were conducted. The interview questions are all based on the structure of the relationships and themes identified in Chapter Two. Therefore, as most analysis of semi-structured interviews begins with the creation of themes from interview transcripts (Leech, 2002), for this research the themes were already identified through the integrative literature review. The interviews were conducted with a view to obtain the experience and perspective of the interviewees in terms of working with PDM in the context of the relationships identified in Chapter Two. The basis for most of the common forms of analysis for interviews consists of the development of themes through a form of thematic or content analysis to help in the decoding and organising of the interview transcripts (Piercy, 2004; Kulatunga, Amaratunga and Haigh, 2007; Burnard, et al., 2008). Yin (2003) discussed that the researcher's role in this process is to look for sequences or patterns that can be used in support of the researcher's propositions. Pope, Ziebland and Mays (2000) explained that the development of categories or themes could either be induced, where the researcher gradually identifies commonalities through the interview transcripts; or the themes could have been developed at an earlier stage in the research. The purpose of interview data in the case where the themes are predefined would be to provide evidence or confirmation for the nature of the relationships within the themes and act as validation for the effect of PDM on SSCM. For analysis of interview data where the themes are predefined the Framework Approach is usually suggested (Pope, Ziebland and Mays, 2000; Smith and Firth, 2011; Burnard, et al., 2008; Huberman and Miles, 2002). Smith and Firth (2011) discussed that the Framework Approach is best suited when the researcher works with highly focused aims, objectives and a structured topic guide. For such cases the Framework Approach provides systematic means for the researcher to explore the data in depth while maintaining a transparent guide to how the data was analysed (Ritchie, et al., 2013). Burnard, et al. (2008) reasoned that within the Framework Approach the researcher imposes their own structure or theories on the data and then uses these to analyse the interview transcripts, which is useful in studies where researchers are already aware of probable participant responses.

Hence, since the themes and relationships connecting PDM to sustainable supply chain management were already identified as a result of the integrative literature review conducted in chapter two, the researcher deemed it best fit to apply the Framework Approach for analysis of the semi-structured interviews (Smith and Firth, 2011; Huberman and Miles, 2002).

The Framework Approach consists of five main stages:

1. Familarisation: this stage consists of thorough review and study of interview transcripts to identify key ideas and issues.

For this stage, the researcher went through all interview transcripts to identify key practices and processes within the case company that reflect the effect of PDM on SSCM.

2. Identifying a thematic framework: this stage focuses on developing key issues and concepts within the data which are derived from the questions developed from the aims and objectives of the study in combination with issues raised by the respondents and their experiences. The result of this stage should be an indexing scheme to enable the researcher to manage the data.

This stage of the research is based in part on the integrative literature review. The researcher was able to develop themes within the literature based on common relationships integrating PDM and SSCM across the three aspects of sustainability. The researcher used Nvivo and Excel to identify the common relationships and develop the themes. The Excel sheets used in the structuring of the thematic framework are provided in Appendix I. The result is a thematic framework, which was used in the development of interview questions that target the specific relationships to identify the effect modularity has on a particular process and how this in turn affects the sustainability of the supply chain.

3. Indexing: in this stage the researcher applies the thematic framework to systematically index all the data. This is done by going through the data and marking areas that relate to a certain theme and then indexing them with codes that relate to that particular theme.

Since the researcher had already divided the interview questions based on the specific relationships, the indexing process was quite simple. The interview transcripts were already divided based on the relationship in question.

4. Charting: in this stage the researcher rearranges the data based on the part of theme to which they relate. Charts are usually developed that link the themes to the summaries of the views and experiences obtained from the interviews.

Within this stage the researcher developed charts linking specific relationships to the main themes. Each relationship beneath a specific theme is then presented with supporting literature discussion followed by the interview question for the respective relationship and transcripts of the respective answers.

5. Mapping and interpretation: Through the charts, the researcher should be able to find associations between themes and use this to provide explanations for the findings. The interpretations should be linked with the original research questions and objectives.

With the help of the developed charts, the researcher presents an interpretation for each relationship. The interpretation is based on three elements:

1. Literature background on each specific relationship
2. Data of processes and practices within the case company
3. Experience and opinions of respondents.

Qualitative and Quantitative data presented in this chapter are used in the following chapter as inputs for the AHP analytical model. Hence, the purpose of this chapter is to validate the relationships, which are the basis for the criteria in the AHP model. Quantitative data regarding the effect of PDM on the different relationships is used to calculate the weights for the pairwise comparison matrices. Interview data interpretations from the respondents are provided as supporting evidence to the subjective weights given by the respondents to also be used as inputs in the pairwise comparison matrices in the AHP model.

4.2 The case company

The case company was chosen based on a number of factors. First the chosen company needed to be in a developing country in order to conform to the constraints presented in section 2.4.3.3 of the literature review so there would be no conflict between economic and social criteria. Accordingly, Egypt was deemed a suitable location that fits the previous constraint. Second, the company would also have to be an OEM where the end item is produced in order to view the intricate relationships the company has in controlling the end item design. Third, the company's operations should be mainly labour intensive to ensure that the social criteria can be tested. Finally, the company should be producing a product that can be modular in nature preferably a company within the electronics, automotive or furniture industry.

The first stage of the research began with conducting preliminary interviews with the company's Chief Executive Officer and with the company's Supply Chain Manager. These interviews were more of informal meetings, which focused on explaining the research questions, aim and scope of the dissertation to the interviewees. The interviews also aimed to identify the availability of the data and willingness of the company to participate in the research. The interview with the Chief Executive Officer was mainly to obtain approval to be allowed to collect data from the company and the Organisational Consent Form (Appendix II) was signed. During the second interview with the Supply Chain Manager the specific relationships were discussed as well as the data required for assessing each relationship.

The Supply Chain Manager provided an introduction for the company and the company's field of industry. The (Company) providing the data is a producer of 'White Electronic Goods'. White goods are identified as home appliances, which were generally white coloured such as fridges, heaters, ovens, and washing machines. The company started as a family business and is still owned and operated by the family. The company is 100 percent Egyptian, unlike a number of competing companies operating in the same field that generally operate under the umbrella of foreign international brands. The company currently has four manufacturing facilities in the main industrial zones of Egypt. The company is an OEM and its main market is Egypt, where it sells its products under its own name. The company also exports to a number of Gulf Countries and African Countries under different brand names.

The product family used for the analysis is washing machines, which provides an example of a product with a modular design. The decision to choose washing machines as the product family was based on discussions with the Supply Chain Manager whom suggested this product family in particular to have most of the required data discussed. The (Company) currently produces 39 different models of washing machines, which are sold both locally and exported to other countries in the Middle East region.

4.3 Identifying the case modules (unit of analysis)

For this research a multi case study methodology was decided upon as discussed in section 3.6 in Chapter Three. The aim is to achieve a literal replication from the two cases within this study to achieve a basis for the relationship between product design modularity and sustainability in supply chain management. Therefore, it was decided to conduct two separate cases and compare the results of each case at the end. This is done with a view to increase the validity of the findings and achieve analytical generalisation depending on whether literal replication is achieved through the analysis (Robson, 1993).

Jiao, Simpson and Siddique (2007) discussed that the best way to view the effect modularity in design has on supply chain operations, the research has to encompass an entire product family. They also discussed that the research cannot be limited to a certain product or a comparison between two products. This is due to the endless variables that can affect the research if the focus is on the products. For example, issues such as marketing and promotions for each product can have an effect on supply chain operations and thus have an effect on the results of this research. Therefore, it was important for this research to find a unit of analysis where a comparative study can be carried out excluding such variables, which can influence the analysis. As discussed previously in section 3.6 the unit of analysis for this research will be the modules within the product family. The study will compare between two modules with one of the modules being more modular in design and the other less modular. By choosing the modules instead of the products as the unit of analysis the researcher aimed at eliminating the possible variables that can affect the results of this research.

The first stage in the design of the multi case study was to isolate the modules within the product family to assess the effect modular design has on the supply chain sustainability for this product family. To identify which modules would be most suitable for each of the two cases, an analysis of all the modules within the product family had to be conducted. Hence, based on the definition of modularity (Ulrich, 1995; Schilling, 2000) the module, which is more common across the end item products in the same product family can be identified as the more modular component (Salvador, 2007). Following the same logic, the module which is shared the least across the end items would be the least modular or most integral. Accordingly, the analysis will compare between the effects each of these modules has on the identified relationships integrating PDM to SSCM.

The company currently uses an ERP system to manage the different aspects of its supply chain operations. All forms of archival data provided by the company were in the form of Excel sheets exported from the ERP system.

The (Company) provided a multi-level BOM for the 39 different models of the washing machines. The multi-level BOM included the modules required for each of the 39 different models. The multi-level BOM demonstrated how the modules are shared across the 39 models. In order to choose the modules for analysis a two stage methodology was implemented. The first stage consisted of identifying the modules that are shared across the end items, which represent the element of commonality. These modules were then arranged according to the number of end items that they are a part of in descending order. From a total of 674 modules shared across the 39 end items, 14 components were shared across all 39 models. However, upon further investigation these items were found to be screws and rubber parts, which as components cannot be considered modules since they are too simplistic, and it is only natural for screws to be shared across all the models.

Hence, the second stage consisted of an interview with the product design engineer, who advised on choosing more complex items to be the modules for analysis. From the interview the product design engineer discussed a number of complex modules, which are shared across the different washing machine models. The module categories discussed during the interview were (motors, timers, rubber pipes, wirings) out of a total of 30 categories. Please refer to Figure 4.1 Module Categories.

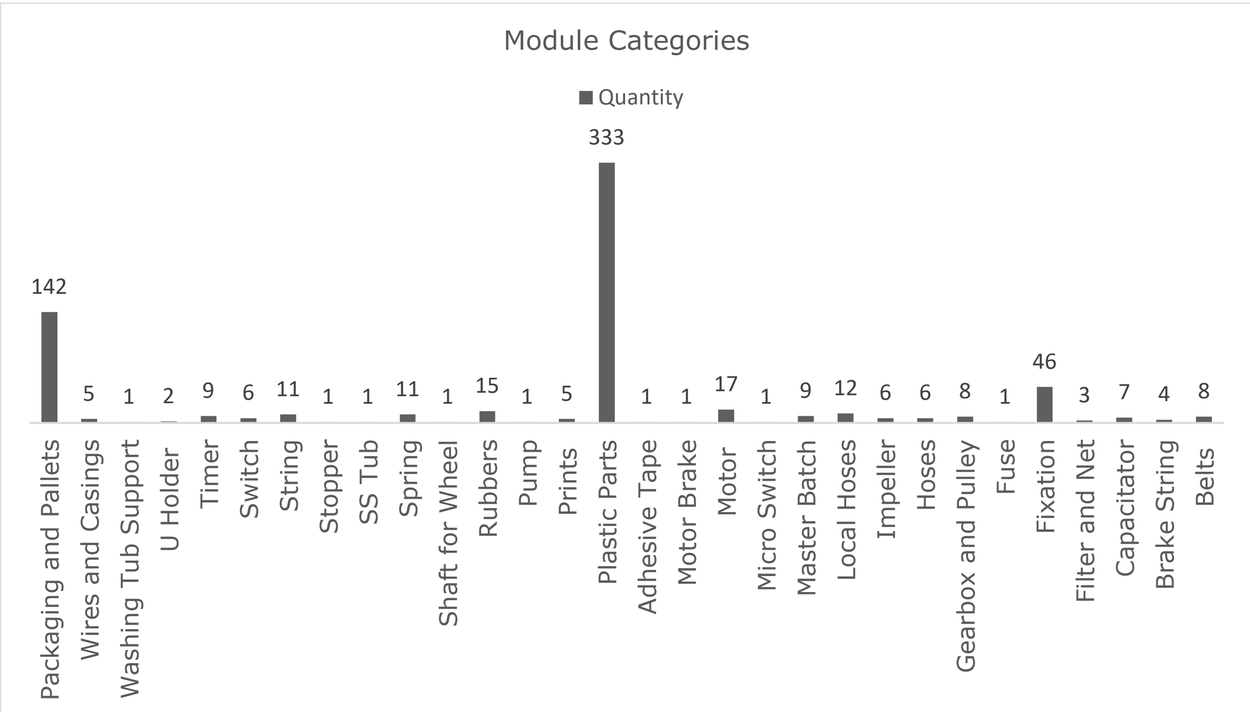


Figure 4.1 Module Categories

Further investigation was carried out with a focus on the motors modules category. There are two kinds of motors within the washing machines' product family one is for rotational washing (RW), while the other is for draining (D) the water out of the clothes. There are 10 (RW) motors and 7 (D) motors (Table 4.1 Motor Module Types).

Table 4.1 Motor Module Types

Motor Modules	No of Washing Machines	Motor Type
Motor 1	1	RW
Motor 2	4	D
Motor 3	1	RW
Motor 4	1	D
Motor 5	2	D
Motor 6	2	RW
Motor 7	3	RW
Motor 8	4	RW
Motor 9	2	RW
Motor 10	13	D
Motor 11	2	D
Motor 12	2	RW
Motor 13	4	RW
Motor 14	4	D
Motor 15	5	D
Motor 16	5	RW
Motor 17	15	RW

Out of a total of the 10 (RW) motors, it was found that a certain rotational washing motor module (Motor 17) (M1) is shared across 15 washing machine models out of the 39, while another rotational washing motor module (Motor 9) (M2) is shared between 2 washing machine models out of the 39 (Figure 4.2 RW Motor Modules). The second case identified was that within the timer module category. Out of 8 different timer modules, one timer module (Timer 1) (T1) is shared across 20 washing machine models out of the 39, and another timer module (Timer 4) (T2) is only shared across 5 washing machine models out of the 39 (Figure 4.3 Timer Modules).

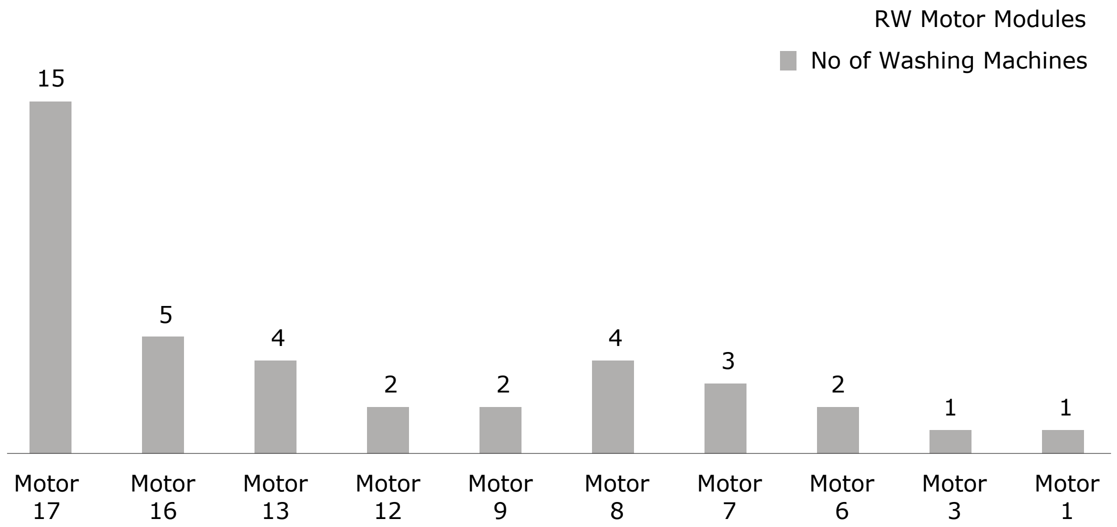


Figure 4.2 RW Motor Modules

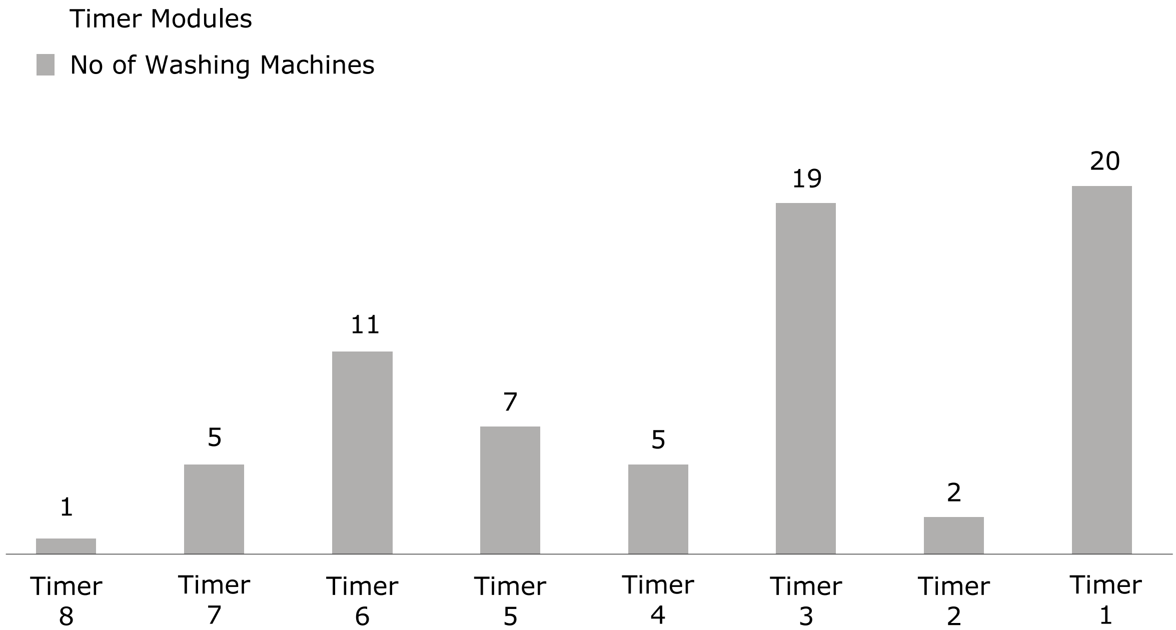


Figure 4.3 Timer Modules

Through focusing the study on one module category this provided further validity for this research. Unifying the category of the module provides less variability when conducting the comparisons to assess the effect each has on the sustainability perspectives within the company's supply chain.

Hence, within this product family two cases have been identified. The first case would be the two motors and the second case would be the two timers.

The second stage of the research as discussed in the research methodology chapter was to conduct a comparison between the two modules identified in each case respectively. The first case will be to conduct the comparison between the two motors (M1 and M2), and the second case will be to conduct the same comparison between the timers (T1 and T2) and analyse the data from both cases.

Each case will compare the modules across the economic, environmental, and social relationships previously identified in an attempt to present empirical evidence to support the four propositions presented previously in the literature review chapter.

4.4 The effect of PDM on the economic performance of the supply chain

The integrative literature review conducted in Chapter Two developed three main themes, which summarise how PDM affects the economic performance of a supply chain (Figure 4.4 Effect of PDM on Supply Chain Economic Performance).
Data collected, and analysis conducted for the relationships identified within these themes will be used to support the first two propositions:

P1: PDM increases supply chain profit
P2: PDM decreases supply chain cost

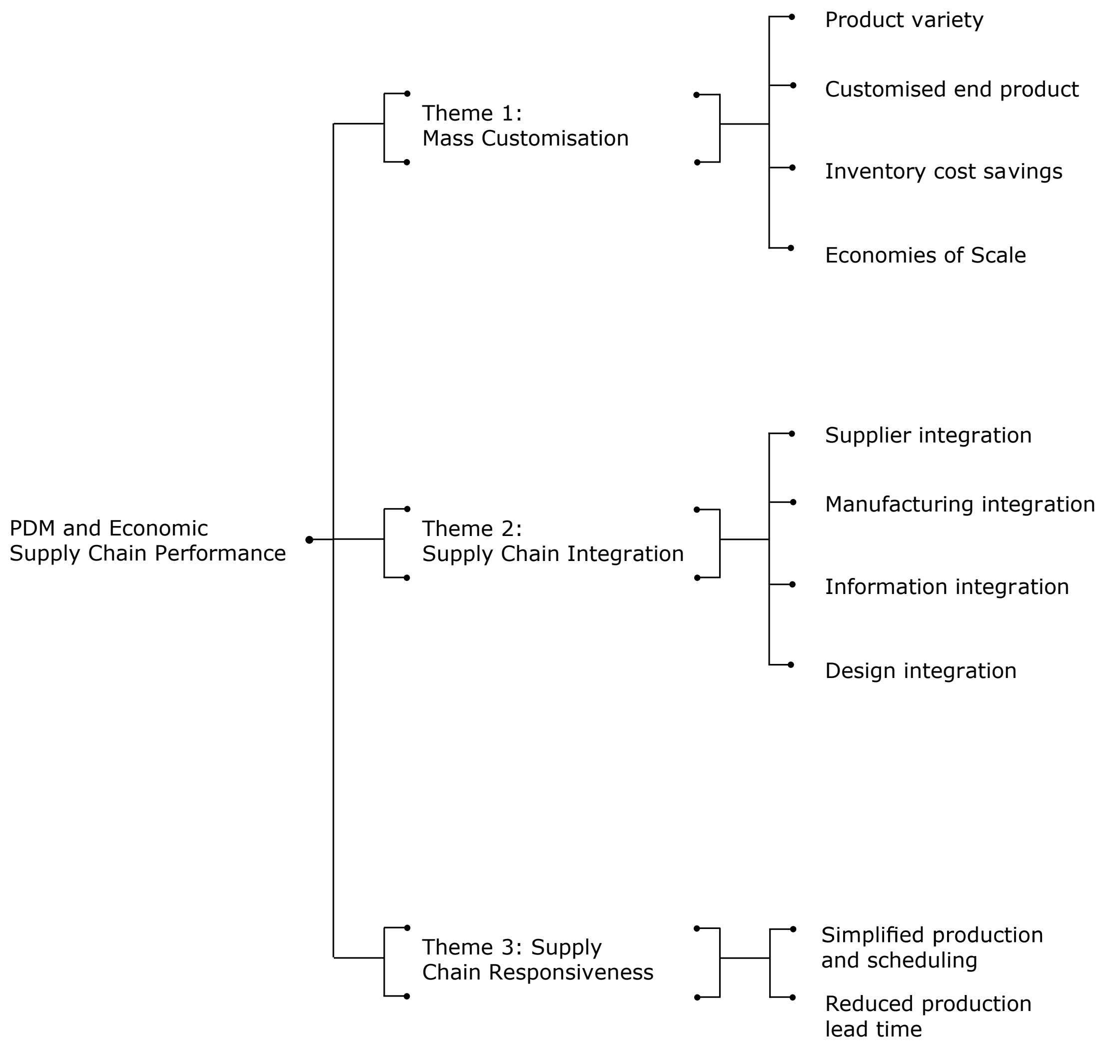


Figure 4.4 Effect of PDM on economic supply chain performance

4.4.1 Mass Customisation

PDM is considered one of the main pre-requirements to achieve mass customisation (Pero, et al., 2010; Zhang, Huang and Rungtusnatham, 2008). Kumar (2005) defined mass customisation from two perspectives. The first perspective focuses on the effectiveness of the supply chain and its ability to offer customers with products custom made to their requirements. The second perspective focuses on the supply chain's efficiency, where mass customisation operations strive to reduce cost and offer customised products at a competitive price.

PDM is connected to mass customisation across four main relationships. In regard to the supply chain's ability to meet customer's increasing demand for customised end products, PDM is directly linked to increasing a company's product offerings through increasing product variety (Zhang, et al., 2017; Chiu and Okudan, 2014). PDM also allows for the customisation of end items through changing certain modules instead of changing the complete product design for each customer order (Pero, et al., 2010; Zhang, Huang and Rungtusnatham, 2008; Ro, Liker and Fixson, 2007). Therefore, for the first two relationships, this study will test the effect PDM has on improving sales through increasing product variety and allowing for customised end products within the washing machines product family. Data gathered, and analysis conducted for the first and second relationships will be used as evidence supporting the first proposition (P1): PDM increases supply chain profit.

The second perspective of Kumar's definition concerning the supply chain's ability to reduce operational cost, the literature connected PDM to mass customisation through inventory cost savings and economies of scale. PDM reduces the number of modules per end item. PDM also allows for the pooling of modules, where more than one end item shares the same module for production leading to inventory cost savings (Brun and Zorzini, 2009; Zhang, et al., 2017). For this relationship, this study will analyse the effect PDM has on the inventory levels of the two motor modules for the first case and the two timer modules for the second case.

As for the economies of scale relationship, PDM develops standardised modules that can easily be shared across different end items within the same product family (Chiu and Okudan, 2014; Danese and Filippini, 2013). This means that quantities purchased or produced from the same module would increase leading to quantity discounts and reduced overhead costs. For this relationship the study will analyse the cost of producing or acquiring the motor and timer modules and compare between the costs of M1 vs M2 for the first case and T1 vs T2 for the second case. Data gathered, and analysis conducted for the third and fourth relationships will be used as evidence supporting the second proposition (P2): PDM decreases supply chain cost.

4.4.1.1 Product Variety

Modularity in design allows the company to produce different products through changing certain modules without the need to develop an entirely different product design (Danese and Filippini, 2013; Pero, et al., 2010; Zhang, Huang and Rungtusnatham, 2008). This allows the company to easily increase its product variety and increase its product offerings.

For the washing machines product family, the company is able to offer 39 different washing machines. Product variety in the offerings is mainly due to the different washing capacity in terms of kilograms for each machine, also in the location of the hatch door, which is either at the top of the washing machine or at the front of the washing machine.

Case 1: M1 vs M2

For the washing machines product family, it was identified through the multi-level BOM provided by the company that within the motors category (M1) is shared across 15 different washing machine models, while (M2) is shared across 2 washing machine models (refer to Figure 4.3).

The company also provided the sales records for the entire product family including the sales records of the 39 washing models across a period of 23 months (all of 2015 and 2016 until November).

This relationship aims to connect the effect PDM has on increasing product variety to improved sales within the company. Thus, to test this relationship, the researcher analysed the total sales for the 15 models that M1 is a part of in comparison to the total sales for the 2 models, which M2 is a part of. Since M1 being more modular is shared across a wider range of product offerings than M2, therefore M1 should be associated with more sales than M2.

M1 was found to be associated with 493,696 sold models out of total sales of 1,123,740 washing machines, which is considered 44% of total sales over the 23 months period of analysis. M2 was found to be associated with 140,546 sold models, which is considered 12% of total sales over the 23 months period (Figures 4.5).

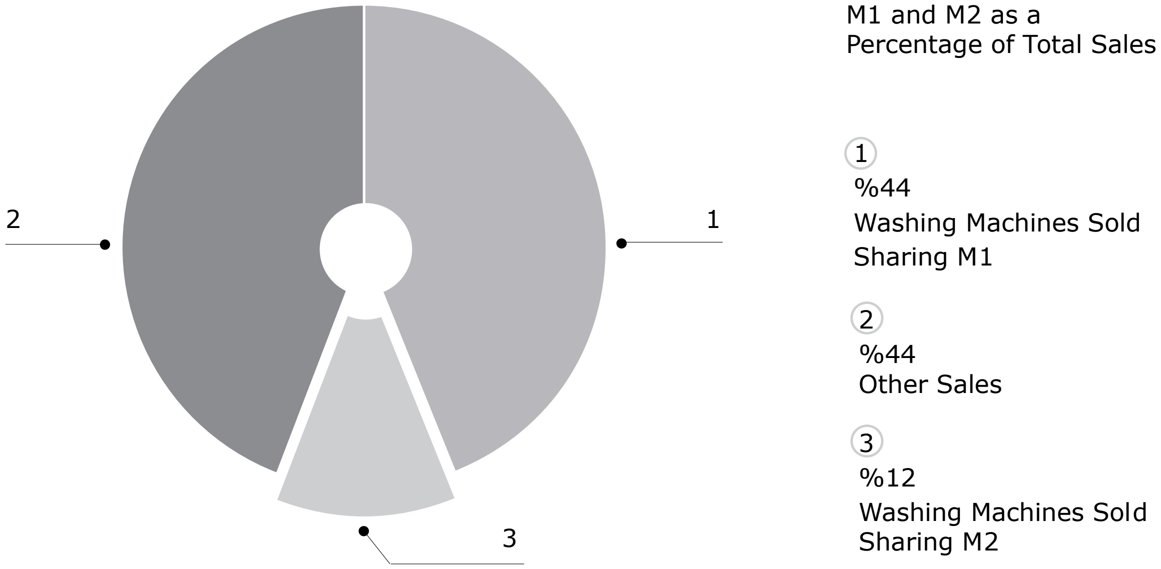


Figure 4.5 M1 and M2 as a Percentage of Total Sales

M1 being more common than M2 in that it is shared across 15 washing machine models, while M2 is only shared across 2 washing models leads to M1 resulting in 44% of total sales in comparison to M2 only 12% of total sales within the 23 months period of analysis. The logic behind this can be associated to customer behaviour, where given more variety to choose from the probability that customers will purchase one of the washing machine models that share M1 increases in comparison to the washing machine models sharing M2. This is proven through the evidence within this case study where sales for the washing machines sharing M1 amounted to 493,696 models in unit sales while washing machines sharing M2 sold a total of 140,546 models only. Hence, this acts as validation for the first relationship, which proposed that product modularity achieved through modularity leads to more sales.

Case 2: T1 vs T2

For the washing machines product family, it was identified through the multi-level BOM provided by the company that within the timers category (T1) is shared across 20 different washing machine models, while (T2) is shared across 5 washing machine models (refer to Figure 4.3).

This relationship aims to connect the effect PDM has on increasing product variety to improved sales within the company. Therefore, to test this relationship, the researcher analysed the total sales for the 20 models, which (T1) is a part of in comparison to the total sales for the 5 models, which (T2) is a part of. Since (T1) being more modular is shared across a wider range of product offerings than (T2), therefore (T1) should be associated with more sales than (T2).

T1 was found to be associated with a total of 594,885 sold models out of total sales of 1,123,740 washing machines, which is considered 53% of total sales over the 23 months period of analysis. T2 was found to be associated with 391,675 sold models, which is considered 35% of total sales over the 23 months period (Figures 4.6).

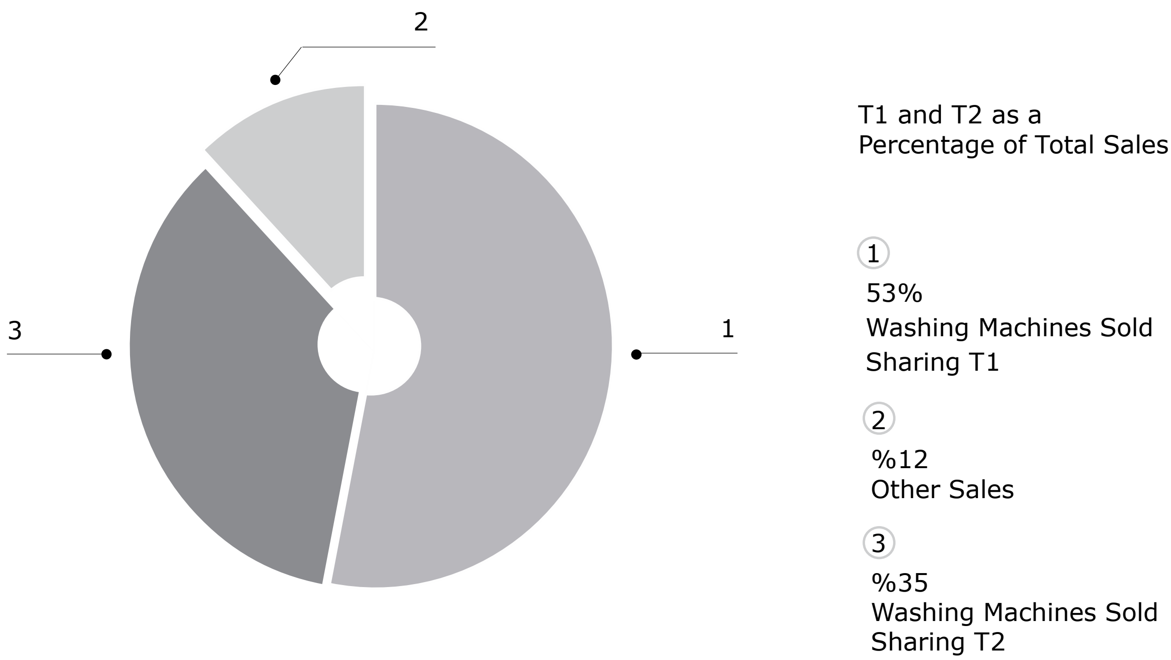


Figure 4.6 T1 and T2 as a Percentage of Total Sales

The purpose of the second case study is to increase the validity of the findings for this research. This is done through conducting a reiteration of the study and a comparison of the findings between the first and second studies. By obtaining similar results to the first study, the findings of this research can then be argued to be more reliable. For the timer modules, T1 being more common than T2, is shared across 20 washing machine models, while T2 is shared across 5 washing models. This led to washing models sharing T1 resulting in 594,885 washing machine unit sales, while sales in units for washing machines sharing T2 were 391,675 units. Hence, it can be argued that the second case provides more validity regarding this relationship. Where through T1 being more modular and being shared across 20 different washing machine models increased the probability of increasing company sales and can be associated with 53% of total sales while T2 is only associated with 35% of total sales.

Therefore, it can be more solidly argued that increased product variety resulting from a more modular design leads to higher sales in units.

4.4.1.2 Customised End Products

The ability of a company to produce products specifically customised to meet customers' requirements is directly linked to increasing sales (Nepal, Monplaisir and Famuyiwa, 2012). Arguments in the literature presented PDM's role in offering mass customised end items through making it easier to customise a product by changing certain modules instead of redesigning the entire product (Pero, et al., 2010; Zhang, Huang and Rungtusnatham, 2008). Offering customised end items is quite different from the product variety relationship. In the product variety relationship, the focus is on offering a wider range of product offerings for the customer to choose from. However, for the customised products relationship, the company would have to have direct communication with the end customer to obtain the specifications for the product and then develop a product to meet the customers' requirements. So, instead of choosing from a fixed set of different products, this would allow the customer to create a custom fit product.

The case company only offers its customers a fixed set of washing machine models to choose from without the customisation option. However, through the interview conducted with the Supply Chain Manager, he was able to identify a link between PDM and customised product offerings from a different perspective. Even though the case company does not offer customised products to its end customers, it does supply customised products to other companies that outsource their production facilities to the case company. These companies usually have specific requirements for their washing machines. The requirements are mainly in changing the logo and brand of the washing machines as well as minor changes to the exterior hull design of the washing machines in the plastic modules. The interiors of the washing machine models, however, are largely unchanged.

So, when asked regarding his experience concerning the relationship between PDM and mass customisation, he discussed the role PDM plays in developing custom fit products to meet these companies' requirements. The ability of the company to standardise its components and to offer customisation options through changing a limited number of these components without requiring an overhaul of the entire design of the end product has boosted the case company's ability to develop custom fit products to companies that outsource their production to the case company. The supply chain manager also confirmed that through his experience he has noticed a direct relationship between PDM and enhancing a company's ability to offer customised end products. He also answered that through his work with the current company he has been able to increase the company's sales through offering customised products to company's looking to outsource their production to the case company.

The washing machines that are supplied for other companies under different brands are exported and not sold in Egypt. Therefore, the Supply Chain Manager provided the company sales records for the exports over the past 23 months period. Based on the data provided, the analysis for this relationship will be to compare the number of units of exported washing machines M1 contributed to versus M2 for the first case and the number of units of exported washing machines T1 contributed to versus T2 for the second case.

Case 1: M1 vs M2

Through the sales records for the exported washing machine models of the case company, the researcher identified that M1 is part of 6 different export washing machine models. M2, on the other hand, is only used in one of the exported washing machine models. M1 contributed to the sales to a total of 177,281 exported washing machines out of a total of 362,788 making up 49% of total exports. M2 contributed to the sales to a total of 44,716 exported washing machines making up 12% of total exports as is illustrated in Figure 4.7.

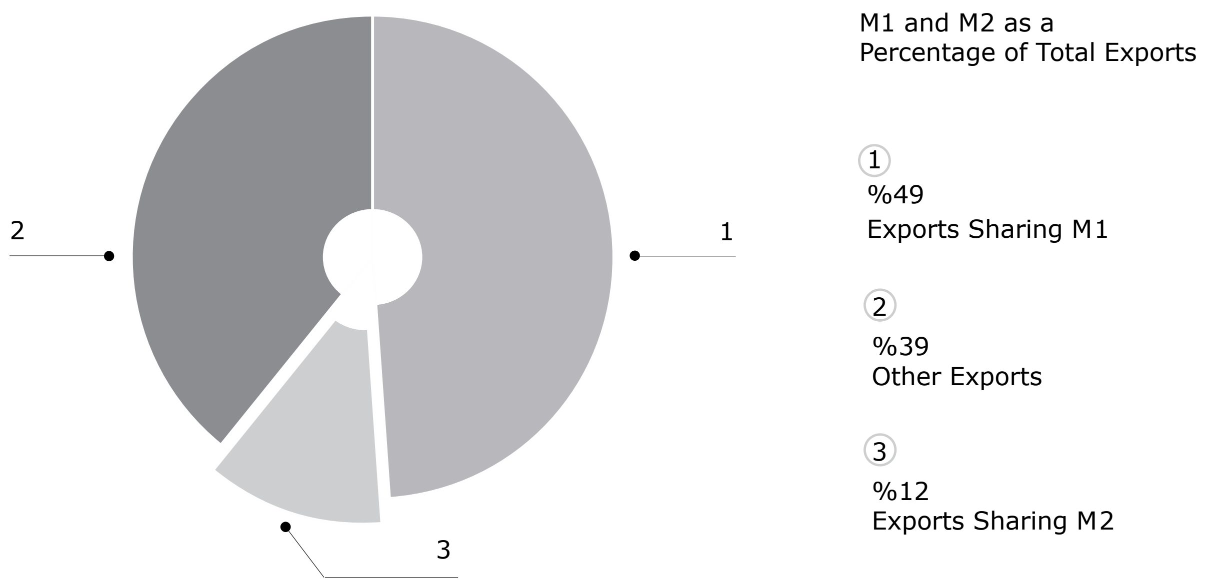


Figure 4.7 M1 and M2 as a Percentage of Total Exports

Even though the company does not provide customised washing machines as an option to the end customer, it does however provide the customisation option to companies that want to outsource their production facilities. In doing so the company offers to manufacture the washing machines according to specific requirements of the purchasing companies. The findings provided that M1 is shared across 6 washing machine models, which are exported by the company under different brand names, while M2 is only used for one of the exported washing machines. The sales in units from the 6 exported washing machine models sharing M1 were 177,281 units, while sales for the exported washing machine model sharing M2 were 44,716 units. Hence, it can be argued that through modularity in design the case company was able to offer customisable washing machines to companies looking to outsource their production facilities through changing a limited number of modules. It can also be argued that M1 being more common can easily fit within more washing models, due to the interfaces between the components being more compatible, making it easier to customise these models according to the purchasing company requirements without changing the entire end product designs. This resulted in M1 being associated with 49% of total exports while M2 is only associated with 12% of total exports.

Regarding the second relationship, it can be argued that the evidence from the findings supports that modularity in design leads to mass customisation, which in turn leads to improved sales.

Case 2: T1 vs T2

Through the sales records for the exported washing machine models of the case company, the researcher identified that T1 is part of 9 different export washing machine models. T2, on the other hand, is only used in two of the exported washing machine models. T1 contributed to the sales to a total of 193,460 exported washing machines out of a total of 362,788 making up 53% of total exports. T2 contributed to the sales to a total of 73,025 exported washing machines out of a total of 362,788 making up 20% of total exports as is illustrated in Figure 4.8.

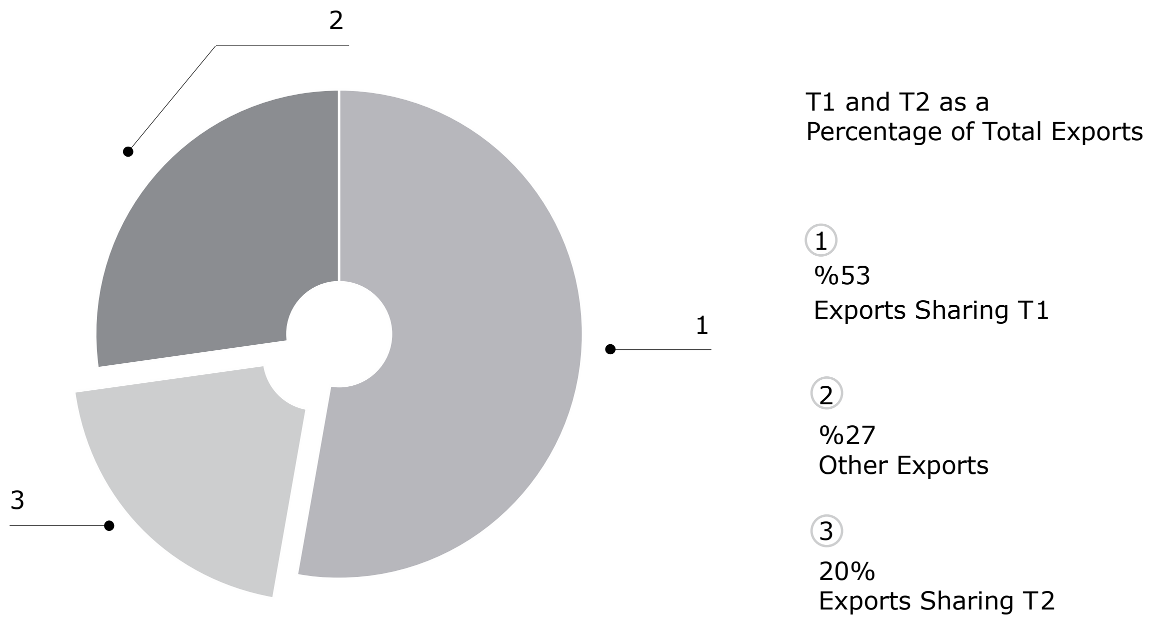


Figure 4.8 T1 and T2 as a Percentage of Total Exports

The findings from the second case provided similar results with T1 being shared across 9 of the exported washing machine models, while T2 is only shared across 2 of the exported washing machines. Therefore, the same argument can be made in that T1 being more common across the different washing machines makes it easier to customise the washing machines without requiring a complete overhaul of the end product design. This is due to the standardised interfaces between the components making it possible to use T1 across the different washing machine models. As the findings show this resulted in T1 being associated with a total of 193,460 in export unit sales summing up to 53% of total export sales, while T2 was only associated with 73,025 summing up to 20% of total export sales.

It can be argued that the second case, having similar results to the first case, provides higher reliability for the findings within this study. The second case also supports the second relationship in that PDM is used for achieving mass customisation, which in turn leads to higher sales.

4.4.1.3 Inventory Cost Savings

Modularity in design is based on the standardisation of inputs that are able to produce a variety of outputs through different combinations (Sanchez, 1995; Salvador, 2007). The concept of input standardisation, or in other terms component commonality across a product family is critical in order to reduce operational cost (Jacobs, Vickery and Droge, 2007; Zhang, et al., 2017). PDM allows for inventory that is shared across different end items to be pooled together instead of requiring separate inventory for each end item and separate safety stock for each SKU. The pooling effect leads to lower inventory holding average per end item (Lau, Yam and Tang, 2010; Brun and Zorzini, 2009).

The pooling effect will be the basis for testing this relationship. Through calculating the total inventory of M1 and dividing this total by the number of end items that share M1, the average inventory of M1 will be obtained per end item. The same calculation will be done for M2 to compare between both averages. The same method will be used for the second case to compare between the average inventories for T1 VS T2.

Case 1: M1 VS M2

This relationship aims to connect the effect PDM has on reducing inventory levels to enhancing the company's operational efficiency. Therefore, to test this relationship, the researcher analysed the inventory for M1 as an average of the 15 washing machine models that share M1 in comparison to the inventory of M2 as an average of the 2 washing machine models that share M2. Since M1 being more modular possess a higher degree of commonality than M2, therefore M1 should have a lower inventory average than M2.

For the 23 months period of analysis the company had a total inventory of 401,838 units for M1. When dividing this total by the number of washing machines, which share M1, the result is that for each washing machine 26,790 units approximately of M1 were kept on hand. As for M2, the company had a total inventory of 149,256 units. When dividing this total by the number of washing machines, which share M2, the result is that for each washing machine 74,628 units of M2 were kept on hand. Meaning that on average the company holds three times as much inventory for M2 in comparison to M1 per end item. So, even though it was established within the previous relationships that M1 leads to more sales than M2, it still shows a lower on hand inventory in comparison to M2.

Therefore, the findings provide evidence in support of the first relationship between mass customisation as a theme and PDM leading to supply chain operational cost reduction. With inventory cost being part holding cost and part order cost, this relationship focuses on the holding cost aspect of inventory cost. A lower number of inventory units held on hand for every end item means that the inventory cost incurred by the company for keeping the component M1 on hand is lower than M2. The findings for the case of M1 VS M2 provides that the company keeps on hand three times the amount of inventory for M2 (74,628) for each washing machine model sharing M2 in comparison to M1, where the company only keeps (26,790) units in inventory for every washing machine model that requires M1. Which means that through the findings it can be argued that PDM leads to reducing total inventory cost.

Case 2: T1 vs T2

This relationship aims to connect the effect PDM has on reducing inventory levels to enhancing the company's operational efficiency. Therefore, to test this relationship, the researcher analysed the inventory for T1 as an average of the 20 washing machine models that share T1 in comparison to the inventory of T2 as an average of the 5 washing machine models that share T2. Since T1 being more modular possess a higher degree of commonality than T2, therefore T1 should have a lower inventory average than T2.

During the same period the company had a total inventory of 384,614 units for T1. When dividing this total by the number of washing machines, which share T1, the result is that for each washing machine 19,231 units approximately of T1 were kept on hand per end item. As for T2, the company had a total inventory of 398,377 units. When dividing this total by the number of washing machines, which share T2, the result is that for each washing machine 79,676 units approximately of M2 were kept on hand per end item. Meaning that on average the company holds five times as much inventory for T2 in comparison to T1. So, even though it was established within the previous relationships that T1 leads to more sales than T2, it still shows a lower on hand inventory in comparison to T2.

The second case provides similar results improving the validity of the data for this relationship. For T1 VS T2 the findings provided that on average the company holds five times more inventory for T2 per washing machine model in comparison to T1. This means that the relationship between PDM and inventory cost reduction is further validated.

4.4.1.4 Economies of Scale

Economies of scale is the second relationship that links PDM to operational cost efficiency (Chiu and Okudan, 2014; Danese and Filippini, 2013). This relationship is also linked to the standardisation of inputs. Previously, in the production era, the focus was on the standardisation of final products to achieve economies of scale. However, due to customer's demand for product variety and customised products this was no longer viable. PDM offers a solution to balance the trade-offs between increasing product offerings and achieving mass customisation while still being able to reduce manufacturing costs (Nepal, Monplaisir and Famuyiwa, 2012). This is achieved through the standardisation of inputs into interchangeable modules with standardised interfaces, or in other terms modularity in design.

Whether the company manufactures the modules or purchases the modules, economies of scale are still achieved. If the company produces its own modules, then economies of scale are achieved through reducing the overhead costs of manufacturing and quantity discounts from the purchase of raw material. For the second case, if the company purchases the modules readymade, then economies of scale are achieved directly through quantity discounts from suppliers. By standardising the inputs, then there is increased demand for the modules through the pooling effect. This allows the company to have more bargaining power when ordering from suppliers and leads to quantity discounts.

For the case company, both the motor modules and timer modules are outsourced and readily purchased from suppliers. The two case motors M1 and M2 are both purchased from the same supplier. The same applies for T1 and T2, which are also purchased from the same supplier. To demonstrate the effect PDM has on economies of scale, the researcher compared between the purchase orders for the modules as well as the unit price per module.

The supply chain manager also provided insights regarding the company’s ordering process. The ordering process is done through the company’s ERP system, which is integrated with the supplier’s ERP. Yearly forecasts are developed and sent to the suppliers with any changes being updated on the ERP system. The cut off period to changes being made is three weeks, which includes the production and transportation lead times needed by the supplier.

Case 1: M1 vs M2

The company provided its purchase records for the case modules over a period of 23 months (all of 2015 and 2016 until November). The company also provided the unit prices of the case modules for 2015 and 2016 (Table 4.2).

Table 4.2 Module Purchase Unit Prices 2015 & 2016

Module	2015	2016	Saving	%
M1	6.79	5.22	-1.57	-23.12
M2	6.94	5.57	-1.37	-19.74
T1	1.07	0.9	-0.17	-15.88
T2	0.95	0.98	0.03	+3.15

For M1 the company ordered a total of 449,769 units over the 23 months period. Unit price for M1 in 2015 was 6.79 EGP per motor, while in 2016 unit price went down to 5.22 EGP per motor marking approximately 23% year over year unit price reduction.

For M2 the company ordered a total of 154,953 units over the 23 months period. Unit price for M2 in 2015 was 6.94 EGP per motor, while in 2016 unit price went down to 5.57 EGP per motor marking approximately 20% year over year unit price reduction.

What can be seen from the findings is that M1 resulted in year over year unit price reduction. This is mainly due to an increase in the purchase orders for M1 by the company in comparison to M2. Where the increased purchase quantities led the company to obtain quantity discounts from the supplier resulting in approximately 23% savings per unit price in comparison to unit price in the previous year. As for M2 the purchase orders increased as well, however, not as significantly as for M1, which resulted in only 5% savings per unit price in comparison to unit price in the previous year. The findings within this case can then be argued to support that PDM results in economies of scale and lead to supply chain operational cost savings.

Case 2: T1 vs T2

For T1 the company ordered a total of 438,900 units over the 23 months period. Unit price for T1 in 2015 was 1.07 EGP per timer, while in 2016 unit price went down to 0.9 EGP per timer marking approximately 16% year over year unit price reduction.

For T2 the company ordered a total of 377,680 units over the 23 months period. Unit price for T2 in 2015 was 0.95 EGP per timer, while in 2016 unit price went up to 0.98 EGP per timer marking approximately 3% year over year unit price increase.

The findings for the second case provided similar results to the first case. Where due to the purchase orders of T1 being significantly higher than T2, the company is able to obtain quantity discounts from the supplier leading to a 15% year over year purchase unit price decrease. Where, on the other hand, in comparison to T2 there actually is a 3% year over year price increase. Therefore, it can be argued that through the empirical evidence gained, PDM is seen to reduce supply chain operational cost through economies of scale.

This section presented and discussed the four relationships connecting PDM to the literature theme mass customisation. The first two relationships focused on the effect PDM has on improving company sales through increasing product variety and allowing for customised end products. For the first two relationships the researcher provided empirical evidence for two separate cases. In each case two modules with differing degrees of modularity were compared in relation to the amount of sales of the washing machines that share one module resulted in comparison to the amount of sales of the washing machines the other module resulted in. The findings for both the first case (M1 VS M2) and the second case (T1 VS T2) within both relationships were similar providing evidence that support the first proposition in this study (P1), which is that PDM leads to increasing supply chain profit.

The third and fourth relationships focused on the effect PDM has on reducing supply chain operational cost. The third relationship linked PDM to inventory cost savings where the researcher calculated the average on hand inventory for one module with a high degree of modularity in comparison to a second module with a low degree of modularity, once for M1 VS M2 and then again for T1 VS T2. The results obtained from both cases provided that components with a higher degree of modularity required lower amounts of inventory to be held on hand by the company leading to overall inventory cost reduction. The fourth relationship focused on the role of PDM in achieving economies of scale. Findings for this relationship were obtained from the company purchase order records, where a comparison between the purchase quantities of the component with the high degree of modularity was compared to the component with the low degree of modularity. The researcher also compared between the purchase price for the component with the high degree of modularity in comparison to the module with the low degree of modularity. The comparisons for both cases (M1 VS M2) and (T1 VS T2) provided that the component with the high degree of modularity led to year over year purchase unit price reduction due to economies of scale obtained from the purchase quantities. The findings from both cases for the third and fourth relationships can therefore be argued to support the second proposition in this study (P2), which is that PDM leads to supply chain cost reduction.

4.4.2 Supply Chain Integration

The second major theme identified in the literature regarding the effect of PDM on a supply chain's economic performance is supply chain integration. The literature review in Chapter Two presented several papers that discussed the relation between product design and supply chain management through the design for supply chain (DFSC) concept (Sharifi, et al., 2006; Gokhan, et al., 2010; Gan and Grunow, 2013; Kremer, et al., 2016). This concept develops the importance of integrating product design and supply chain design from an early stage due to the dependency of one on the other. Supply chain integration can only be achieved through coordinating between product design decisions and understanding the impacts they have on shaping supply chain design. Product design can affect critical decisions within the supply chain such as supplier selection, transportation routes, inventory levels, make or buy decisions, and information sharing between supply chain tiers (Danese and Filippini, 2013; Jacobs, Vickery and Droge, 2007).

Lau, et al. (2010) defined supply chain integration as the process of integrating suppliers, customers and internal functional units in a supply chain with the objective of optimising the overall performance of the supply chain. Optimising the performance of the supply chain as discussed by most of the literature on supply chain integration is mainly linked with increasing supply chain profit and reducing operational costs (Zhang, et al., 2017; Ulku and Schmidt, 2011; Danese, Romano, and Bartolotti, 2011). Therefore, findings in this theme will also be used to support the first and second propositions:

P1: PDM increases supply chain profit
P2: PDM decreases supply chain cost

Through the integrative literature review conducted in Chapter Two, PDM is seen to contribute to achieving supply chain integration across four distinct relationships, which are: supplier integration, manufacturing integration, information integration, and design integration. The data collected for this theme was purely primary in nature through semi-structured interviews with the Supply Chain Manager and Product Design Engineer.

4.4.2.1 Supplier Integration

Doran (2003) described the supply chain as being a value chain with members in the supply chain each contributing to increasing the value of the end item that will reach the consumer. In order to remain competitive, companies have forsaken the ideology of attempting to produce everything internally. Instead, companies have evolved focusing their resources on their core competencies, while outsourcing the processes that are not core to offering a competitive advantage.

PDM naturally fits into this new business model. PDM allows the design of the product to be divided into set modules where each module can be independent from the actual end product. This allows the original equipment manufacturer (OEM) to not tie down resources in the manufacturing of modules, which are not core to their business (Nepal, Monplaisir, and Famuyiwa, 2012; Lau, et al., 2010; Doran, 2003). In most cases, what usually happens is that the OEM will outsource the production of certain modules to upper tier suppliers (Lau, Yam and Tang, 2010; Antonio, Richard and Tang, 2009; Doran, et al., 2007). This in turn promotes closer collaboration between supply chain members, whom now each share part of the value creation process for the end item.

Data for this relationship was obtained through a semi-structured interview with the Supply Chain Manager of the case company. The interview was conducted with the supply chain manager in particular because it lies under his managerial responsibilities to select suppliers and sign on supply agreements.

In regard to the effect PDM has on supplier integration three questions were asked. These three questions in particular represent the effects of PDM on supplier integration as identified through the integrative literature review conducted in Chapter Two.

The first question asked the effect PDM has on the make or buy decisions the case company makes for the washing machines product family. Below is the transcript of the Supply Chain Manager's response.

'Modularity in design has had a deep impact on the white electronic goods sector especially in Egypt. It has allowed companies to add more product offerings and even add entire product families to their production. As for the washing machines product family that we produce, PDM greatly affects the make or buy decision. For every part we produce we have to consider if there are suppliers available that can do the same thing for a better price than us. This question has created many cases where we have decided to stop producing a certain module and outsource it and a number of cases where we decided to build our own modules.

A case where we have decided to insource rather than outsource has been for our plastic components. Over the past 5 years we have been able to build our own facilities for the manufacture of all plastic modules since a lot of our products rely heavily on such components. The facilities now supply all of our plastic needs and cover the demand for all our product families.

At the moment we still outsource a number of modules for the washing machines product family. A major module category that is still completely outsourced is the motor category, which is more economic to outsource at this stage.

Of course, there are considerations other than cost that need to be taken into account such as lead time, supplier flexibility in handling our orders, availability of more than one supplier to reduce supply risks. However, having a product that consists of a set of independent modules allows for the flexibility to make such decisions. Where, on the other hand, if the design for the product was made in such a way that it was difficult to separate components, we would either have to purchase the entire product from a supplier or build it all on our own.'

This question's focus was to identify the company's position when it came to insourcing VS outsourcing decisions, which will directly affect the supplier selection process. Through integrating product design decisions with supply chain design decisions, the company will be able to isolate the components that it wants to outsource VS the components it plans to insource. Accordingly, once the outsourced components are identified, the company will be able to begin the supplier selection process. PDM's role in this scenario is in helping the company to have pre-set standardised components with standardised interfaces. This allows the company to have the flexibility to make such insourcing VS outsourcing decisions without worry that outsourced components will not fit with the current product design. It also enables the company to have the flexibility to choose between a range of suppliers based on the company's supplier selection criteria. It also allows the company to clearly identify the components, which its manufacturing process is most heavily dependent on. Based on the supply chain manager's answer, the company has a balanced approach, where it has already identified the components that it is most heavily reliant on and has already implemented plans to have more control over the production of such components through insourcing and opening manufacturing facilities dedicated to such components. The Supply Chain Manager also indicated that there are some components, which the company relies on outsourcing due to the ability of the suppliers to provide higher quality components at lower costs such as the motor and timer modules. For such components, it is more favourable for the company to create strategic partnerships and enhance the integration of supply chain processes between itself and its suppliers. This is done with a view to improve operational performance.

The second question asked was if the Supply Chain Manager considered PDM to be beneficial for the case company in allowing it to focus on its core competency. Below is the transcript of the Supply Chain Manager's response.

'Currently the case company's core competency has been in being flexible enough to comply with changing market demands. For example, a while ago the new craze in the market was for digital screens on all the white electronic goods from washing machines to water heaters. Some of our competitors found it hard to keep up to such changes, because they have their manufacturing facilities fixed and it would cost them a lot to have these facilities and not use them. It has been our strategy from a very early stage in this company to only focus our resources on long-term investments. Meaning we only invest in the standard components, which we are sure will be used in more than one product family. However, when it comes to components that are specific to only one product family or to a few set of products we always opt to outsource from suppliers. Another case is when as a company we don't have the required know how to produce a specific component to the quality standards we require. In such cases as well the ability to outsource these components allows us to remain competitive within this industry. And we are able to do this knowing that due to the standardised interfaces in PDM they will fit within our current designs without requiring any changes. So to answer your question, yes, I think PDM has played a large role in helping the company focus on its core competencies.'

The focus of the question aimed to highlight the role PDM has on allowing the company to focus on its core competencies through having the flexibility to outsource non-core processes to suppliers. This question provides basis for the benefits of outsourcing through allowing the company to focus its resources on core strategic activities. This resource focused approach will in turn create dependencies on the suppliers for the non-core processes. The supply chain manager's response discussed how the company currently uses PDM with a view to enable the division of the components into which components the company deems core to its operations and which components the company deems best to outsource. He also discussed how PDM can be used to overcome the company's limitations in manufacturing know how, through enabling the company to outsource such components with ease of mind that they will fit within their current designs. This in turn also leads the company to become dependent on suppliers of such components.

The third question asked the nature of agreements with current suppliers for the M1 and M2 modules as well as the T1 and T2 modules. Below is the transcript of the Supply Chain Manager's response.

‘We currently have the M1 and M2 modules outsourced from the same supplier. The T1 and T2 modules are also outsourced from the same supplier. Over the years we have had dealings with many suppliers. What modularity in design has offered us is a range of suppliers to choose from. This reduced the risks associated with module availability; however, it did take us some time to settle on a supplier. We tested out more than one supplier for the same module and eventually settled on a main supplier for each module with long-term agreements. We are very much integrated with our main suppliers, where they produce certain modules just for us with specific designs we ask for. They also share the same IT systems and have certain reporting files that are conjoint with our procurement employees and their sales employees manage together.’

This question aimed to assess the nature of the supply chain agreements created with the company’s suppliers. This is done with a view to evaluate the role PDM plays in creating long term strategic partnerships with the company’s suppliers. The supply chain manager’s answer discussed the role of PDM from a number of perspectives. The first perspective was the role PDM plays in reducing risks associated with outsourcing through allowing the company to have the flexibility in changing suppliers or depending on more than one supplier for the same component to ensure component availability. The second perspective identified that it was within the company’s best interest to create long term strategic agreements its main suppliers. The supply chain manager also discussed how PDM enables the company to choose the best supplier that fits with their own supply chain structure based on certain supplier selection criteria. Through having more than one supplier manufacturing the same standard module this allows the company to choose from among a range of suppliers. Where if the component was only manufactured by one supplier this would have created a power imbalance for the supplier.

Supplier integration was identified as the first relationship within the effect of PDM on supply chain integration. This relationship focuses on the nature of dependencies between the OEM and its suppliers, and the role PDM has on the strength of such dependencies. Even though, PDM allows the companies to have flexibility to choose from among different suppliers, evidence from the literature as well as from the interview responses identified that PDM also leads to the creation of long term strategic partnerships with the OEM’s main suppliers. The three questions within this relationship began by first identifying the role PDM has on the company’s outsourcing decisions. This is followed by recognising the role PDM has on enabling the company to identify and focus on its core competencies. At the same time recognise the components, which it will require to be outsourced. The last question focused on identifying the nature of supply chain relationships between the OEM and its suppliers regarding the outsourced components. This supplier integration in turn leads to further integration in terms of information sharing, design integration, and manufacturing integration.

Due to the data providing that M1 and M2 as well as T1 and T2 are both supplied form the same suppliers, the researcher was not able to conduct a comparison between the case modules in terms of the specific effects of each module on supplier integration. However, the responses from the interview questions presented an answer regarding the role PDM has on supplier integration in general in comparison to integral design.

4.4.2.2 Manufacturing Integration

As discussed in the previous relationship, the concept of a supply chain encourages companies to focus their resources on their core competencies while outsourcing processes that are not considered value adding. PDM breaks down the design of the end item into a set of independent modules allowing the production of such modules to be outsourced to upstream suppliers (Doran, et al., 2007). Hence, the manufacturing of the end item has become divided between members of the supply chain with each member in charge of producing certain modules. The OEM oversees assembling the final product as the interface with retailers and consumers. Production is no longer centralised under one supply chain entity. This results in the need for the OEM and the module suppliers to integrate their manufacturing through synchronised production (Jacobs, Vickery and Droge, 2007).

Data for this relationship was obtained through a semi-structured interview with the Supply Chain Manager of the case company. The supply chain manager was also chosen for this relationship because it lies within his responsibilities to set up the company's manufacturing strategy. The sales department and the procurement department are both under the supply chain department and both departments report to the supply chain manager. The supply chain manager is in charge of developing the production schedule based on inputs from both departments.

Concerning the effect PDM has on manufacturing integration, four questions were asked. These four questions represent the identified effects of PDM on manufacturing integration as identified through the integrative literature review conducted in Chapter Two.

The first question was divided into two parts. Part one asked how the case company integrates its manufacturing with its module suppliers. Part two asked what role PDM played in this process. Below is a transcript of the Supply Chain Manager's response.

‘For a company that produces physical end items such as ours, manufacturing integration between the different supply chain tiers and us as an OEM is my core business as a supply chain manager. The on-time availability of all the modules necessary for production to meet the agreed service levels with our retailers is one of the main goals of my department. The process actually begins from the supplier selection stage. This is where we test to see if the supplier will integrate with our framework of operations. We focus on a few indicators such as: lead time, flexibility in changing orders, production capacity, order fulfilment. For a certain module it is quite normal to have our needs divided between more than one supplier with a third supplier being tested just in case.

Another important point I would like to highlight is that our company’s production operations and assembly are all done on a push basis. We have forecasts compiled from our sales over the past 15 years and from them we develop our annual forecasts. However, the forecasts focus more on the month-to-month sales from each year. Our major markets here in Egypt are to big Tech retailers who we supply in bulk like wholesale and they oversee sales to the actual consumer. We have deals with these retailers to supply certain amounts of each product we produce, and we have a designated space for our products inside these retailers. The retailers also have their own warehouses, which is where we make our deliveries.

To talk about manufacturing integration, it is quite important to understand that we are a link in the supply chain with supply chain entities and organisations before us in the chain and others after us. We all need to work together as if we are one entity to be able to meet our deadlines.

Coming back to your question how we integrate our manufacturing operations is through having a detailed value stream map of each end item we produce. On this value stream map, we have every process required to produce that particular end item. These processes include the production of the modules for the end item and whether the production is done by us or outsourced as well as the expected lead time for each process. We are dependent on the suppliers of the outsourced modules to supply us with the right quantity at the right time and according to our quality standards. This has led us to share our yearly forecasts with our suppliers. We also conduct combined trainings with our major suppliers on new supply chain concepts and a number of trainings on lean production management and lean six sigma. We’ve also integrated our reports and one of our requirements for suppliers to work with us is to have an ERP system which can integrate with our own to facilitate the ordering process and transfer of information between our companies.

The role of PDM in this process is dividing up the end item into a set of independent and identifiable components. So even though the end item is divided it is very easy to see the complete picture. Through the value stream map, the value creation process for the end item becomes clear and who is in charge of creating which value. PDM helps in my opinion in setting up clear boundaries and responsibilities within the supply chain so every entity knows its role in the value creation process allowing it to better integrate with its partners for a win-win overall scenario where all entities in the supply chain gain in profit and reduce their operational costs.'

The objective of the first question was to identify whether PDM is considered to enhance manufacturing integration and if yes what role PDM plays in enhancing this integration. The supply chain manager's response confirmed that PDM has a positive effect regarding the manufacturing integration process. He first began through outlining the importance of manufacturing integration through the synchronising of supply chain activities across all supply chain members. The second part of his answer focused on how PDM simplifies the synchronisation process through 'setting up clear boundaries and responsibilities within the supply chain so that every entity knows its role in the value creation process'. He also identified that manufacturing integration is critical in achieving a win-win supply chain model, where all entities can through this integration create profit and reduce their operational costs.

The second question regarding whether the company shared its production schedule with its suppliers was already answered within the first question. The company does indeed share its yearly production schedules with its suppliers in an attempt to better synchronise their production schedules.

The second question aimed to identify if the manufacturing integration carried on including the sharing of production schedules to achieve manufacturing synchronisation. The supply chain manager within his answer to the first question already confirmed this. He also outlined how the manufacturing integration led to the development of mutual training programs between the case company and suppliers to work on such areas as lean manufacturing and lean six sigma manufacturing approaches.

The third question asked how often there are changes in the yearly production schedule and if PDM had a role in facilitating these changes to be made. Below is a transcript of the Supply Chain Manager's response.

‘We usually update our orders automatically on our ordering systems if any changes are to be made. As mentioned before, one of the main indicators we use in choosing our suppliers is flexibility in meeting our demands. It is very common for us to make an update to orders depending on market conditions. Over the past couple of years, the markets have been extremely turbulent due to the political situation in Egypt. Also, quite recently the government has taken a few measures, which make it quite hard for us to import in terms of limiting the amount of US Dollars available in banks and increasing import taxes. To cope with such measures, we’ve had to increase our orders and stock up on the parts we need. A lot of our orders recently are not according to the forecasts and are for a strategic purpose to ensure our productions don’t stop.

Since we also export and sell our products outside of Egypt we get paid in US Dollars. This has given us a competitive edge over other companies that only sell locally. Due to the availability of US Dollars we are still able to import, while some of our competitors have had to slow down production due to import problems. This has actually increased our market share over the past year.

I can’t think of a direct relationship between PDM and changing orders with our current suppliers from my perspective as an OEM. However, if we look at this from the supplier’s perspective it would seem that PDM here is very beneficial. On one hand if any of the customers of the supplier changes their orders whether increasing or decreasing the supplier can then balance out the orders, which have been reduced with the orders that have been increased.

However, because of these new regulations set upon us by the government recently we have been striving to look for local suppliers. We are also working on a few projects to develop our own modules and make instead of buy. Due to the design being modular this has allowed us the flexibility in finding more than one supplier for the modules here in Egypt. The only concerns are related to quality issues, which we are working on with the local suppliers and if fixed then some of our major importing problems can be fixed as well.’

This question aimed to identify if PDM affected the ability of a supply chain’s manufacturing in dealing with changing market demands. The supply chain manager indicated there was no direct relationship that he can see in terms of PDM influencing the supplier’s compliance to changing order amounts. However, he highlighted that the benefits can actually be from the supplier’s side. Where due to the component supplied being standard the supplier can shift production quantities from one customer to another depending on changing order levels.

The fourth question for this relationship regarding the cut off dates on changing orders for M1 and M2; T1 and T2 was not asked. This is due to the Supply Chain Manager's previous response in seeing no relationship between PDM and changing orders.

For this question as well, the researcher could not make a comparison between the specific modules because both M1 and M2 modules, and the T1 and T2 modules are purchased from the same supplier. Meaning that the supplier would follow the same procedure for order changes for both modules. Another factor is that the supply chain manager saw no direct relation between PDM and their ability to change order levels. The supply chain manager, however, did indicate how PDM could be beneficial for the supplier through allowing suppliers to better comply with changing order level by allocating the excess production to other customers.

Manufacturing integration is the second relationship identified regarding the effect of PDM on supply chain integration. The literature mainly focused on the role of PDM in enhancing manufacturing integration through improving synchronisation between different supply chain entities. Accordingly, the researcher asked four questions to assess the role of PDM on improving manufacturing synchronisation between the case company and its suppliers and its customers. The supply chain manager's response provided that PDM helped in identifying the role of each supply chain entity in the value creation process and the division and sharing of the different supply chain responsibilities. Therefore, manufacturing integration is positively influenced by PDM because it allows for the synchronisation of manufacturing operations between different supply chain entities.

4.4.2.3 Information Integration

Products are assembled according to their product architecture, which details the modules and their order of assembly needed to construct the end product (Baldwin and Clark, 2000; Pashaei and Olhager, 2015). PDM helps break down an end item into a set of independent modules giving component suppliers and OEM's a common language. The module itself becomes the language between suppliers and OEMs (Bush, Tiwana and Rai, 2010). This makes it quite easy to integrate information systems using the same module names and standardising the SKU's between the companies. This also allows companies to easily integrate their ERP systems for order management and sales using the same identifiable units.

Data for this relationship was obtained through a semi-structured interview with the Supply Chain Manager of the case company. The supply chain department for the case company is also in charge of writing and updating the master data for the company's ERP system. The company currently has a user license for several SAP modules including: production planning module, materials management module, sales and distribution module.

Regarding the effect PDM has on information integration two questions were asked. These two questions represent the identified effects of PDM on information integration as identified through the integrative literature review conducted in Chapter Two.

The first question asked aimed to investigate if there is a relationship between PDM and information integration from the supply chain manager's perspective. Below is a transcript of the supply chain manager's response.

'I think PDM definitely has a positive effect on information integration. Over the past few years we have been systematically following a strategy of updating our information systems in an attempt to automate a number of our day-to-day reports. The benefits of having an information system have been numerous especially for our department where everything is very much time sensitive.

PDM has been a major contributor in our ability to update our information systems. A critical part of the whole process as you might know is the coding phase. Where all end items and their bill of material breakdown need to be coded on the system. It was quite easy to code each and every single end item as well as the entire module components required to build each end item. PDM reduces the number of components per product family due to the commonality feature. This helped us immensely, where instead of coding and keeping track of millions of components, we only have to manage a much reduced number, which made it simpler to write and update the master data on our SAP modules. It has also been a blessing on our servers and databases.

Once our systems were updated, all new part code names were sent to our suppliers to integrate our ordering system with their sales system. When selecting our main suppliers, one of the main criteria is for them to have either Oracle or SAP systems that can provide outputs, which can be integrated directly with our systems. So, I can confirm to you now that these part codes provided in the multilevel BOM are the same codes used by our suppliers and our suppliers' suppliers and we have access from our systems to see their production schedule and product availability.'

This question aimed to identify how PDM enhances information integration between different supply chain entities. The supply chain manager's response focused on PDM's role in simplifying the coding process for the different manufacturing components. This coding process is critical to have a unified language between all supply chain members in coordinating the different supply chain processes. Through coding all their modules, the case company has been able to update its operational reports. These reports once standardised have been set up on ERP systems connecting the case company to its suppliers and customers, where a majority of these reports are now automatically created by through the company's ERP system. In addition to providing a unified language the supply chain manager also highlighted PDM's role in reducing the number of components managed. Having fewer components to manage also greatly simplified the communication problems between the case company and its suppliers.

The second question was asked to investigate the level of information integration between the company and its suppliers. However, this part of the question was already answered as part of the answer given to the previous question. The second part of the question focused more on identifying if there is an effect between PDM contributing to information integration and the company's ordering process, production schedule, and inventory control. Below is a transcript of the supply chain manager's answer.

'Now that we have the module codes unified, the ordering process is in part automated. We have certain quantities pre-ordered every year depending on our forecasts at fixed times throughout the year. We schedule the orders based on our materials management SAP module, which provides the material requirement plan based on our production forecasts. This material requirement plan is then sent to our suppliers, who synchronise their production schedules based on it. However, of course, minor adjustments are made based any market turbulence. These changes have to be made on average at least a month in advance to take into account production as well as transportation lead times. These changes can be updated directly on our systems and they will be mirrored on our suppliers' systems as well with notifications of the updated quantities and delivery dates. So, definitely a positive effect on the ordering process.

In terms of the production schedule, what PDM offers is organisation. It used to be quite a complicated process to transform a forecast into a production plan. Worst yet, to accurately calculate the material requirements needed for production. With modularity in design everything is organised. Decreasing the number of components, you have to manage makes the job a lot simpler. For the washing machines product family, we have 674 components, which are used in producing 39 different washing machines. These 674 components, some we make here at our production facilities and others we outsource from suppliers. For each of these components we have an estimated production or order lead-time. So, what PDM does is it allows us to integrate all this data together to set a realistic production schedule.

Finally, as for inventory control, we rely on the material management SAP module to calculate our material requirements as mentioned before. But by decreasing the number of components we have to control less SKU's. Which means less inventory overall for the product family. Also the end items that share the same modules eliminate each other's error in forecasts. If for example we forecasted on washing machine model to have a 1000 sales and we only sell 500 actual units, while another washing machine model that shares a modular component with the other washing machine had a forecast of 500 units sold, but in reality demand was for a 1000, we would still have stock and the discrepancy made in one forecast will be corrected by the discrepancy in the other forecast.'

The second question builds on the response from the first question. So, after it was identified that PDM helps the company in terms of information integration and simplifying the sharing information and communication with other supply chain entities, the next question was to identify how this translates into the everyday operations of the company. Therefore, the researcher focused the question on how PDM assists in such processes as order processing, production scheduling, and inventory control. The supply chain manager's response regarding order processing signified PDM's role in managing order processing. Where he indicated that order processing for the case company is mostly automated through strategic partnerships with suppliers. Integrating the information systems of both the case company and the suppliers by unifying the component codes and unifying the report formats as well helped in achieving this automation. Regarding production scheduling, the supply chain manager focused mainly on how PDM helps in organising the process. Specifically, he discussed the role PDM has in transforming a forecast into a production schedule and accurately calculating the material requirements accordingly. Finally, for inventory control, the supply chain manager focused on PDM's role in reducing the number of overall components per end item and per product family and discussed how this greatly simplifies inventory control through having fewer SKU's to manage.

Hence, through these interview questions it can be argued that PDM has a positive impact on improving information integration between supply chain members through providing a common language. This unified language in turn helps in simplifying day-to-day operations through the automation of such process as order processing, production scheduling, and inventory control. This can also be related to having positive effects on both the efficiency and effectiveness of the company's operations.

4.4.2.4 Design Integration

Design integration is a major part of the supply chain integration process. With companies now each focusing on developing components and modules instead of whole products, a main concern becomes how to integrate all these modules together to offer a final product (Voordijk, Meijboom and Haan, 2006; Mikkola and Gassmann, 2003). It is necessary for product design to become a collaborative process between the OEM and its suppliers to develop an end product with no quality or integration issues while at the same time taking account of the cost factor (Mikkola and Gassmann, 2003; Danese and Filippini, 2013). It is an extremely costly process to develop new product designs, which will require new process designs and might even require new supply chain designs with new material being acquired from new suppliers.

Modularity in design offers a common interface for the modules, which design engineers integrate in their new designs (Lau, Yam and Tang, 2010). Modularity in design also allows for the development of new product design through minor changes to the overall design or through different combinations of pre-existing modules (Jiao, Simpson and Siddique, 2007).

Data for this relationship was obtained through a semi-structured interview with the Product Design Engineer of the case company. The Product Design Engineer is in charge of transforming customer requirements into functional requirements. He is also in charge of updating designs for current products to meet such requirements or developing entirely new designs.

Regarding the effect PDM has on design integration two questions were asked. These three questions represent the identified effects of PDM on design integration as identified through the integrative literature review conducted in Chapter Two.

The first question aimed to identify the relation between PDM and changes in current product designs within the washing machines product family. Below is a transcript of the Product Design Engineer's response.

'What you need to understand is that product design is not a stand-alone process. Product design is very much a response to new marketing fads and changes in customer needs and expectations. It is then my job to translate all this into functions that the product will have to do. After the functions that the product will need to do are set comes the product design. The planning and production departments also need to be informed of the required changes to obtain their inputs regarding the current design and if they prefer any specific improvements. Some changes from the production department might aim at optimising their production operations. For example, focusing on a product design that will best utilise their machinery and process design. The planning department also needs to be kept notified of all changes in order to include any new updates in their forecasts, which will be translated into material requirement orders within the supply chain department.

This usually happens on an annual basis during the setting of our yearly production plans. The sales department is usually the provider for the customer needs and expectations. After that all four departments (product design, production, planning, and supply chain) have a separate meeting to see if updates to existing products are needed and if they can be accomplished or if new products are required and if they can be accomplished. The planning and supply chain departments are further in charge of conveying any new material requirements or updates to the current components being supplied to the suppliers. There are two scenarios here, first being that the new function already has a module that is being produced by the supplier, which is around 90% of the cases. The other case is that we need to meet with the suppliers to outline the functional requirements and work together to come up with the best design for the module to achieve these functions.

For example, taking the washing machines product family, the main function is to wash clothes. For this function to be accomplished, the product has to have the components necessary for washing the clothes and for draining the clothes. At this stage we need to allocate the functions that are required of the product onto the components that make up the product. Meaning that each component of the product will be responsible for a certain function. There are two paths that as a product design engineer I can take. The first path is to maximise the number of functions per component or the second path obviously is to minimise the number of functions per component. To give you a better example, let's look at the composition of the modules making up the washing machine product family. Now as you notice there are two motor modules, one is for washing and the other is for draining. As a design engineer, I can have both functions carried out by the same motor, or as is the case here, have two separate motors for each function with a motor for washing and another for draining. The benefit of having a separate module for each function allows me as a design engineer to equate this module with the function it accomplishes. So, when I have to update a product design or even come up with a new design, I can put the list of required functions in front of me and automatically translate these functions into modules. It is a lot more complicated to do this if the component has more functions, because then it will become more specific to that product and will be more difficult to transfer this component in other designs. So, even though I opted for having a separate module for each function, you might think that this increases the total number of modules per product family. However, by having a set of modules that are flexible enough to be used in different combinations within the entire product family, this reduces the total number of modules per product family. This is of course instead of having a set of modules that are fixed to a certain product only, which will require a different set of components per end item.'

This question aimed to identify the effect of PDM on design integration through first recognising the role of PDM when it comes to changing product designs. The product design engineer's response highlighted the case company's process when it comes to updating or changing product designs. This process begins with developing customer requirements into functional requirements, which are then translated into the product design. This is very much in line with what Tomiyama, et al. (2009) discussed in terms of the design structure matrix being based on inputs from the functional requirements, which in turn are based on the customer requirements. The product design engineer also discussed the complexity of the process due to the decisions affecting more than one department. Through his discussion it was clear the different trade-offs that come into effect when product design changes need to be made, with each department having its own objectives, which can sometimes be conflicting in nature. This gives further insight regarding the integration of multiple supply chain entities in the design process. Where the process starts from customer inputs through data collected from the case company's retailers. This data is then translated to functional requirements and design parameter requirements by the product design engineer, after which this is then conveyed to the production department to ensure the company's capabilities are compatible with such changes. It is also conveyed to the planning department, which translates these changes into material requirements, which need to be conveyed to suppliers. Finally, the supply chain department is in charge of coordinating the delivery and availability of the new components to ensure production lines do not stop. He also outlined the role PDM has in changing or updating product designs by giving an example using the motor modules category within the washing machine's product family. From his example it was clear that the process of changing product designs is much simplified when there is a one to one function to module relationship. He further explained that if an update needs to be made to include a specific function, the process of isolating the module, which is in charge of this function, and then updating or changing it can be much easily achieved with modularity in design. The process of conveying these changes to suppliers then becomes very specific, where the suppliers can update the specific module without changing the interface to ensure it still fits with the current washing machine models. Furthermore, this leads to reducing the total number of modules per product family, where more of the washing machines can share the same modules.

The second question aimed to investigate the effect of PDM on the process development for new product designs. Below is a transcript of the Product Design Engineer's response.

'During the process of designing a new product what we attempt to achieve first is the best quality fit. The new design might in fact use a number of the old modules already used within that product family. However, it also might require a completely new module. If this is the case and a new module is required, we have to look at how this new module will integrate with our current modules. We might need to update our current modules to fit with the new component or design the new component to fit with our current modules. It depends on whether we are manufacturing the module or outsourcing it. If we are making it ourselves that gives us more control over the process. We also might ask our suppliers for certain design specs. It all comes down to a cost benefit analysis project for each new module required. After that comes the decision whether to make it ourselves considering our capabilities and if we have the-know-how to build it, how much it will cost us, or if we will outsource it.

In some cases, we have had to redesign modules for an entire product family to fit a new module. However, the modules are redesigned with an overall objective of standaradisation to become modular and interchangeable between the different end items.

I can give you an example of this within the washing machines product family. We have recently introduced a new model. The story for this new model started when the sales department informed us that the customers in Egypt are now looking for washing machines that are sturdier, can withstand heavy duty, and has a longer life span (the average life span of a washing machine is five years under heavy use and can last up to 10 years with good use and maintenance).

The product design team then translated this requirement into functions and the functions were then translated into a product design as I explained to you. To comply with the customer expectations, we came up with a new design that can fulfil such demands. The concept of the new design was to change the basins module in the washing machine from plastic to stainless steel, which even though is a little costlier is known to be harder to ware than the plastic basins. So, you see we were able to come up with an entirely new product through changing only one module. As we already have our own stainless-steel production lines, we opted for this module to be insourced and is manufactured based on the design specifications we set in the design department. The product is in production now and we designed the stainless-steel basins to fit with all the modules within the washing machines product family.'

This question aimed to determine the role of PDM on process design and to investigate whether modularity in design led to the collaboration of process design across multiple supply chain entities. The product design engineer's answer gave much indication towards the effect of product design on process design. However, the example given only indicated the effect changing the product design had on internal processes within the case company and not across multiple supply chain entities. However, he also indicated that in cases where the module is outsourced the suppliers needed to be included in the design changes process if the module or component that needs to be changed or updated.

In regard to the effect of PDM on design integration the literature provided two main aspects: one in terms of the role of PDM in changing or updating product designs; and the other in terms of the effect of PDM on process design integration across the different supply chain entities (Howard and Squire, 2007). The interview with the product design engineer provided evidence towards the advantages PDM offered the case company in terms of achieving design integration with its suppliers on hand and customers on the other hand.

This section presented the findings supporting the second theme (supply chain integration), which was identified in the literature review as being one of the major areas that PDM affects to achieve operational improvements. PDM was found to affect four areas in particular, which are supplier integration, manufacturing integration, information integration, and design integration. Through the interviews conducted with the supply chain manager and the product design engineer it can be concluded that PDM affects all four dimensions positively. With PDM being a major factor helping the case company achieve supply integration with its supply chain members. Therefore, these findings are also used as evidence in support of the first and second research propositions (P1 & P2).

4.4.3 Supply Chain Responsiveness

Supply chain responsiveness has been defined as the ability of a supply chain to respond to changes in customer demand in terms of the time of delivery, quantity ordered, change in ordered items, or even cancellation of orders (Thatte, 2007; Holweg, 2005; Duclos, et al., 2003). This means that on an operational level a supply chain needs to be able to respond rapidly to changes in product volume and product mix through swift reconfiguration of manufacturing resources (Wang, Aydin and Hu, 2009).

Supply chain responsiveness was also identified under the umbrella of the economic themes linking PDM to economic sustainability. The more responsive a supply chain is the easier it is for the supply chain to maintain its competitive advantage. A responsive supply chain manages its resources more efficiently and can respond to customer demands in a more efficient manner resulting in market share and profitability performance (Qrunfleh and Tarafdar, 2013). Therefore, findings from this theme will also be used as evidence in support of the first and second propositions:

P1: PDM increases supply chain profit
P2: PDM decreases supply chain cost

Through the integrative literature review conducted in chapter two, PDM is identified to have an effect on two distinct relationships that positively enhance supply chain responsiveness: simplified production and scheduling; reducing production cycle lead time.

The first relationship is simplified production and scheduling. PDM has been identified in numerous literatures to reduce the number of overall components in a product family (Lau, Yam and Tang, 2010; Khan and Creazza, 2009; Jose and Tollenaere, 2005). Hence, reducing the overall number of components managed would in turn lead to flexibility of the manufacturing system. This would allow the supply chain to accommodate changes in product volume and product mix (Thatte, 2007). Managing fewer components has a number of positive effects in terms of simplifying production and scheduling. Firstly, fewer components mean fewer suppliers to manage (Doran, et al., 2007; Doran, 2003). Secondly, in terms of inventory control it would be easier to keep track of stock levels to a smaller range of items (Jacobs, Vickery, and Droge, 2007). Thirdly, through end items sharing modules, forecast error and discrepancies can cancel each other out (Mikkola and Gassmann, 2003).

This study focused on providing empirical evidence as to the effect of PDM on simplifying production and scheduling through a comparison between the case modules M1 versus M2 then repeated for T1 versus T2. The study first investigated if modularity in design affected the number of suppliers the company deals with on a regular basis. Secondly, the study compared between M1 versus M2 within the motors module category to examine the effect of modularity on reducing the number of modules managed (and repeated for T1 versus T2 within the timers module category). Thirdly, the study examined the planned production versus the actual production of the end items that share M1 compared to end items that share M2 to examine the forecast errors and discrepancies (and repeated for T1 versus T2).

The second relationship is production cycle lead-time. PDM is closely connected with process design. Having a modular product design would generally generate modular processes to manufacture it (Jacobs, Droge and Vickery, 2011). Swaminathan (2001) defined a modular process as one where products can be manufactured through separate stages. Each stage would lead to a semi-finished form of the product. The result is a more dynamic supply chain able to respond to changes in customer demand more promptly without incurring higher production and inventory costs (Thatte, 2007). Hence, this study also examined the production lead time for installing M1 the time required for installing M2 to investigate if M1 being more modular than M2 had an effect on the overall production cycle lead time of the end items (and repeated for T1 versus T2).

4.4.3.1 Simplified Production and Scheduling

The link between PDM and simplified production and scheduling has been developed in the literature from a number of angles. The first factor is the effect of PDM on reducing the overall number of suppliers (Danese and Filippini, 2013; Doran, 2003; Doran, et al., 2007). To examine this effect the researcher obtained purchase order records provided by the case company and analysed the suppliers of the 674 components required to produce the 39 washing machines. The case company grouped similar components into categories where the 674 components comprise 30 categories as is illustrated in Figure 4.1. From these categories the plastic parts, packaging and pallets, local hoses, SS tub and hoses are all manufactured by the case company. The components within the remaining categories are all outsourced with the case company contracting one main supplier per category. This means that the same supplier supplies all the motors, and the same supplier as well supplies all the timers.

In terms of reducing the number of suppliers, the effect of PDM can be seen in terms of the entire product family. The case company has divided its 674 components into 30 categories and contracts one main supplier per category group reducing the total number of suppliers the company has to manage greatly. However, since the case modules are both within the same category they are both outsourced from the same supplier. Therefore, even though the effect of PDM can be seen on the product family in general it could not be captured within the scope of comparing M1 to M2, T1 to T2.

The second factor is the effect of PDM on reducing the number of components in a product family, which leads to fewer components managed and easier tracking of inventory (Lau, Yam and Tang, 2010; Khan and Creazza, 2009; Jose and Tollenaere, 2005). To test the effect of PDM on reducing the number of components managed the researcher obtained the bill of material provided by the company. The study examines M1 as a percentage of the motor module category in comparison to M2 also as a percentage of the motor module category. This is done to validate the data where the comparison is conducted between variables of the same kind and at the same time the effect of the other module categories is controlled.

Case 1: M1 VS M2

As can be seen in Fig 4.9 M1 (Motor 17) comprises 38% of the motor module category compared to M2 (Motor 9), which comprises 5% only. By covering 38% of the motor needs of the washing machines product family, M1 hence reduces the total number of modules required within this module category and hence within the washing machines product family.

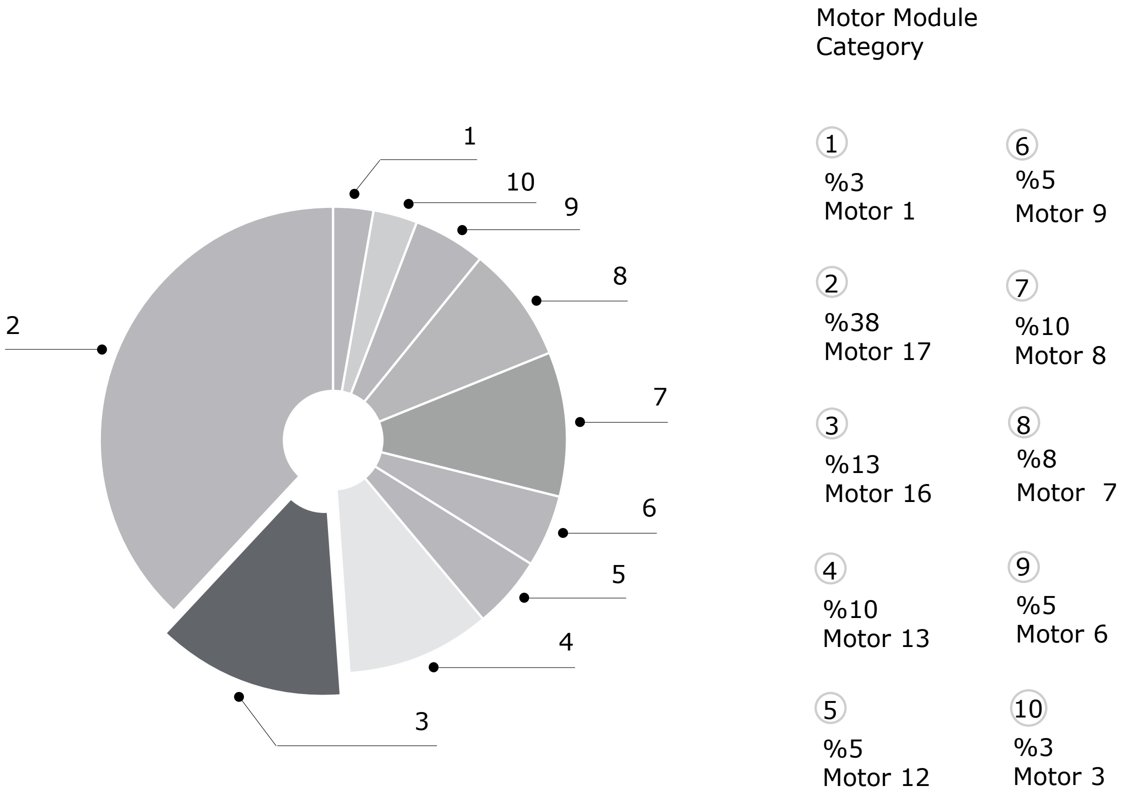


Figure 4.9 Motor Module Category

Case 2: T1 VS T2

As can be seen in Fig 4.10 T1 (Timer 1) comprises 29% of the timer module category compared to T2 (Timer 4), which comprises 5% only. By covering 29% of the timer needs of the washing machines product family, T1 hence reduces the total number of modules required within this module category and hence within the washing machines product family.

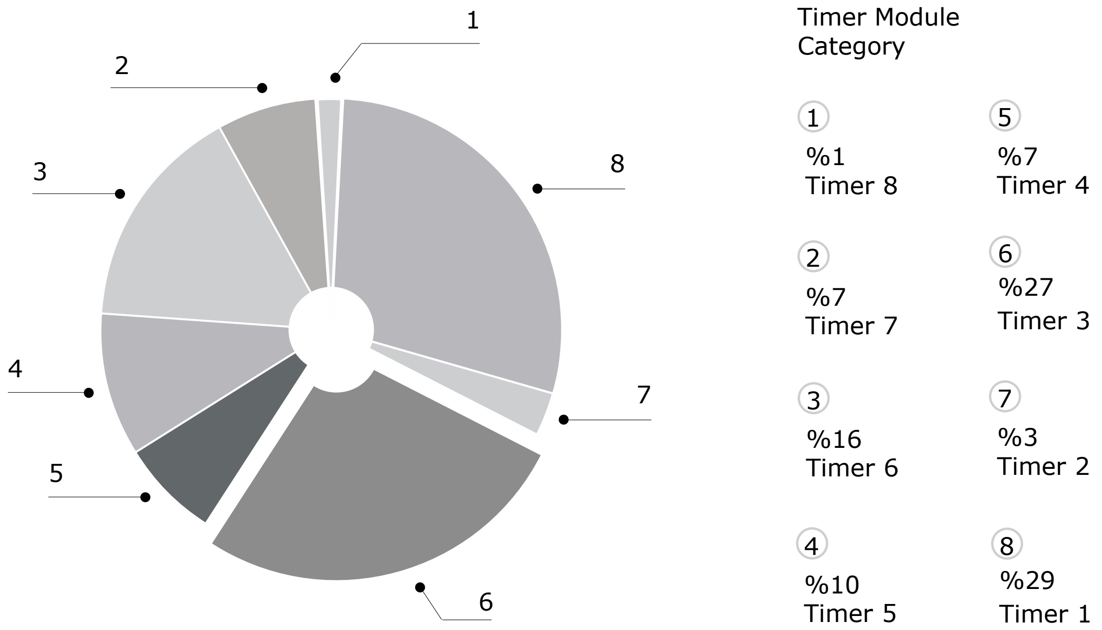


Figure 4.10 Timer Module Category

This relationship focuses on the commonality definition of PDM. The literature argued that a common module that is shared across a product family would lead to a reduction in the total number of components managed within that product family (Lau, Yam and Tang, 2010; Khan and Creazza, 2009; Jose and Tollenaere, 2005). Therefore, by presenting a comparison between each module in terms of the number of end items that depend on that specific module demonstrates the effect of commonality in reducing the total number of components. The first case compared between M1 and M2, where M1 is seen to cover 38% of the end items and M2 covers 5% only. The second case compared between T1 and T2, where the data shows similar results with T1 covering 29% of the end items and T2 covers 7% only. Having fewer components to manage adds to the company's flexibility when dealing with changing market conditions and therefore adds to the supply chain's responsiveness. Improved responsiveness is directly linked with a company's ability to capitalise on its opportunities in creating profit and manage its risks to avoid loss.

The third factor is the effect of PDM on counterbalancing forecasting errors through the inventory risk pooling effect (Pero, et al., 2010; Khan and Creazza, 2009). The researcher obtained records of actual versus planned production from the case company for a period of 23 months (all of 2015 and from Jan till Nov in 2016). The researcher also obtained the inventory records provided by the case company for the same time period. The study was conducted on the end items that share the motor module M1 with a view to identify whether M1 being common between the washing machines had an effect on reducing forecasting discrepancies. The same study is then carried out for M2 and a comparison between the effects M1 and M2 have is conducted. The same comparison is then also conducted for T1 versus T2 in the second case study. Table 4.3 and 4.4 present the planned versus the actual production of the 15 washing machine models sharing the M1 motor module for the year 2015 and the year 2016 till the month of November respectively.

Case 1: M1 VS M2

Table 4.3 Planned Versus Actual Production for 2015 for washing machines sharing M1

Model		Total 2015			
		Production			
	Opening Balance	Plan	Actual	Dev.	%
500002364	1,941	12,900	7,783	-5,117	-40%
500002363	9,763	10,080	10,086	6	0%
500002361	3,832	18,400	19,281	881	5%
500002377	3,693	3,650	5,979	2,329	64%
500002380	13,135	57,800	42,571	-15,229	-26%
500002460	0	3,200	0	-3,200	-100%
500001928	10,322	78,525	77,527	-998	-1%
500002004	2,823	29,000	32,249	3,249	11%
500001717	2,002	17,450	18,051	601	3%
500001802	0	0	0	0	0%
500001654	7,597	25,425	28,369	2,944	12%
500001645	29	0	0	0	0%
500001721	10	0	13	13	0%
500001916	4,628	6,250	3,555	-2,695	-43%
500001918	1,007	6,675	3,801	-2,874	-43%
Total	60,782	269,355	249,265	-20,090	

Table 4.4 Planned Versus Actual Production for 2016 for washing machines sharing M1

Model		Total 2016			
		Production			
	Opening Balance	Plan	Actual	Dev.	%
500002364	7,019	32,215	31,231	-984	-3%
500002363	5,177	17,830	14,422	-3,408	-19%
500002361	3,957	29,200	17,353	-11,847	-41%
500002377	3,871	7,000	2,913	-4,087	-58%
500002380	6,010	41,000	25,662	-15,338	-37%
500002460	0	0	0	0	0%
500001928	7,262	86,860	74,906	-11,954	-14%
500002004	2,381	35,400	29,952	-5,448	-15%
500001717	2,349	20,020	16,401	-3,619	-18%
500001802	0	0	0	0	0%
500001654	3,424	28,000	22,817	-5,183	-19%
500001645	0	0	0	0	0%
500001721	0	0	0	0	0%
500001916	942	4,750	4,893	143	3%
500001918	137	4,810	3,881	-929	-19%
Total	42,529	307,085	244,431	-62,654	

The opening balance in the tables represents the beginning inventory of finished washing machines already manufactured. The opening balance is taken into account when calculating the production requirements. The planned production column is the forecasted quantity of washing machines required. The actual production column is the quantity actually manufactured.

As can be seen in the tables 4.3 and 4.4 the deviation between the actual and planned is the forecasting error. For some models there is an overestimation in the forecast, which came up to a total of 30,113 washing machines and for other models there is an underestimation, which came up to a total of 10,023 washing machines for 2015. For 2016 there was a total of 62,797 overestimated washing machines and 143 underestimated washing machines.

M1 being common between all 15 models allowed for flexibility in production where the excess motor modules from the washing machines that were overestimated can be used in the washing machine models that were underestimated. Overall the case company has overestimated its production by 20,090 washing machines for 2015 and 62,654 washing machines for 2016. Total actual production for both 2015 and 2016 amounted to 493,696 washing machines. Total actual production excluding the opening inventory amounted to

390,385. Total inventory for the same period of M1 amounted to 401,838 motors. The total difference between actual production of washing machines manufactured with M1 and total inventory of M1 over the 23 months period equal 11,453 motors.

Table 4.5 Planned Versus Actual Production for 2015 for washing machines sharing M2

Model		Total 2015			
		Production			
	Opening Balance	Plan	Actual	Dev.	%
500002375	8515	28,300	20,229	-8,071	-29%
500001705	3692	50,430	50,930	500	1%
Total	12207	78730	71159	-7571	

Table 4.6 Planned Versus Actual Production for 2016 for washing machines sharing M2

Model		Total 2016			
		Production			
	Opening Balance	Plan	Actual	Dev.	%
500002375	6555	25,100	24,487	-613	-2%
500001705	4308	52,715	44,900	-7,815	-15%
Total	10863	77815	69387	-8428	

As can be seen in the tables 4.5 and 4.6 for one model there is an overestimation in the forecast, which came up to a total of 8,071 washing machines and for the other model there is an underestimation, which came up to a total of 500 washing machines for 2015. For 2016 there was a total of 8,428 overestimated washing machines and 0 underestimated washing machines.

Overall the case company has overestimated their production by 7,571 washing machines for 2015 and 8,428 washing machines for 2016. Total actual production for both 2015 and 2016 amounted to 140,546 washing machines. Total actual production excluding opening inventory amounted to 117,476. Total inventory for the same period of M2 amounted to 149,256 motors. The total difference between actual production of washing machines manufactured with M2 and total inventory of M2 over the 23 months period equal 31,780 motors.

When comparing M1 to M2, it is noticeable that since M1 is shared across more washing machines there are more opportunities where the commonality feature allows M1 to be transferred from overestimated planned production to underestimated actual production. This occurs in 10,166 washing machines during the 23 months period of analysis compared to 500 washing machines for M2. M1 being common also means that even if it is overestimated it is still flexible so that any excess inventory can be used in any of the 15 models for the following year. It is also noticeable that on hand inventory of M1 is very close to actual production with only an excess of 11,453 motors, while for M2 there is an excess of 31,780 motors. When this is calculated as excess inventory per end item the difference in numbers is magnified even further. M1 excess modules per washing machine equal 763 units, while M2 excess modules per washing machine equal 15,890 units.

Case 2: T1 VS T2

Table 4.7 Planned Versus Actual Production for 2015 for washing machines sharing T1

Model		Total 2015			
		Production			
	Opening Balance	Plan	Actual	Dev.	%
500002361	3,832	18,400	19,281	881	5%
500002375	6,555	28,300	20,229	-8,071	-29%
500002376	3,207	12,200	2,230	-9,970	-82%
500002377	3,693	3,650	5,979	2,329	64%
500002421	6,010	25,860	15,002	-10,858	-42%
500002460	0	3,200	0	-3,200	-100%
500002461	0	1,450	0	-1,450	-100%
500002462	0	200	0	-200	-100%
500002471	0	2,100	0	-2,100	-100%
500002160	1,835	9,760	7,789	-1,971	-20%
500002004	2,823	29,000	32,249	3,249	11%
500001705	4,308	50,430	50,930	500	1%
500001717	2,002	17,450	18,051	601	3%
500001802	0	0	0	0	0%
500001654	7,597	25,425	28,369	2,944	12%
500001645	29	0	0	0	0%
500001721	10	0	13	13	0%
500001916	4,628	6,250	3,555	-2,695	-43%
500001918	1,007	6,675	3,801	-2,874	-43%
500002214	37	0	537	537	0%
Total	47,573	240,350	208,015	-32,335	

Table 4.8 Planned Versus Actual Production for 2016 for washing machines sharing T1

Model		Total 2016			
		Production			
	Opening Balance	Plan	Actual	Dev.	%
500002361	3,957	29,200	17,353	-11,847	-41%
500002375	8,518	25,100	24,487	-613	-2%
500002376	7,300	9,500	2,864	-6,636	-70%
500002377	3,871	7,000	2,913	-4,087	-58%
500002421	6,423	27,300	15,584	-11,716	-43%
500002460	0	0	0	0	0%
500002461	0	0	0	0	0%
500002462	0	0	0	0	0%
500002471	0	0	0	0	0%
500002160	1,105	10,740	6,779	-3,961	-37%
500002004	2,381	35,400	29,952	-5,448	-15%
500001705	3,692	52,715	44,900	-7,815	-15%
500001717	2,349	20,020	16,401	-3,619	-18%
500001802	0	0	0	0	0%
500001654	3,424	28,000	22,817	-5,183	-19%
500001645	0	0	0	0	0%
500001721	0	0	0	0	0%
500001916	942	4,750	4,893	143	3%
500001918	137	4,810	3,881	-929	-19%
500002214	0	0	600	0	0%
Total	44,099	254,535	193,424	-61,711	

As can be seen in tables 4.7 and 4.8, for some models there is an overestimation in the forecast, which came up to a total of 43,389 washing machines and for other models there is an underestimation, which came up to a total of 11,054 washing machines for 2015. For 2016 there was a total of 61,854 overestimated washing machines and 143 underestimated washing machines.

T1 being common between all 20 models allowed for flexibility in production where the excess motor modules from the washing machines that were overestimated can be used in the washing machine models that were underestimated. Overall the case company has overestimated their production by 32,335 washing machines for 2015 and 61,711 washing machines for 2016. Total actual production for both 2015 and 2016 amounted to 401,439 washing machines. Total actual production excluding the opening inventory amounted to 309,767. Total inventory for the same period of T1 amounted to 384,614 motors. The total difference between actual production of washing machines manufactured with T1 and total inventory of T1 over the 23 months period equal 74,847 motors.

Table 4.9 Planned Versus Actual Production for 2015 for washing machines sharing T2

Model		Total 2015			
		Production			
	Opening Balance	Plan	Actual	Dev.	%
500002364	1,941	12,900	7,783	-5,117	-40%
500002363	9,763	10,080	10,086	6	0%
500002016	24,765	105,230	112,700	7,470	7%
500001866	0	29,000	0	-29,000	-100%
500001928	10,322	78,525	77,527	-998	-1%
Total	46,791	235,735	208,096	-27,639	

Table 4.10 Planned Versus Actual Production for 2016 for washing machines sharing T2

Model		Total 2016			
		Production			
	Opening Balance	Plan	Actual	Dev.	%
500002364	7,019	32,215	31,231	-984	-3%
500002363	5,177	17,830	14,422	-3,408	-19%
500002016	13,963	119,035	94,483	-24,552	-21%
500001866	0	0	0	0	0%
500001928	7,262	86,860	74,906	-11,954	-14%
Total	33,421	255,940	215,042	-40,898	

Tables 4.9 and 4.10 show that for some models there is an overestimation in the forecast, which came up to a total of 35,115 washing machines and for other models there is an underestimation, which came up to a total of 7,476 washing machines for 2015. For 2016 there was a total of 40,898 overestimated washing machines and 0 underestimated washing machines.

Overall the case company has overestimated their production by 27,639 washing machines for 2015 and 40,898 washing machines for 2016. Total actual production for both 2015 and 2016 amounted to 423,138 washing machines. Total actual production excluding opening inventory amounted to 342,926. Total inventory for the same period of T2 amounted to 398,377 motors. The total difference between actual production of washing machines manufactured with T2 and total inventory of T2 over the 23 months period equal 55,451 motors.

When comparing T1 to T2 it is noticeable that since T1 is shared across more washing machines there are more opportunities where the commonality feature allows T1 to be transferred from overestimated planned production to underestimated actual production. This occurs in 11,197 washing machines for the same 23 months period of analysis compared to 7,476 washing machines for T2. T1 being common also means that even if it is overestimated it is still flexible so that any excess inventory can be used in any of the 20 models for the following year. In this case the role PDM plays on reducing the discrepancies only becomes clear when the comparison is based on the excess inventory of timer modules per washing machine. T1 excess modules per washing machine equal 3,742 units, while M2 excess modules per washing machine equal 11,090 units.

The findings present that PDM plays a major role in helping the company manage its forecast discrepancies. This is done through either allocating the modules, which were assigned to overestimated washing machines to underestimated washing machines. This can be seen in both the M1 (10,166) VS M2 (500) case and the T1 (11,197) VS T2 (7,476) case. PDM also allows the company to use the modules, which are assigned to overestimated washing machines as opening inventory for the next production period. When comparing the number of on hand inventory for M1 to M2 in relation to actual production, the data provides that the company can manage its production for washing machines sharing M1 (763) with considerably less inventory than it requires for the production of washing machines sharing M2 (15,890). The same was seen to be true as well for T1 (3,742) VS T2 (11,090).

The focus of this relationship is on outlining how PDM simplifies the production and scheduling leading to improved supply chain responsiveness through three effects. The first was regarding reducing the number of suppliers. The second was in terms of the effect of PDM on reducing the number of modules within a product family. The third focused on PDM's ability to help the case company manage discrepancies in forecasts through giving the company the flexibility to use the common modules in other end items or using the modules as opening inventory for the next production period.

4.4.3.2 Reduced Production Cycle Lead Time

The second relationship linking PDM to supply chain responsiveness is the effect of PDM on reducing the production cycle lead-time. Jacobs, Vickery and Droge (2011) linked PDM to modularity in process design, arguing that a modular product design would lead to a more dynamic process design able to promptly respond to changes in customer demand without increasing production or inventory costs. Modularity in design leads to the standardisation of modules and components used in production (Lau, Yam and Tang, 2007). This standardisation process leads to a more efficient process design, where opportunities for automation and a more efficient work force would generally lead to higher production volumes due to reduced production cycle lead times.

The researcher obtained the production man minutes and machine hours required in production and assembly of all 39 washing machine models, which were provided by the case company. The researcher then proceeded to compare between the production man minutes and machine hours required in the assembly of M1 in comparison to M2. The researcher followed by analysing the overall effect the assembly time of M1 has on the overall production cycle lead time in comparison to M2. This was done by comparing the man minute and machine hours used in installing M1 in actual units of washing machines produced over the 23 months period in comparison to M2. This study is then repeated for the second case study as a comparison between T1 and T2.

Table 4.11 Man Minute and Machine Hours for Case Modules

	Man Minute and Machine Hour	Total Production (for 23 months period of analysis)
M1	0.258772	390,385
M2	0.281547	117,476
T1	0.254144	309,767
T2	0.272367	342,926

Table 4.12 Time Saved in Minutes

	Time Saved in minutes	Total Time Saved (for 23 months period of analysis)
Difference between M1 and M2	0.022775	8891.14
Difference between T1 and T2	0.018223	5644.89

Case 1: M1 VS M2

Total instalment time for M1 including man minute and machine hours is 0.26 minutes approximately. While total instalment time for M2 is 0.28 minutes approximately. There is a slight difference of 0.02 minutes approximately between M1 and M2 instalment times. However, over the 23 months period when comparing this time difference to actual washing machine units produced would lead to 8,891 saved minutes approximately.

Case 2: T1 VS T2

Total instalment time for T1 including man minute and machine hours is 0.25 minutes approximately. While total instalment time for T2 is 0.27 minutes approximately. There is a slight difference of 0.02 minutes approximately between T1 and T2 instalment times. However, over the 23 months period when comparing this time difference to actual washing machine units produced would lead to 5,645 saved minutes approximately.

The focus of this relationship is on highlighting the effect PDM has on streamlining process design. Where through PDM the workers are more acquainted with the process of assembly for the M1 and T1 modules in comparison to the M2 and T2 modules.

Therefore, in terms of the effect of PDM on improving supply chain responsiveness, the data provides that through PDM both production and scheduling, and production cycle lead times are improved. This gives the company an edge in dealing with changing market requirements allowing the company to capitalise on opportunities where it can increase its sales and reduce its operational costs. Data from this relationship is therefore also used as evidence in support of the P1 and P2 research propositions.

4.5 The effect of PDM on the environmental performance of a supply chain

The integrative literature review conducted in Chapter Two helped the researcher to identify the main areas where PDM influences the environmental performance of a supply chain (Figure 4.11 Effect of PDM on Supply Chain Environmental Performance).

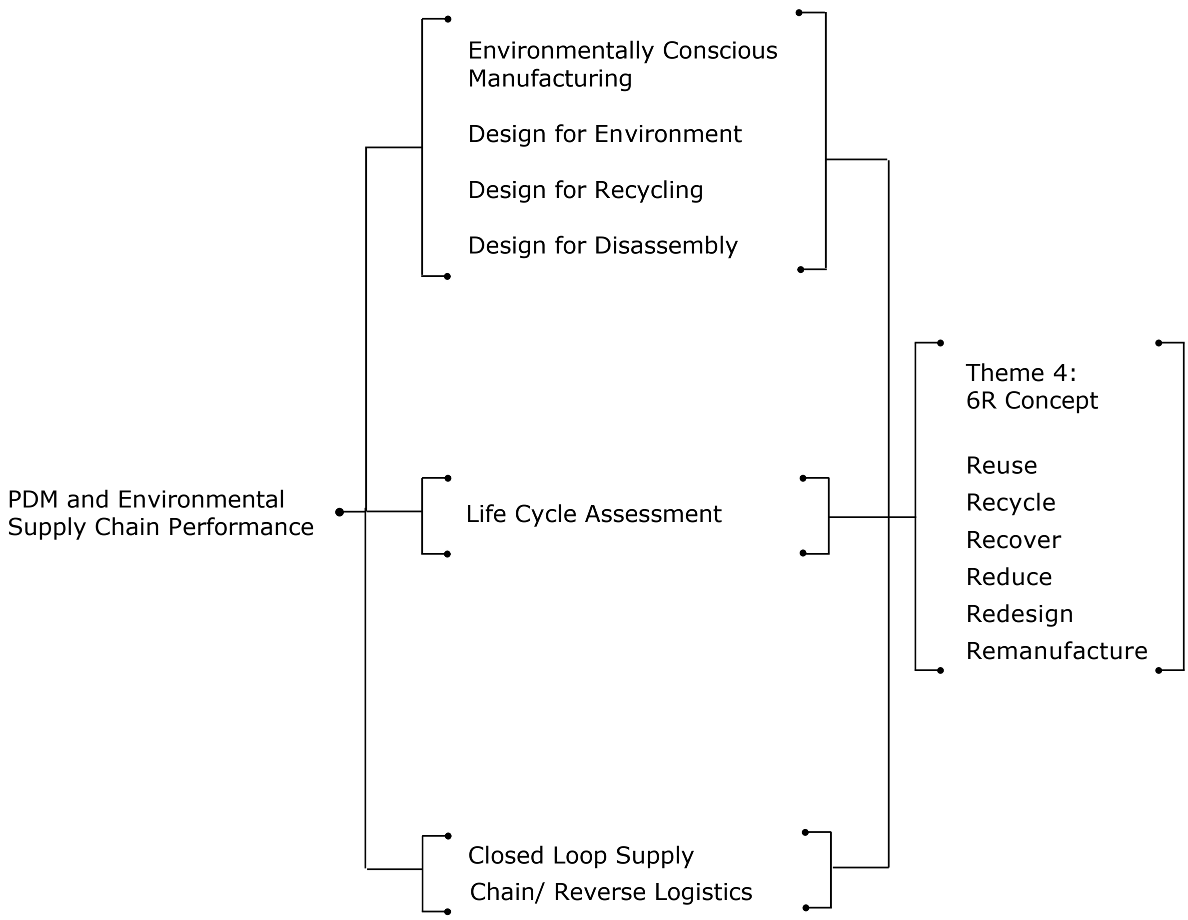


Figure 4.11 Effect of PDM on Supply Chain Environmental Performance

PDM is considered a major facilitator to enhancing environmental performance in three distinct areas of the literature. The first group of literature discussed the evolution of manufacturing strategies to include environmental considerations. The main manufacturing strategies, which discussed a relation between modularity in design and environmental enhancement, were environmentally conscious manufacturing (ECM), design for the environment (DFE) and design for recycling (DFR) (Gu and Sosale, 1999; Meehan, et al., 2007; Zian and Zhang, 2009; Kristianto and Helo, 2015). The second group of literature signified the role of PDM within the life cycle assessment (LCA) process of a product, where a product's life cycle is conjoint to the life cycle of its modules (Tseng, Chang, and Cheng, 2010; Yu, et al., 2011; Seuring, 2013; Beske and Seuring, 2014). The third group of literature discussed the role of PDM in managing product returns, incorporating a reverse logistics channel and the redesign and transformation of a supply chain into a closed loop system (Taticchi, Tonelli and Pasqualino, 2013; Bask, et al., 2013; Aydinliyim and Murthy, 2016).

4.5.1 The 6R Concept

A common element across all three streams of literature was the basis for their arguments in signifying the role of PDM in improving environmental performance. All three streams of literature based their arguments on the role modularity in design has on improving the reuse, recycling, recovery, reduction, redesign, and remanufacture of components and products (refer to Table 4.13). Therefore, the fourth theme identified within the integrative literature review conducted in Chapter Two was the 6R Concept. This theme focuses on the effect PDM has on improving the 6R's through either implementing environmentally conscious manufacturing, product life cycle assessment, or reverse logistics and closed loop supply chain management.

Table 4.13: The 6Rs

Reuse	'The means that a product or its components could be reused in similar products' (Yan and Feng, 2013).
Recycle	'The process of converting material such as metals and plastics to improve the reuse of potentially useful materials' (USEPA, 2008).
Recover	'The process of collecting used products at the end of life or during maintenance, and then disassembly, sorting, and cleaning for utilization' (Joshi, et al., 2006).
Reduce	'Is to use less of any non-renewable resource through focus on reuse, recycling and recovering activities' (Joshi, et al., 2006).
Redesign	'Is to improve next generation product designs through innovative techniques to make them more sustainable' (Joshi, et al., 2006).
Remanufacture	'Is the reprocessing of used products or components through innovative techniques without loss of functionality' (Joshi, et al., 2006).

Figure 4.12 builds a relation between all 6Rs denoting the recovery process as the initiator for the reuse, recycling, and remanufacturing processes. Redesign is identified as an independent process. All these processes ultimate aim is to reduce the energy consumed during production and the use of non-renewable resources.

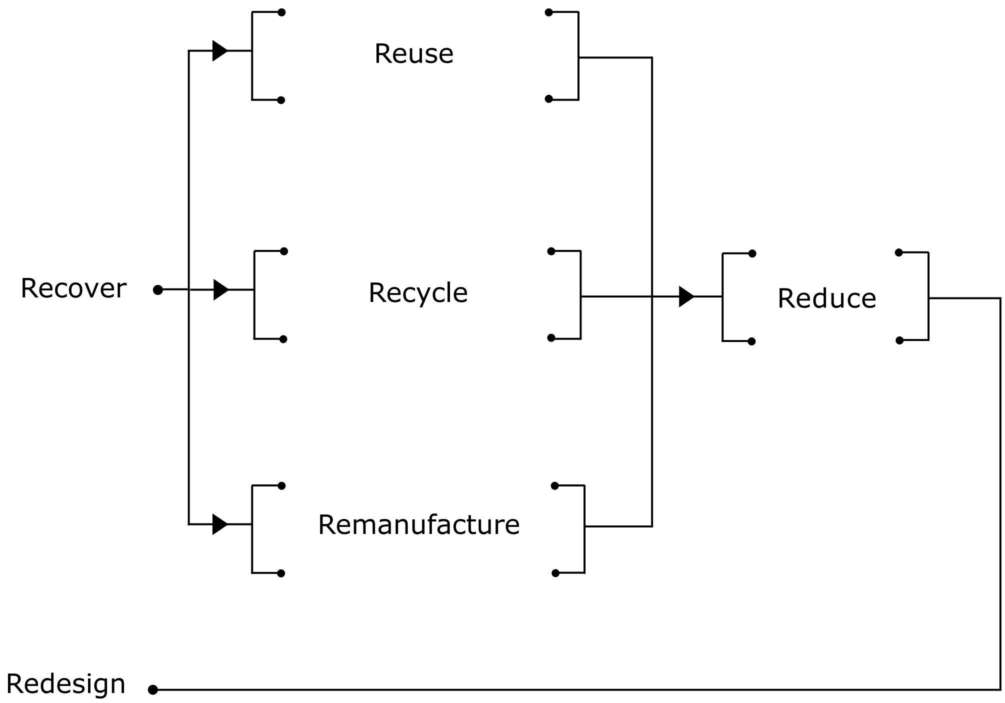


Figure 4.12 6R Concept

Data collected, and analysis conducted for the relationships identified within this theme will be used to support the third proposition:

P3: PDM reduces environmental harm within a supply chain

4.5.1.1 Environmentally Conscious Manufacturing / Design for Environment / Design for Recycling

The basis for environmentally conscious manufacturing is to change the manufacturing strategies focus from purely economic to strategies that consider environmental elements such as recycling, reuse and reduce (Yan and Feng, 2013). Modularity in design develops products with modules, which can be easily separated and interchanged. Therefore, PDM allows for the possibility of removing or replacing certain modules from the end item without affecting the functionality of the end item. This leads to reducing the bulk material required in manufacturing. Another aspect is through modular design it becomes easier to change the modules, and to choose greener suppliers and greener modules without necessarily changing the entire design of the product, with the change being concentrated to a limited number of modules (Yu, et al., 2011).

Data for this relationship was obtained through a semi-structured interview with the Product Design Engineer of the case company. The Product Design Engineer is in charge of maintaining and updating designs for existing products and developing designs for new products.

In terms of the effect PDM has on environmentally conscious manufacturing four questions were asked. These four questions in particular represent the identified effects of PDM on environmentally conscious manufacturing as identified through the integrative literature review conducted in Chapter Two.

The first question aimed to identify whether the Product Design Engineer considered PDM as a driver towards ECM within the washing machines product family. Below is transcript of his response.

'I would have to say that in recent years the way we design our products has changed quite considerably. From my own view of things this can be attributed to a number of reasons:

1. Pressure from the Egyptian Environmental Affairs Agency (EEAA) regarding new regulations on the disposal of solid wastes that encourage and enforce recycling. (Full regulations provided in Appendix V)
2. Our company offers 3 to 5 year warranties on washing machines, which requires us to offer maintenance and after sales service in case of any malfunctions during that period.
3. Customers purchasing trends have changed requiring products that have wider range of functions.

From my perspective these three reasons have attributed to the changes in product design and have been a major driver towards PDM for washing machines over the past 10 years. We have had to include environmental considerations such as waste disposal at end of life and recycling due to the regulations imposed by the EEAA in our product designs. Our warranty program also requires us to offer maintenance and repair to products for either 3 or 5 years depending on the product. Finally, customers now expect their washing machines to not only wash their clothes, but to also have a timer, more than one washing program, digital display, ability to add more clothes mid washing cycle. All these customer requirements must be translated into functional requirements and incorporated within the product design. But with the addition of more functions the risk of more malfunctions increases as well.

We have had major scale projects over the past 10 years to incorporate modularity in a number of our products. Through having our end products composed of modules, where each module has a particular function, it becomes easy to disassemble modules from the end item without affecting the functionality of the end item.

This has simplified our maintenance and repair operations significantly. Our after sales service and maintenance crew carry their own inventory for modules, which are required on a regular basis during their maintenance operations. They are more flexible and able to offer customers maintenance in their own homes. Costs associated with maintenance and repairs have also gone down significantly from an operational perspective. Our maintenance crew can either replace the faulty module on the spot or in some cases the module is taken back to the workshop where it is fixed and then replaced.

This has also allowed us to enhance our recycling operations. We are now operating a facility in charge of recycling all plastic and rubber components recovered.
What we do is we focus on a product family and we look at the components used in the manufacturing of the end items within that product family. We then look at opportunities where we can standardise one of these components across the entire product family. Once said components that can be standardised are identified we then work on updating the interface designs of the entire product family to accommodate this standardised component. This allows us to reduce the total number of components within a product family. This standardisation also helps in making this particular component more available due to the risk pooling effect.

There is also a relationship between PDM and the energy consumed during manufacturing since PDM influences process design as well. Through simplifying the process design this would also lead to reducing the energy consumed during manufacturing. '

The second question asked focused on identifying if there was an existing case within the company where PDM has already been used to enhance design for environment through either substituting an existing module or redesigning new or existing modules with greener material. Or if the company has ever changed its suppliers on the basis that one supplier ranked better in terms of environmental performance for using renewable material or green methods for manufacturing. Below is a transcript of the Product Design Engineer's response.

‘Such a scenario has not occurred yet within our company. However, it is very possible. I can definitely understand how a product being modular makes it simpler to change one module or one supplier for a greener one.’

Questions regarding the effect of PDM on design for recycling and reducing the total number of components within a product family were already answered within the first question and therefore were not asked again.

The product design engineer’s answer broke down the drivers for ECM from the perspective of the case company. Outlining that the main driver towards manufacturing strategies that focus on the environmental criteria being the regulations imposed from the EEAA. However, factors such as maintenance and repair considerations as well as customer requirements also played a major role leading to the dependence on PDM as a design strategy. The EEAA regulations outline disposal procedures and waste management for electronic products, which the washing machines are classified under. These regulations stipulate that the manufacturing company should provide the customer with waste disposal options at the end of life of the product. Therefore, the case company already applies PDM as a design strategy to facilitate this process. The process design engineer mainly focused on PDM facilitating the breakdown of the end items into their base modules, which enables the company to separate parts that can be recycled, parts that can be remanufactured, and parts that the company sells as scrap. This greatly reduces the amount of waste that results from each washing machine, with more parts being recycled or remanufactured. This also reduces the amount of new material the company requires in its manufacturing operations. The product design engineer also mentioned a relation between modular products leading to modular processes arguing that modular processes lead to energy reduction in the manufacturing process. All these points validate the relationship between PDM and ECM identified in the literature review leading to overall improvement in the environmental aspect.

4.5.1.2 Life Cycle Assessment (LCA)

LCA has been defined as a design methodology, where a designer develops a life cycle scenario for the product by assigning life cycle options such as maintenance, upgrading, recycling and reuse for different stages through a product’s life (Umeda, et al., 2008). Through the integrative literature conducted in Chapter Two it became apparent however that the nature of the design process has changed from focus on a product’s life cycle to a focus on a module’s life cycle (Yu, et al., 2011; Ijomah, et al., 2007). Modularity in design allows for products to be composed of independent components, which can be easily separated and changed without affecting the overall functionality of the product. Hence, life cycle options such as maintenance, upgrading, recycling and reuse are no longer only attached to the end item, but are now attached to the modules making up the end item. By changing the focus to the modules instead of the end item allows for chances to elongate the end item's life cycle; to upgrade the end item through changing certain modules while keeping the remaining modules within the end item in tact; to simplify the maintenance and repair processes (Agrawal, Atasu, and Ulku, 2016; Beske and Seuring, 2014; Qian and Zhang, 2009).

Data for this relationship was obtained through a semi-structured interview with the Product Design Engineer of the case company. The Product Design Engineer is in charge of maintaining and updating designs for existing products and developing designs for new products.

Regarding the effect PDM has on life cycle assessment four questions were asked. These four questions in particular represent the identified effects of PDM on life cycle assessment as identified through the integrative literature review conducted in Chapter Two.

The first question aimed to identify if there has been a shift in focus from a product life cycle focus to a module life cycle focus within the design strategies of the case company in an effort to improve the company's environmental performance. Below is a transcript of the Product Design Engineer's response.

'As a design engineer my concept of a product's life cycle begins a little earlier than say for example someone in marketing. For me a product's life cycle begins from pre-manufacturing on to manufacturing then usage then post use and end of life (disposal). At each of these four stages there are very specific constraints that have to be considered. To begin with, as discussed before our whole design concept has to be in line with our customer requirements, which is an overarching constraint that we have to abide at all stages of the product's life cycle.

At the pre-manufacturing stage we must consider the material input into the product. Is this material from a renewable source? If not is it at least recyclable? Is the supplier where we purchase the material from following green procedures in the processing of this material?

At the manufacturing stage we must consider the energy usage in the production stage. This of course has economic implications as well as environmental implications. Trade-offs in the process design stage have to be considered in terms of productivity versus energy usage.

At the usage stage we must consider issues related to maintenance and repair. Another important criterion is the energy consumption of the product when in use.

At the end of life and disposal stage many of the decisions we already made during the previous stages come into play. For example, the decisions related to the material used in the product whether it is renewable and biodegradable or recyclable will have a direct effect on the end of life options for the product. Some considerations for this stage have to be made during the product design stage, mainly the disassembly of the product. We must think in a way that all the material used within the product will either be recycled or end up in a landfill.

Now coming back to your question whether the company still focuses on a product's life cycle or have we started changing our focus to modular life cycle. I would have to say that even if we still think we are focusing on the product's life cycle, the nature of our product is modular. Our company has had an overhaul of its product designs over the past 10 years and we are becoming more modular. So, yes, our focus has definitely changed.

Modularity plays a role in enhancing our environmental performance at each of these four stages. In the pre-manufacturing stage it allows to easily choose suppliers or new material when needed and change modules or suppliers with ease without necessarily affecting the rest of the design. At the manufacturing stage, modularity directly affects our process design allowing for more energy efficient operations, due to reduced errors and reworks for the end items. Also, because each process is clearly linked to a specific module this gives us more control over the amount of energy each process requires. At the usage stage it greatly simplifies our maintenance and repair operations for our after sales service crew. It also greatly helps in elongating the product's life cycle during usage by simply replacing damaged modules with new ones allowing for the product to remain functional. At the disposal stage, modularity allows for the easy dismantling of the product and separation of the modules to see what options there are for each module whether recycling or scrap or landfill.'

This question aimed to identify the degree to which the case company utilises PDM in its planning for product life cycle options. The product design engineer's response highlighted how that the case company breaks down a product's life cycle into four distinct stages: 'pre-manufacturing, manufacturing, usage, end of life (disposal)'. The product design engineer also highlighted the main constraints at each of these stages in a product's life cycle and how modularity in design helps in achieving a product design that can abide by these constraints. For the pre-manufacturing stage he discussed issues such as sourcing decisions for the material to be used in the product. He explained that through PDM the case company has been able to have the flexibility in choosing the best suppliers that provide modules, which achieve the required function and at the same time are widely recyclable. At the manufacturing stage the constraints originate from requirements to enhance productivity and reduce energy consumption. PDM is seen to affect the manufacturing stage through its effect on process design, where PDM leads to a more streamlined process. A streamlined process design leads to less errors and reworks in the end items and with each process seamlessly linking into the next there is more control and understanding of the amount of energy each process requires. The usage stage PDM is seen to simplify the process of maintenance and repair. It is at this stage that PDM's effect on elongating overall product life can be truly seen. Through maintenance and repair a washing machine can be used for up to 10 years with only slight changes in overall product performance. Finally, relating to the disposal stage, PDM simplifies the process of dismantling of the washing machines into their base components. This allows the case company to easily distinguish which modules will be recycled, sent to a landfill, or sold as scrap. Table 4.14 shows the module categories for the washing machine product family with 49% of the modules being considered plastic components, which are recycled through the case company's recycling facilities. Therefore, the case company's focus is already on a modular level and not on the end item level in terms of planning a product's design. The product design engineer's response provides evidence to how PDM is used as each of the different stages in a product's life cycle to improve the environmental aspect through:

- Flexibility in choosing greener suppliers
- Streamlining process design to have more control on energy consumed during manufacturing
- Elongating the washing machine life cycle, hence reducing the amount of material and energy required in manufacturing a new one
- Allowing for more recycling of modules

Table 4.14 Module Categories for Washing Machine Product Family

Module Category	Quantity	Percentage
Belts	8	1.19
Brake String	4	0.59
Capacitator	7	1.04
Filter and Net	3	0.45
Fixation	46	6.82
Fuse	1	0.15
Gearbox and Pulley	8	1.19
Hoses	6	0.89
Impeller	6	0.89
Local Hoses	12	1.78
Master Batch	9	1.34
Micro Switch	1	0.15
Motor	17	2.52
Motor Brake	1	0.15
Adhesive Tape	1	0.15
Plastic Parts	333	49.41
Prints	5	0.74
Pump	1	0.15
Rubbers	15	2.23
Shaft for Wheel	1	0.15
Spring	11	1.63
SS Tub	1	0.15
Stopper	1	0.15
String	11	1.63
Switch	6	0.89
Timer	9	1.34
U Holder	2	0.30
Washing Tub Support	1	0.15
Wires and Casings	5	0.74
Packaging and Pallets	142	21.07

The second question aimed to investigate the effect the case modules have on the life cycle options of the end items. Therefore, the researcher asked the product design engineer whether M1 being more modular than M2 has had an effect on enhancing the life cycle options (in terms of upgradability, maintenance and repair, life expectancy, and end of life options) for the end items sharing M1 versus end items sharing M2. The question was also repeated to include T1 versus T2. Below is a transcript of the product design engineer's response.

‘To answer this question, I need to first explain to you the function of the motor within the context of the function of washing machines. The main function of any washing machine is to wash clothes. This is done through a number of steps. The first step from a customer’s point of view is to place the clothes in the washing machine. Choosing a program is the next step, which usually depends on the type of clothes being washed. As soon as clothes are added into the washing machine, the weight of the clothes is identified by the washing machine and accordingly the correct amount of water is added. The water is automatically mixed with the detergent. Depending on the program chosen by the customer the washing machine’s operation is set. Now, three main modules come into play in order to carry out the customer’s program: the timer module, the gearbox module, and the motor module. Each of these modules is set to carry out a specific function. The timer module sets a time for the rotation (at which water, detergent, and the clothes are mixed) and a time for rinsing (at which there is a rotation at full speed to expel as much water as possible from the clothes). The gearbox module sets different rotational speeds depending on the chosen program. The motor module transforms electrical energy into movement. So, after the customer chooses a program, each program has different times for rotational cycles, different time for rinsing cycles, and different rotational speeds.

This means that if any of these three modules is not working for any reason the whole functionality of the washing machine is affected. It also means that these three modules dictate the main function of the washing machine.

Upgradability: These are the three main modules that are usually upgraded during any product redesign. Not all three together necessarily, but for example we have upgraded all our motor modules to more energy efficient modules.

Maintenance and repair: These are the three main modules kept on hand by the service crew. These are the modules that are generally changed during maintenance to increase the life cycle of the product.

Life expectancy: the total life cycle of the product has increased considerably for washing machines through the ability to replace these modules with new ones. The general life expectancy of a washing machine is from 5 to 10 years and can even be further with the correct usage and maintenance.

End of life options: in terms of the motor and timer modules in particular they are considered widely recyclable and the company already has its own facilities for recycling plastics and as for metals we sell them to the scrap market.

A module that is shared across more end items will automatically standardise processes related to product upgrade, maintenance, repair, and end of life options. However, practically within our company these processes are already standardised for both M1 and M2 as well as for T1 and T2. The concept and design advantage from modularity has been our main focus. We have not yet investigated the degree of modularity in relation to the environmental performance as much.'

This question was more specific to the case modules of this research. The first question attempted to understand the role PDM has in general over the company's implementation of LCA for its products. This question focuses on the effect PDM has on the motor and timer modules in terms of upgradability, maintenance and repair, life expectancy, and end of life options. In order to answer my question the product design engineer first explained how a washing machine functions to outline the role of the motor modules and timer modules within the washing machines. This was important because the motor and timer modules are considered critical components in the functionality of the washing machine. This signifies that if there is a malfunction in any of them this can affect the overall functionality of the washing machine. This also signifies that these modules in particular receive extra attention in the design process when considering upgradability, maintenance and repair, and life expectancy issues. In terms of upgradability, the washing machines are usually upgraded through changes in the design of one or more of the critical components. The engineer discussed a case where the company has already upgraded the design for a motor module to be more energy efficient. He also discussed how once a design is established it is then standardised. The company then also works on updating the interface designs and standardise them between the washing machines and the new module to allow for transferability of the module across a range of washing machines. In terms of maintenance and repair, since these specific modules are considered critical to the functionality of the washing machine, the case company maintains separate inventory of these modules for maintenance and repair operations. In terms of life expectancy issues, the engineer explained how that the life expectancy of a washing machine is directly linked with the life expectancy of the critical modules. He also discussed that by replacing such modules the life expectancy of the end item is greatly increased. Finally, the motor module is made mainly from metal, which is generally sold as scrap by the case company and is melted and resold through the scrapping operations. As for the timer modules, they are mainly composed of plastic components and are recycled by the case company's recycling facilities. This answer gives more validation towards the integration of PDM in LCA. The company focuses on specific modules in its operations to manage the life cycle stages of its end items. The focus is on certain processes, which are upgradability, maintenance and repair, life expectancy and disposal. PDM is seen to enhance each of these processes, where focus on a modular level leads to an overall reduction in the use of material required for manufacturing. Therefore, LCA is seen to affect the environmental aspect positively through integrating PDM in the washing machine's life cycle options.

4.5.1.3 Closed Loop Supply Chain/Reverse Logistics

Closed loop supply chain management (CLSCM) and reverse logistics are the final streams of literature identified through the integrative literature review conducted in Chapter Two that present a relationship between PDM and environmental supply chain performance. Closed loop supply chains are defined as supply chains that manage and integrate both their forward and reverse material flows allowing for material to be used more than once (Ilgin and Gupta, 2010; Seuring, 2013; Bask, et al., 2013). PDM not only influences the forward material flow within a supply chain, but is also seen to enhance recovery, recycling and reuse operations. What this means is that material that has already been used through reverse logistics is returned and through recycling or remanufacturing can be used again as part of other products (Krikkie, et al., 2003). PDM is used as a design strategy within design for recycling (DFR) and design or disassembly (DFD). Modularity allows for the end item to be disassembled into separate independent modules simplifying the breakdown of end items or separate modules at the end of their life cycles to be returned for remanufacturing and reuse, or recycling (Yan and Feng, 2013).

For this relationship the researcher conducted an interview with the supply chain manager who is in charge of both the forward and reverse material flows within the case company. However, instead of answering the research questions, the supply chain manager instead explained the different scenarios the company has in dealing with reverse material flow.

The case company has two scenarios for product recovery depending on whether the washing machine is a total recall, or the washing machine contains damage to single or multiple of modules. The company has a designated workstation for the repair and maintenance of recovered damaged modules, and for the disassembly of recovered washing machines.

The case company provided numeric evidence in support of each scenario respectively providing product recovery reports, and maintenance and repair reports.

It is important to note that the data for all the cases in both scenarios is lump sum data for all washing machines produced by the case company and not specific to washing machines sharing M1, M2, T1, and T2. The research was first conducted with a view to focus on only the specified case modules, however the results obtained were inconclusive. The data obtained from the company (maintenance records and product recovery records) was also provided in lump sum format of the total number of washing machines recovered, without classifying specific modules that were recycled or remanufactured. The data provided in the maintenance records was for the total number of work orders and not specific to a particular module. The only data that specified the modules was for the number of new module requests made by the maintenance and repair crew. The case company has its own maintenance and repair crew in addition to 27 outsourced after sales service centers (one for each governorate in Egypt). The records obtained were a summary from both the maintenance records of the case company as well as the records from the after sales service centers outsourced by the case company.

Scenario 1: Total Recall

There are two cases within this scenario. The first case is when the washing machine is damaged beyond repair. The definition of damaged beyond repair from the Supply Chain Manager's view is when it would be costlier to fix the washing machine than to purchase a new one; or when the module that is damaged is beyond repair and is no longer in production by the company. In some situations the company might have discontinued the production of a certain module in preference of another module, which is more efficient in the use of water or electricity.

The second case is when the customer chooses to upgrade his current washing machine to a new model. The average life expectancy of the case company's washing machines is approximately eleven years. However, some customers opt to upgrade their washing machines due to the technological developments and the enhanced efficiency in water and electricity usage of the new washing machine models. If a washing machine meets the conditions of either of these two cases, then the company follows a three-step procedure. Data for both cases within this scenario was obtained from the product recovery records of the case company.

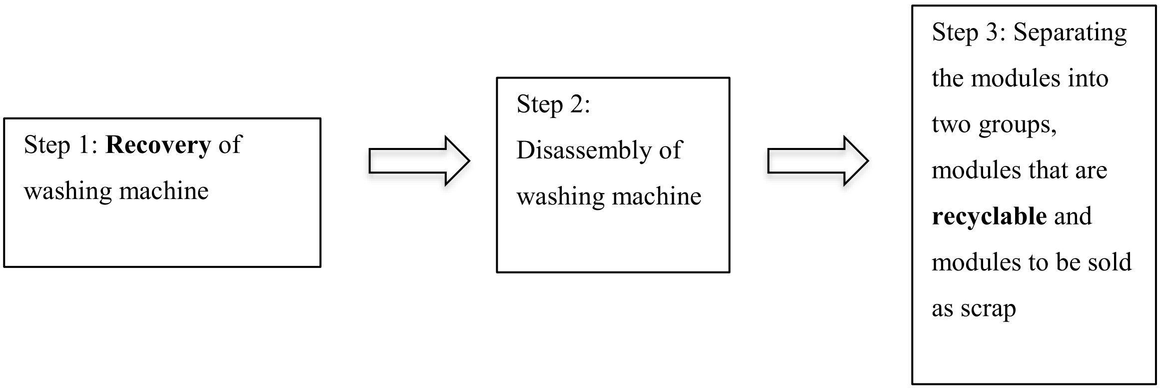


Table 4.15 Total Recall Scenario

Scenario 1	
Case 1	Case 2
5619 Washing Machines	136 Washing Machines

In a sense the supply chain manager does answer the interview questions presented in Chapter Three for this relationship through providing the procedures the case company follows in dealing with its reverse product flow. The first scenario the supply chain manager identified was for cases of total product recall. He classified total recall cases into two categories. The first was for cases where the product is damaged beyond repair. The second was for cases where the customer opted to upgrade the washing machine. Again, the role PDM plays in both these cases is seen beginning from the second step, which is the disassembly of the washing machine. PDM is used as design strategy in DFD, where products are designed to be easily disassembled with clear interface boundaries between the components. This is critical for the next step, where the components are then divided based on their material composition into materials, which can be recycled, sold as scrap, or sent to the landfill. With 49% of the washing machine modules consisting of plastic parts this greatly reduces the dependence on sourcing new plastic material with the case company already owning its own plastic and rubber recycling facilities.

Scenario 2: Damage to Single or Multiple Modules

The second scenario is when there is partial damage to the washing machine. According to the Supply Chain Manager this is when there is damage to single or multiple modules, which can be fixed or replaced without affecting the functionality of the washing machine. For this scenario there are three cases.

Case 1: the maintenance and repair crew fix the damaged module on the spot. Data for this case was obtained from the maintenance records, where no requests were made for replacement modules.

Case 2: the damaged module is replaced with another temporary module till the original is fixed at the case company's repair site. Data for this case was obtained from the maintenance records, where further work was requested on the module to be fixed (**remanufactured**).
Case 3: the damaged module is replaced with a new one, while the old module is either recycled or sold as scrap. In some of the cases the washing machines are upgraded with updated modules, which fit in the older washing machines due to the interfaces between the modules being standaradised. Data for this case was obtained from the maintenance records requesting new modules.

Table 4.16 Damage to Single or Multiple Modules Scenario

Scenario 2		
Case 1	Case 2	Case 3
54,983	8,684	10,180

In Case 1 the damaged module is **remanufactured** and **reused**.
In Case 2 the damaged module is **recovered**, **remanufactured**, and **reused**.
In Case 3 the damaged module is **recovered** and **recycled**.

In all two cases of Scenario 1 and all three cases within Scenario 2 the result is a **reduction** in the use of new material and energy consumed for the disassembly and disposal of the washing machines. In Scenario 1 PDM assisted in simplifying the breakdown of the washing machine to its base modules. The base modules are then either recycled if they are recyclable (all plastic and rubber modules) or sold as scrap (usually the metal components are sold as scrap).

In Scenario 2 modularity in design played several roles. PDM develops independent modules, which can be separated from the end item without affecting the functionality of the washing machine. This allows for the module to be either replaced with a new module or allows for the module to be replaced with a temporary module while the original one is fixed. Having set interfaces between the modules also allows the maintenance and repair crew to be able to work on a wide range of washing machine models with minimal training. Finally, in some cases the washing machines were upgraded with through changing old modules with more updated ones due to the interfaces between the modules being standardised.

Therefore, it is also evident here the role of PDM in simplifying the maintenance and repair operations of the company. Through maintenance and repair the life expectancy of the washing machines increases and thus the need to acquire material to build new ones is reduced. Another important factor is PDM's role in the disassembly of the washing machine. Simple disassembly allows for easy replacement of damaged modules, which can either be completely replaced with a new one or remanufactured and reused. It also allows the company to easily distinguish between which modules can be recycled and which will be sold as scrap. Both scenarios presented the role of PDM in simplifying the remanufacturing, reuse, and recycling of material, which evidently leads to reduction in new material requirement. Therefore, PDM is seen to improve CLSCM, which evidently has a positive effect on the supply chain's environmental aspect.

4.6 The effect of PDM on the social performance of a supply chain

The literature provided no direct link between PDM and social variables within a supply chain. However, a relationship can be derived when looking through a slightly bigger scope when coordinating the integration of product, process, and supply chain design decisions. Fine (1998) first introduced the concept of three-dimensional concurrent engineering (3DCE), which is defined as the integration of the planning phases for product, process, and supply chain designs simultaneously. 3DCE is the fifth theme identified in the literature, which integrates between PDM and social sustainability in supply chain management (refer to Figure 4.13)

Through integrating the decision phase of all three domains (product, process and supply chain) it was identified that when modularity in product design is considered as a design goal it will consequently affect both supply chain design and process design decisions. From a supply chain design point of view, modularity in product design leads to the restructure of supply chain networks leading to the formation of industrial (modular) clusters. This in turn leads to more job opportunities and reducing unemployment in the geographic areas of such clusters (Navidi and Barrientos, 2004; Lei, 2009; Thomsen and Pillay, 2012). From a process design point of view, modularity in product design leads to work path simplification through the standardisation of the process design (Fixson, 2005). This in turn leads to improving employee learning curves and provides increased opportunities for knowledge sharing (Jacobs, Vickery and Droge, 2007; Liao, Tu and Marsillac, 2010).

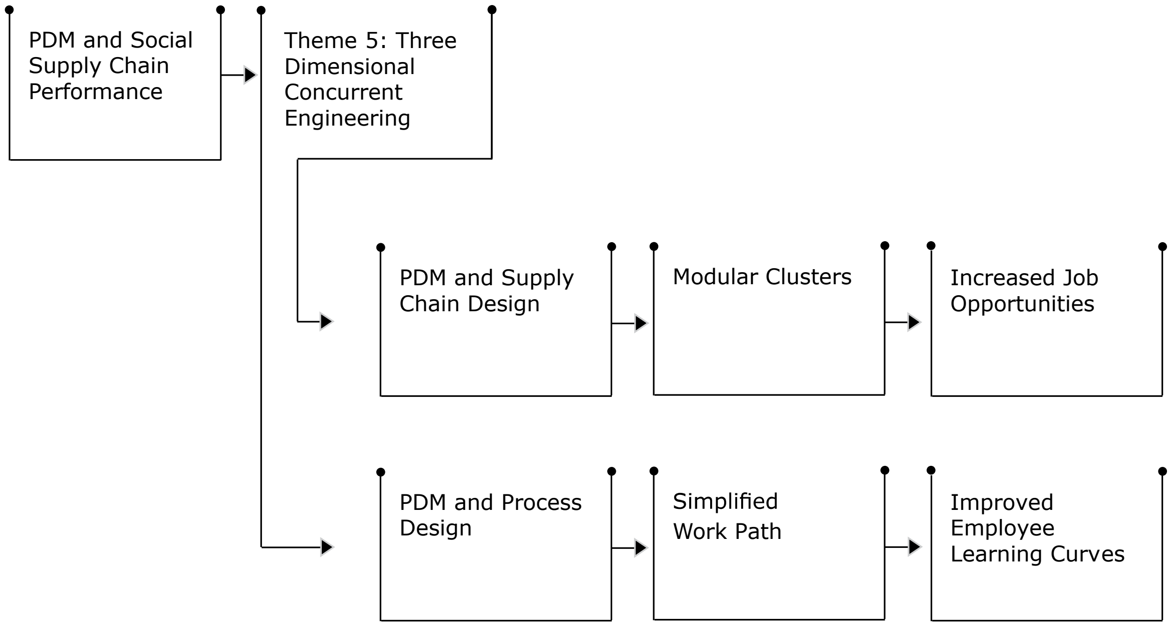


Figure 4.13 PDM and Social Supply Chain Performance

However, the literature also identified that PDM's effect on improving social sustainability in supply chain management to be subject to certain conditions (Thomsen and Pillay, 2012; Navidi and Barrientos, 2004; Sturgeon, 2003), which are:

1. The location of the industrial cluster should be in a developing country
2. The production output of the company is still below the level requiring automation of processes.
3. The supply chain process should be labour intensive.

The chosen case company for this thesis meets all three conditions. Regarding the first condition, the case company is located in Egypt. According to the World Economic Outlook developed by the International Monetary Fund (IMF) in 2017, Egypt is considered an emerging and developing economy. In terms of the second condition according to the case company's CEO it is not feasible for the company to invest in automation currently or in the near future due to market and demand conditions being too volatile. He explained that they are dependent on human labour for its flexibility in learning new processes to adhere to changing market demands. Regarding the final condition, according to the case company's supply chain manager, the case company's processes are considered to be quite labour intensive. The case company mostly operates in final product assembly where there is an assembly line with line workers conducting the assembly of the modules into finished products.

4.6.1 PDM and supply chain design (modular/industrial clusters)

The data for this relationship was gathered through semi-structured interviews with the case company's Supply Chain Manager who is in charge of decisions related to facility locations, and human capacity requirements calculations to meet demand requirements. Therefore, the Supply Chain Manager was deemed best fit to collect data on the effect between PDM and supply chain design from. Data relating to the development of industrial clusters in Egypt is gathered from the Egyptian Ministry of Industrial Development and the Egyptian Authority for Free and Industrial Zones. Appendix VI provides a full list of the industrial zones in Egypt. The case company is currently operating from the 10th of Ramadan industrial zone.

The first question aimed to identify if there is a relationship between PDM and the development of industrial clusters. Therefore, the researcher asked the Supply Chain Manager whether he thought there was a relationship between their washing machine's design being modular and the development of related industries in the 10th of Ramadan industrial zone. Below is a transcript of the Supply Chain Manager's answer:

'Personally, I think that a large number of businesses in Egypt are currently operating due to modularity in product design. Due to the availability of relatively cheap labour and skilled workers, many businesses choose to outsource their manufacturing processes here and this can be seen in many industrial zones. Major automotive players such as Mercedes, Jeep, BMW, just to name a few, have assembly plants located in a number of industrial zones across Egypt. However, they never outsource the entire manufacturing process. They usually only outsource the assembly process. For example, Egypt is considered a supplier to the MENA Region, so what they do is they take orders from surrounding countries and leave the final assembly to be done in Egypt where they can differentiate the cars according to each customer order. This can only be done since the product design is modular, so yes there is definitely a huge relation between modularity in design and the development of industrial clusters.

In regard to our company, we are also an assembler, but we are continuously investing in research and design to learn more about the modules we import. We do not envision remaining just in the assembly of home appliances forever. We are currently working on a project to open a plant for producing our motor modules, which we have been mainly outsourcing from Chinese suppliers in the past. This will open even more job opportunities and the workers will receive new training programs to be able to work in these new facilities. So, another advantage is that when you work long enough in the assembly of the modules you start acquiring the know-how of how to build it as well. Another method we also apply is that we pay the suppliers to share the know-how with us in return for further integration and strategic business partnerships across different modules for example.

Regarding the 10th of Ramadan industrial zones there are three other smaller companies also operating in the electronic home appliances sector and I expect many more will open in the coming years. There are also a number of other industrial zones across Egypt that are specialised in the electronic home appliances sector, such as the Ousna Industrial Zone for example.'

The purpose of this question was to validate the relationship between PDM and the development of industrial zones. The development of industrial zones has been noticeable in Egypt over the past 25 year periods, where the focus of the economic development of the country is trying to balance between agricultural produce and industrial production for exports. The supply chain manager's response highlights how PDM has been an integral part in the development of industrial production in Egypt. Due to Egypt's location being central between Asia, Africa and Europe, many companies choose to outsource the final assembly of their products to Egypt, where Egypt acts as a distributor of these products to nearby regions. The focus here is given on the postponement of the product customisation, where the main components of the product are already produced, and the assembly of the final product is assigned to factories in Egypt after which the distribution of the products takes place. Therefore, modularity in design has allowed for the development of a number of assembly operations in the electronics and automotive industries in Egypt. The Egyptian government also stipulates that a percentage of the product has to be manufactured in Egypt, which means that some of the modules have to be manufactured in Egypt. This has created several industrial zones focused on the assembly and manufacturing of supporting modules for a particular industry. The supply chain manager also sees the assembly operations as a stepping-stone towards learning the know-how of the manufacturing of modules. He gives an example of how this is done through the case company through combined research and development projects and further integration in product design with the module suppliers.

The second question aimed to identify if there is a relationship between the development of industrial clusters and increasing job opportunities for the surrounding geographical areas. Accordingly, the researcher asked the Supply Chain Manager if he considered that there is a relationship between PDM and the number of facilities you have and the number of employees you hire. Also, is the standard of living for the employees affected positively through the relation between PDM and industrial clusters. Below is a transcript of the Supply Chain Manager's answer:

'In regards to our company, we have four manufacturing facilities. One for washing machines, one for refrigerators and air conditioners, one for heaters and fans. In this particular manufacturing facility, which is for washing machines, we have 5 production lines with a minimum of 13 workers on each production line. Each production line is not fixed to a certain model and is flexible to operate to produce any of the washing machine models. At certain times we also face unexpected demand due to seasonality. At such times we also employ some flexible labour by the hour, which we pay the minimum hourly wage to. Regarding our full-time employees they receive standard wages plus bonuses as motivation for the line able to produce more end items at the end of each day. They also receive health insurance for themselves and their families.

So, to answer your question, yes, there is a positive relation between modularity in design and the formation of industrial clusters that I have seen from my work experience in this company and in my previous positions as well. This has definitely created more job opportunities. Accordingly, these job opportunities not only provide a steady source of income for the workers, but also usually provide health benefits for the workers and their family members.'

These questions examined the relationship between PDM and industrial clusters with a view to link PDM to increasing job opportunities through the development of these industrial clusters. The creation of job opportunities can be considered a positive social impact leading to reduced unemployment, which is one of the major social measures. The supply chain manager provided that the case company has four manufacturing facilities, with each facility hiring permanent staff as well as flexible staff during seasons. Full time personnel are also entitled to monetary benefits depending on their production outputs and to health benefits. Therefore, PDM is seen to increase job opportunities leading to reduced unemployment and through job opportunities it also improves the standard of living of the personnel.

4.6.2 PDM and process design (simplified work path)

Data for this relationship was collected through a semi-structured interview with the product design engineer of the case company. Part of the responsibility of the product design engineer includes coordinating between product design requirements and process design requirements. He is also in charge of creating new training programs for the line workers to update them on any changes in product design or to introduce them to new product designs. Therefore, the product design engineer was deemed best fit to collect data regarding the effect of PDM on process design from.

The first question aimed to identify if there was a relationship between PDM and employee skill learning curve. Therefore, the researcher asked the product design engineer on his opinion regarding modularity in design and how it affects employees' ability to learn and acquire new skills. Below is a transcript of the product design engineer's response:

'Our manufacturing operations here at this facility are mainly related to assembly processes. This means that it all comes down to the interfaces between the modules. We conduct a number of tutorials on a quarterly basis throughout the business year. Through these tutorials a team from the engineering department demonstrates how to best assemble the different end items. We also have diagrams and figures distributed on the workers and posted throughout the facility showing a step by step guide for the correct way to assemble the end items. This is not only important for the manufacturing of end items with minimum amounts of reworks, but it is also quite critical for the workers' safety. These diagrams ensure that the workers are always wearing the required protective gear and follow the safety procedures at all times. Modularity in design has allowed for a standardisation of the interfaces between the different modules. So, for example if we talk about the motor module, even though it differs between different end items, the interface is pretty much standard across all the end items. This means that I can teach the workers a standard process that will allow them to work on more than one model at a time. From one point of view this is quite economic, because this allows for our workers to be flexible to work on any model depending on demand requirements and we don't need specific teams for each end item. From another perspective it is quite easy to teach the workers these processes, because it minimises the total number of processes they need to learn. They also become quite good in a very short time due to the repetition of the processes they perform.'

Skill learning curve in this case is associated with the performance of the employees in terms of manufacturing efficiency. It is related with the ability of the employees to learn new skills and techniques quickly to achieve flexibility and efficiency in the manufacturing process. Since the case company's manufacturing operations as an OEM generally lies within the assembly of the end items, this means that the focus for the skills the employees are required to learn lie within the assembly of the end items. The purpose of this question is to validate the relationship between PDM and workers ability to acquire and become proficient in new skills. The product design engineer's response highlighted the relation between PDM and process design, where modularity in design has led to a simplified work path with clear steps in the assembly process for the production of the end items. He also explained that due to modularity standardising the interfaces between the components, the skills learned by the employees in assembling a certain module could therefore be transferred into the assembly of more than one end item. This also leads to higher job retention by the employees, where due to the improved performance and simplicity in learning new skills the workers have higher chances of keeping their jobs.

The second question aimed to investigate if there was a relationship between PDM and the skill set requirements for employing new workers in the case company. Therefore, the researcher asked the product design engineer what are the standard requirements for employing line workers and if these requirements were in any way related to modularity in product design. Below is the product design engineer's response:

'The job requirements for line workers are pretty standard. What we mainly ask for is a high school diploma, just to ensure that the workers are literate. We also cannot hire any workers with physical disabilities and this is due to the nature of the work they will be required to carry out. Most of all what we do look for in the workers is a motivation to work and learn. Most of the applicants are eager to be able to gain a steady pay plus the standard health insurance for the employees, so we have many applicants at all times and there is no shortage of workers.

Because we mainly operate assembly lines, this makes it quite easy to find labour. We do not necessarily require the workers to have previous experience, because it is quite easy to train them, and this can be attributed to the modular aspect of the products we manufacture. So, in a sense, yes, modularity in design does affect the skill set requirements by making it possible for anyone to apply due to the minimal requirements.'

Not requiring high standards such as higher education and previous work experience actually provides improved opportunities for members for the less fortunate members of society. Jobs like this can also be considered a stepping-stone by the workers, which offer steady pay while the worker can try to improve his education and look for better opportunities. Such work also adds to the experience of the employees if they choose to apply for other positions later on in their career paths. Hence, even though the literature provided no clear link between PDM and social supply chain aspects, it can be induced that PDM leads to increased job opportunities through the development of industrial clusters. PDM is also seen to improve employee skills through simplified work paths.

Since the line workers are the main stakeholders when it comes to the effect of PDM on social sustainability in supply chain management, it was deemed important to get their input regarding their experiences in working in such an environment. The researcher did this to present a complete picture from the employers' perspective as well as from the employees' perspective.

The researcher was allowed to conduct a focus group interview with the line workers of the morning shift on (date) during their lunch break. There were 10 workers in total with 7 being male and 3 being female. The employee names are replaced with alphabetical letters to comply with the confidentiality agreement with the case company.

Focus group Questions and Answers:

Question 1: Please provide your employment history in the company in number of years and months?

A	B	C	D	E	F	G	H	I	J
2 Years, 4 Months	3 Years, 11 Months	2 Years	4 Years, 2 Months	3 Years	1 Year, 4 Months	2 Years	3 Years	3 Years, 6 Months	2 Years, 8 Months

Employment history is important to assess job retention by the company. From the 10 workers interviewed, all workers have been working at the company for over one year and up to 4 years. The view was to evaluate whether the company provides temporary job opportunities or sustainable job opportunities for its employees. The findings provide that the company does provide sustainable job opportunities where all the workers have been there for over 1 year.

Question 2: Please provide your total employment history working in a related assembly operation?

A	B	C	D	E	F	G	H	I	J
4 Years	8 Years	2 Years	4 Years, 2 Months	6 Years	1 Year, 4 Months	7 Years	3 Years	7 Years	2 Years, 8 Months

Total employment history gives an idea regarding how long employees have been in similar positions before.

Question 3: Please state in yes or no response if your previous employment history was also in an industrial zone?

A	B	C	D	E	F	G	H	I	J
Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes

This is used for more validation regarding the relationship between PDM, industrial clusters, and increasing job opportunities. Both questions two are three are used to validate this link, with question two focusing on the number of years in experience the line workers have had in a similar industry; and question three investigating if these positions were also within industrial zones. From the responses of the line workers, it is clear that for some of them (C, D, F, H, J) this is their first position in this line of work. However, for the others all except one confirmed their previous position to also be within an industrial zone.

Question 4: How many training sessions has each of you received from the case company?

A	B	C	D	E	F	G	H	I	J
9	15	8	16	12	5	8	12	13	10

This is used in support of the relationship between PDM and employee skills development. The product design engineer already mentions that there are quarterly training sessions, which the line workers are required to attend. From the line workers responses, it is clear that the workers do receive these trainings.

Question 5: Have these trainings assisted you in increasing your knowledge and skill set? (Yes/No)

A	B	C	D	E	F	G	H	I	J
Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Question four and five both support the relationship between PDM and employee skill development. The line workers confirmed that they do receive regular trainings and that these trainings have helped them increase their knowledge and improve their skills. The trainings development as discussed with the product design engineer focus on process design, which is based on product design. Therefore, modularity in design affects the development of these training sessions, which all the line workers confirmed as beneficial for them.

Question 6: Do you think that the skill sets you have gained from working in the case company will assist you in further developing your future career? (Yes/No) (Why?)

A	B	C	D	E	F	G	H	I	J
No	Yes	No	No	Yes	Yes	No	No	Yes	No

The reasons the four respondents gave for answering yes was mainly based on the workers' expectations for their future career to continue in the same industry. The main reason was due to their belief of continuing in the same line of work for the foreseeable future. So, through the experience and trainings received while working for this company this will allow them to continue working for the case company or find similar positions in other related industries. Another reason was the workers' belief that the continuous trainings they receive allows them to work on different end items giving them more skills and learning opportunities.

The six respondents, that answered with no, provided that they believed that there were no real future career opportunities from this line of work. They explained that even if they look for other work opportunities it would also be in a similar position. They elaborated that even though they do receive trainings and work experience, it is all constricted in the field of assembly operations. They also believed that the only way for them to actually progress towards better positions would be to continue their education. They further clarified that there is a ceiling in terms of the job promotions they can receive, where they can only become a title called 'line boss' after certain years of experience.

There were conflicting views regarding this question. Most of the respondents, however, did not see this line of work provided opportunities for career advancements. The respondents that did consider this position having potential for further career development based their answer on their career development being in a similar position. Therefore, the relationship between the types of positions offered by industries focusing on PDM might not offer much in terms of further career developments for line workers.

Question 7: Which do you consider better to work on, products with modular components (M1, T1) or products with integral components (M2, T2)? (Why?)

A	B	C	D	E	F	G	H	I	J
Modular	Modular	Modular	Modular	Modular	Modular	Modular	Modular	Modular	Modular

For this question there was a consensus from all ten workers. They all provided that when working on modular components, the processes are usually standardised, which makes their jobs easier. They elaborated that when the process is standardised the assembly process becomes more of a reflex action. Even though they all agreed that it can become repetitive and boring at times the advantage of having a faster production flow that allows them to claim the extra production pay bonus at the end of the day makes it worth it. Also, the amount of product reworks or pauses during the production line are greatly reduced making their overall performance indicators improve greatly in comparison to working on integral modules.

Question 8: Do you consider that working in this industry has improved your standard of living? (Yes/No) (Why?)

A	B	C	D	E	F	G	H	I	J
Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

There was a consensus from all 10 respondents. They all believed that receiving standard pay and health benefits has greatly improved their standard of living. They also explained that the support they receive from the company in the form of extra pay benefits during special periods of the year (Eid, Ramadan, School Entry) makes them all very loyal to the company.

4.7 Chapter Summary

The main focus of this chapter was on presenting the data for each of the relationships as identified within the company. The data presented for each relationship was for M1 vs M2 and then again for T1 vs T2 in order to compare between the effect modularity in design has on the respective supply chain process. For all the relationships it can be seen that M1 and T1 offer better economic, environmental and social performance than their counterparts M2 and T2. This empirical evidence provides basis for the propositions presented in Chapter 2, where the modules with a more modular design are seen to achieve better profits, lower costs, reduce environmental harm in terms of reducing the dependence on non-renewable resources, improve the social wellbeing of the line workers within the company. The next chapter will use the findings as inputs within an analytical model to integrate all the findings and obtain an indicator for the effect modularity in design had on the over all sustainability of the company’s supply chain operations.

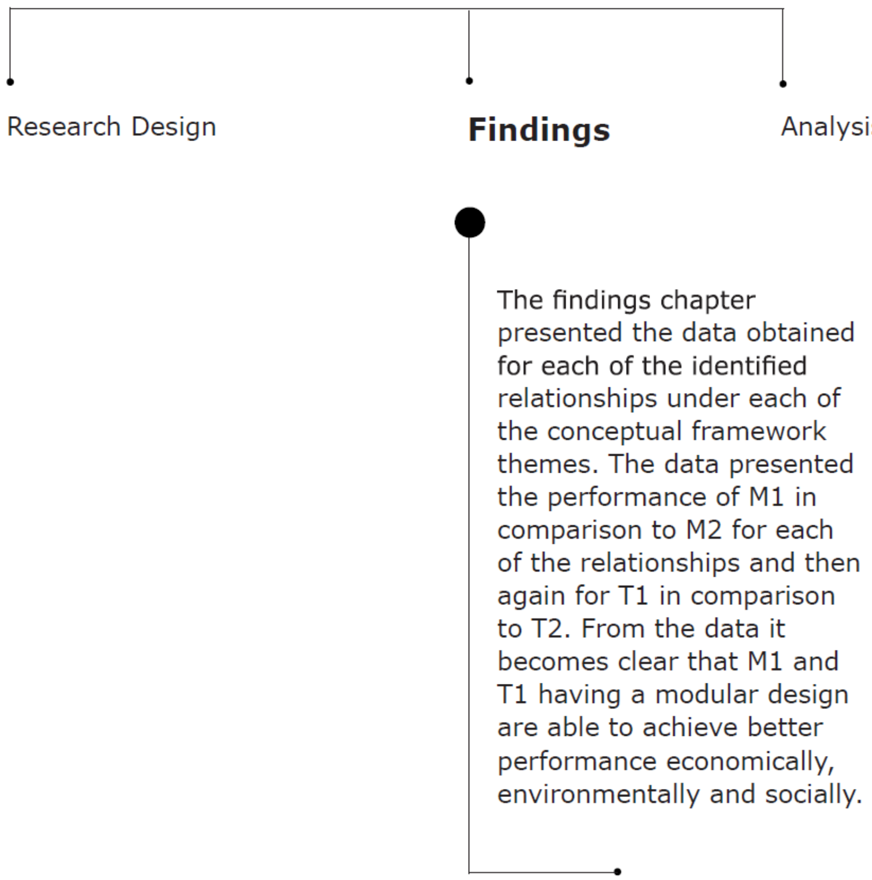


Figure 4.14 Findings Chapter Summary

Chapter 5 Analytical Hierarchy Processing Model for Measuring the Effect of PDM on Sustainable Supply Chain Management

5.1 Introduction

In this chapter the focus will be on presenting an analytical tool to aggregate all the data obtained into one cumulative model. The findings discussed in the previous chapter will be used as inputs for the AHP model. This chapter will begin with a general introduction on multi criteria decision analysis in section 5.2. Section 5.3 will discuss AHP as an analytical tool for measuring sustainability in supply chain management when considering the three aspects of sustainability (economic, environmental, and social) as multi criteria which need to be met in order to achieve sustainability. Section 5.4 will present the hierarchy model developed from the integrative literature review conducted in Chapter Two. Section 5.5 will present the model implementation and the pairwise comparison matrices for all of the identified variables in order to calculate an accumulative weight of the effect of PDM on supply chain sustainability for M1 VS M2 and T1 VS T2. Section 5.6 will discuss the meaning of the results and outline future uses for this analytical model. Therefore, the structure for this chapter is as follows:

5.2 Multi Criteria Decision Analysis
5.3 AHP as an Analytical Tool for Measuring Sustainability
5.4 PDM and Sustainable Supply Chain Management Hierarchy Model
5.5 Model Implementation
5.6 Conclusion

5.2 Multi Criteria Decision Analysis

Multi criteria decision making (MCDM) is considered a branch of operational research (Liou and Tzeng, 2012; Zavadskas, et al., 2014). MCDM is often used in supply chain management related decisions due to the nature of conflicting criteria in this area of management (Rallabandi, et al., 2016). For example, opposing criteria such as supply chain costs versus customer responsiveness versus supply chain risk usually need to be taken into consideration simultaneously by managers to ensure rigor in the decision making process.

MCDM is divided into multiple objective decision making (MODM) and multiple attribute decision making (MADM) (Potvin, et al., 2004). Rallabandi, et al. (2016) presented another view towards the type of MCDM problems, identifying problems with finite solutions as multiple criteria selection problems. Problems with infinite solutions were identified as multiple criteria mathematical programming problems.

MCDM is also considered one of the most common branches of operational management that include tools for evaluating sustainability within supply chain management (Taticchi, Tonelli and Pasqualino, 2013; Brandenburg, et al., 2014). MCDM can be seen to naturally integrate within the field of sustainability management, which is defined as the simultaneous integration of economic, environmental, and social aspects (Carter and Rogers, 2008). These aspects are therefore considered the criteria upon which supply chain managers need to coordinate in their decision making process. The different variables beneath each of the three aspects can then be seen in relation to each other and the trade-offs between the three aspects can be clearly identified to reach the best alternative.

For this research, MADM or multiple criteria selection problems were deemed best fit. MADM is used for making preference decisions over available alternatives, which are characterised by conflicting attributes (Jahan, Edwards and Bahraminasab, 2016). This research questions whether modular or integral components are best suitable to achieving a more sustainable supply chain. The modularity or integrality of components hence is identified as an attribute of the component. Also, the question is related to a selection of the most appropriate design methodology, whether to follow a path towards modularity or integrality in order to improve supply chain sustainability.

5.3 Analytic Hierarchy Processing as an analytical tool for measuring sustainability

Thomas Saaty developed analytic Hierarchy Processing (AHP) as a decision making methodology for problems affected by multiple criteria in the 1970's (Saaty, 1972). It is considered one of the most commonly used MCDM methods (Ishizaka, Balkenborg, and Kaplan, 2011). This can be attributed to its ability of breaking down complex decisions into smaller problems, where decisions are made through the aggregation of the simpler problems (Saaty, 1994). It can also be attributed to AHP's flexibility in allowing both quantitative and qualitative data as inputs when considering different decisions (Vaidya and Kumar, 2006). This flexibility is critical in decision making for problems affected by subjective criteria where value is given to knowledge and experience, which is not numerical in nature (Gonzalez, et al., 2014). Saaty (1994) discussed that there are three general kinds of judgments where the decision maker evaluates decisions based on importance, preference, or likelihood. Judgments can be based on either knowledge in memory, benefits, costs, risks or a combination of them. AHP is considered a nonlinear framework for problem solving that allows both deductive and inductive thinking (Saaty, 1987). It is based on the creation of numerical trade-offs to formulate answers.

What distinguishes AHP as an MCDM is its approach to modelling the problem. Saaty (1994) discussed the development of AHP to be based on human's ability to make sound judgments regarding small problems. However, when it comes to complex situations that are affected by more than one variable with several possible alternatives, the decision making process becomes quite complex. AHP presents a systematic means of breaking down a problem into its base elements. The problem is modelled as a hierarchy with a clear main goal/question as the top most level. All criteria and variables, which have a direct effect on this goal, are then placed on the following level. Each criterion is then considered separately to identify further affecting variables. Saaty (1987) explained that the elements in each level might be constraints, refinements, or decompositions of the element above. Saaty (1987) provided that the structure of the hierarchy is based on certain axioms. The first axiom, which he defined as the reciprocal axiom denotes that when comparing two criteria, whatever weight given to one criterion the other criterion would receive the reciprocal of that weight. The second axiom is the homogeneity axiom, which denotes that criteria should be clustered together based on their homogeneity to make logical comparisons. Criteria, which are related, and homogeny should be clustered under the same heading and within the same level. The third axiom is the dependence axiom, which denotes that each level in the hierarchy is dependent on the level below it. However, the lower levels are independent of the upper levels. The final axiom discussed was the axiom of expectation. Saaty (1987) explained that all alternatives, criteria and expectations, whether explicit or implicit should be represented in order to create a reliable non-biased hierarchy.

The goal of modelling a problem in AHP hence becomes to break down the problem to its most simplistic elements and compare the decision alternatives based on these elements. The best alternative is then chosen through the aggregation of the decisions made on the simpler elements.

AHP as a methodology also provides a rating scheme for the criteria based on the development of pairwise comparisons to develop weights for the respective criteria (Saaty, 1987). Criteria on the same level and under the same branch of the hierarchy are placed in an $(n \times n)$ matrix with n being the number of criteria to be compared. The number of comparisons would be equivalent to $n(n-1)/2$. In such a matrix, diagonal elements are denoted by 1. Comparisons between the criteria are based on a scale of absolute numbers from 1 to 9, which was developed by Saaty (1972). When comparing two criteria, the value of 1 signifies that they are of equal weights. Weights are then assigned in multiples of 3, where 3 means that criterion A is 3 times more preferable, important or likely than criterion B. The maximum value of importance based on Saaty (1987) table of weights would then be 9. Even values are (2,4,6,8) are assigned if the weight is considered between one of the absolute values. Comparisons are hence based on the type of judgment being made; how many times is one alternative more (preferable, important, likely) than the other. Therefore, once judgment is made, whatever value one criterion gets, the other criterion would receive the reciprocal value.

The next step is to derive the scale of priorities (or weights). Solving for the principal eigenvector of the matrix and then normalizing the result obtain this scale. This is called the local derived scale before weighting by the priority of its parent criterion (which for the second-level elements is always equal to unity, the weight of the focus). After weighting, it is called the global derived scale. The weight for each alternative is then obtained through normalising the elements in each column of the judgment matrix and then averaging over each row.

AHP also develops a consistency ratio (CR) for the matrices as a ratio to measure the inconsistencies between the weights assigned to the criteria. Saaty (1987) identified that a matrix is consistent if a positive reciprocal matrix of order *n* has a corresponding eigenvalue of *n.* When it is inconsistent the eigenvalue of the matrix will exceed the value of *n.* This is used as a measure for the inconsistency of the decisions made through forming a ratio identified as the CR. The calculations for the CR are shown below. There is a 10% tolerance for inconsistencies within AHP as shown in Table 5.1 below; if the inconsistency exceeds 10%, then the judgments would need to be reconsidered and the weights would need to be reassigned until it is less than or equal to the 10% allowance (Saaty, 1987). The CR is calculated by dividing the consistency index by a random index. The random index developed by Saaty (1972) is based on a sample size of 500 of a randomly generated reciprocal matrix using the scale 1/9, 1/8, …, 1,…, 8, 9 to see it is equal to or less than 10%.

Table 5.1 Random Index Values

Number of Comparisons	2	3	4	5	6	7	8	9	10
Random Index Value	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

Adapted from Saaty (1987)

Average Consistency = Total Consistency / No of Comparisons

Consistency Index = (Average Consistency – No of Comparisons) / (No of Comparisons – 1)

Consistency Ratio = Consistency Index / Random Index

AHP has already been used as an analytical tool in papers, which focused on the incorporation of sustainability in supply chain management. Kumar and Rahman (2017) used interpretative structure modelling (ISM) to identify supply chain enablers for sustainability. They then applied fuzzy AHP to develop a system to categorise and assign weights for the respective enablers. Mathiyazhagan, et al. (2015) used AHP to develop rankings for major pressures to the application of green supply chain initiatives within the mining and mineral industries in India. Larimian, Zarbadi and Sadeghi (2013) investigated the sustainability of security issues in major urban cities. They applied a fuzzy AHP model to assess and rank the different risks found in major urban cities.

AHP has also been in the integration of sustainability and product design decisions. Chang, Wang and Raffoni (2014) used fuzzy AHP to integrate between environmental management accounting and life cycle assessment to measure the environmental and organisational performance of alternative green product designs. They focus mainly on the economic and environmental impact of product design and their effect on sustainable supply chain management. The paper, however, does not include any indicators for social sustainability. Hassan, et al. (2012) integrated between Morphological Analysis and AHP to develop weights for sustainability indicators. They based their study on the design for sustainability indicators developed by Jawahir, et al. (2006).

The literature on AHP provided that it is usually combined with other analytical tools, such as Kumar and Rahman (2017) combining AHP with ISM and Larimian, Zarbadi and Sadeghi (2013) using fuzzy AHP. However, the researcher deemed it best fit to use the standard form of AHP for this particular case. The overall aim for this research is to identify the effect of PDM on SSCM. This is broken down to three objectives, which are to assess the effect of PDM on the economic, environmental, and social aspects of SCM respectively. The AHP model is therefore structured in such a way to achieve this overall aim. The data inputs for the model were obtained from a single source per relationship respectively. Accordingly, neither DS-AHP, nor fuzzy AHP models were required.

5.4 PDM and sustainable supply chain management hierarchy model

Saaty (1994) argued that how the problem is modelled with AHP will have a significant effect on the decision making process. The best way to present a problem in AHP is to decompose it into the most general and most easy controlled factors. Elements on the lowest level of the hierarchy are then used in the decision making process with questions regarding the importance, preference, or likelihood of one decision alternative in comparison to others. The best decision alternative is then obtained through aggregating the decisions made in each criterion going up the hierarchy reaching the main goal or question the hierarchy was modelled to answer.

The researcher modelled the structure of the hierarchy (Figure 5.1) with the main objective being in line with the overall objective of this research to assess the effect of product design modularity on sustainable supply chain management. The decomposition of this overall goal into its base criteria follows the conceptual framework developed as a result of the integrative literature review in Chapter Two.

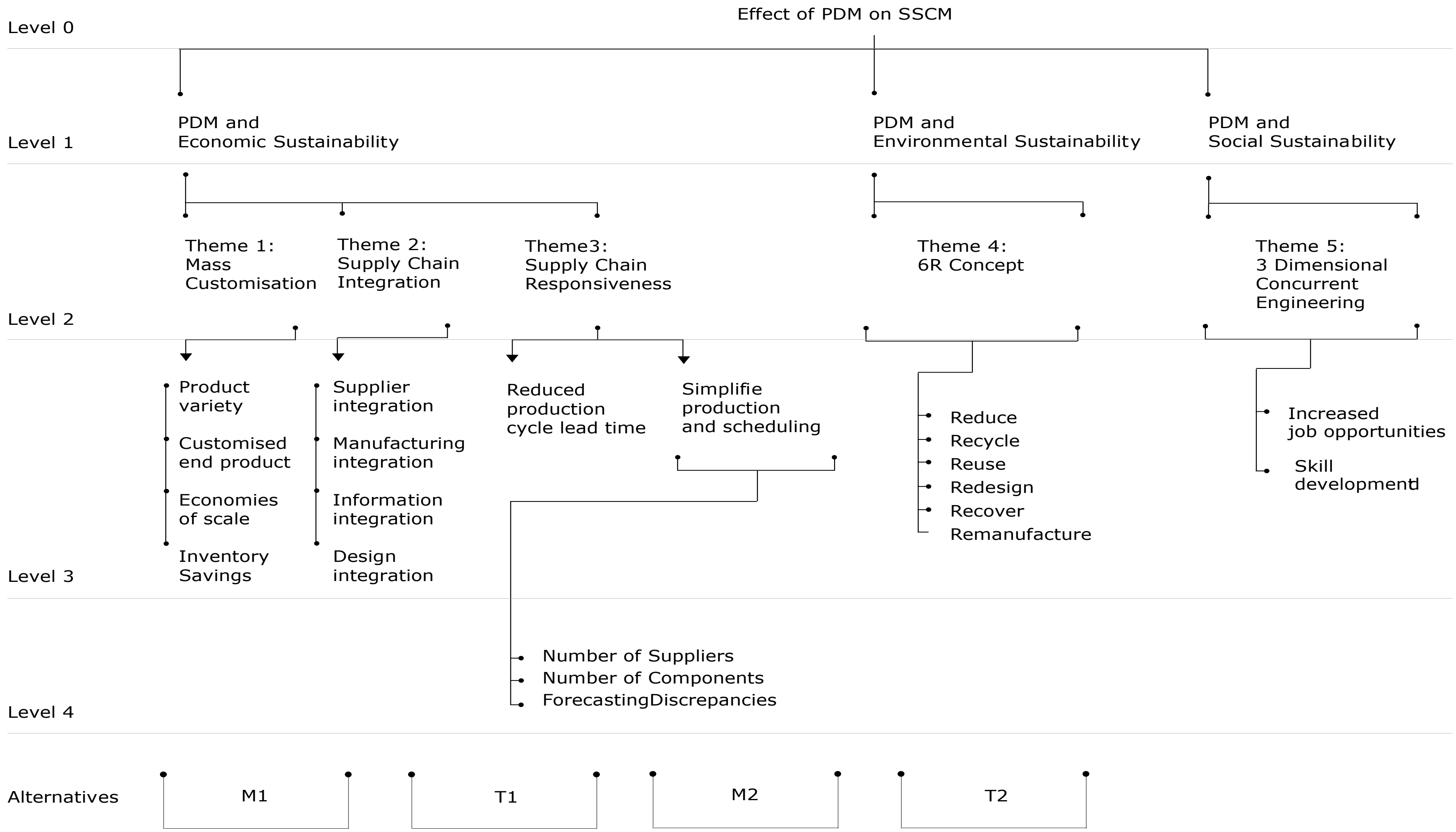


Figure 5.1 AHP Model for PDM and SSCM

Accordingly, at the top most level of the hierarchy (Level 0) is 'The effect of PDM on SSCM'. The following level includes the three main aspects of sustainability as identified through the literature (Carter and Rogers, 2008; Seuring and Muller, 2008). Hence, Level 1 of the hierarchy has three main criteria, which are:

1. Effect of PDM on Economic Supply Chain Performance
2. Effect of PDM on Environmental Supply Chain Performance
3. Effect of PDM on Social Supply Chain Performance

Level 2 criteria, breaks down each aspect of sustainability even further and is based on the themes developed in the literature. The themes ensure the homogeneity of the criteria in this level. The themes present supply chain processes that are affected by the modularity or integrality of product design. Consequently, Level 2 criteria branching under the Effect of PDM on Economic Supply Chain Performance will be:

1. Mass Customisation
2. Supply Chain Integration
3. Supply Chain Responsiveness

Level 2 Criteria presenting the breakdown of the Effect of PDM on Environmental Supply Chain Performance will be based on the 6Rs concept identified in the literature. In the literature it was identified that the 6R's concept can be achieved and improved through three processes, which were LCA, DFE/DFR, and CLSCM/RL. However, these tools or processes cannot be identified as criteria since they act as instruments to be used towards achieving the actual criteria, which for this research are considered the 6Rs. All three processes were found to integrate PDM with a view to improve environmental supply chain performance through trying to improve the 6Rs. Therefore level 2 criteria under the effect of PDM on environmental supply chain performance are:

1. Recover
2. Remanufacture
3. Recycle
4. Redesign
5. Reuse

6. Reduce

Level 2 criteria branching from the effect of PDM on the social supply chain performance are based on the 3D concurrent engineering theme. This theme integrates between product design, process design, and supply chain design. Accordingly, the effect of PDM on process design led to the identification of employee skill development and learning as a potential relationship. Also, the effect of PDM on supply chain design, which leads to the development of industrial clusters, led to the identification of increasing job opportunities as another potential relationship. Both relationships have already been validated through the findings chapter. Hence, level 2 criteria under the effect of PDM on social supply chain performance are:

1. Employee Skill Learning and Development
2. Job Opportunities

Following Saaty (1994) guide for the structure of the hierarchy, it was identified that the supply chain process under the economic effect can further be broken down into simpler elements. Therefore level 3 criteria were only developed as a breakdown for the supply chain processes under the economic aspect. For the mass customisation theme, PDM is seen to have four specific effects, which are:

1. Product Variety
2. Customised End Product
3. Inventory Cost Saving
4. Economies of Scale

As for supply chain integration, PDM was also seen to effect specific supply chain processes the lead to improved supply chain integration. Accordingly, the level three criteria under the supply chain integration theme are:

1. Supplier Integration
2. Manufacturing Integration
3. Design Integration
4. Information Integration

The same was found to be true for supply chain responsiveness. Therefore, level 3 criteria here represent the effect of PDM on the responsiveness of the supply chain that could be broken down to two specific relationships, which are:

1. Simplified production and Scheduling
2. Reduced Production Lead Time

Regarding the simplified production and scheduling relationship level 4 criteria were developed since it could be broken down into:

1. Number of Suppliers
2. Forecasting Discrepancies
3. Number of Components per product family

The data obtained for this research comprises both quantitative data and qualitative data. Data inputs for analysis were obtained from the previous Findings Chapter. The quantitative inputs are based on the data from the operational reports of the case company. This research focuses on the effect of PDM through comparing two similar modules in terms of how they affect certain supply chain processes in an attempt to determine which module design will achieve improved sustainability. Hence, pairwise comparisons for the relationships with quantitative data were created as a ratio between the data from the first module in comparison to data from the second module. However, this was not achievable for qualitative data since the data obtained was not specific to module VS module. Therefore, the researcher did follow up phone interviews with the supply chain manager and the product design engineer. The background to the research was already discussed at previous visits and during the interviews already conducted. This allowed the researcher to proceed with the questions without the need to re-discuss the objective of the research. The questions in the phone interviews were close-ended structured questions, where the interviewees were asked to assign a weight for the first module in comparison to the second module in the context of the specific relationships. Saaty (1987) weight scheme was used.

A critical use for AHP is its ability to provide ranking weights for the criteria in terms of developing dominance relationships between them. However, for the purpose of this research, this feature of AHP was not required. The definition of sustainability relies significantly on the simultaneous integration of the economic, environmental, and social aspects. To incorporate this definition into the model, the researcher deemed it best to give the criteria equal weights. With no one criteria dominating over the others, this leads to the only variable in the decision making process being the modularity or integrality of the components in question. The focus of this thesis is to assess the effect of PDM on sustainable supply chain management. This is done through comparing components within the same product family with different design attributes, where one component is considered modular and the other integral to identify which design is more preferable. Accordingly, equal weights were given to all the criteria in the Effect of PDM on SSCM model from level 1 to level 4, leaving the only variable in the model as the attribute of the components that are being compared. If the criteria were ranked, the weight of each criteria would then have affected the decision making process making it hard to assess whether the decision can be attributed to the design of the component or the different weight distribution of the criteria. The full AHP model including all the criteria, calculations for local and global averages, and consistency ratio calculations are included in Appendix VII. The T1 vs T2 final aggregated weights will be presented at the end of this chapter and compared in relation to the results from the M1 vs M2 case. However, since the particular weights developments for the T1 vs T2 case followed the same process for M1 vs M2, the full weight calculations for the T1 vs T2 case are demonstrated within Appendix VII in order to avoid repetition.

The next section will present the pairwise comparison matrices between the M1 vs M2 case modules for each of the bottom level criteria. The discussion will go through each identified literature theme, which are the level 2 criteria in the hierarchy and break it down to its base criteria presented on the subsequent levels in the hierarchy. The local weight for each of the case modules is then aggregated across the levels to reach a global weight. The global weight will represent the accumulated weight received by each module across all the criteria in the different levels. Accordingly, the global weight will represent the aggregated effect of the modularity in design of the module on the sustainability of the supply chain across the economic, environmental, and social aspects.

5.5 Model Implementation

5.5.1 Theme 1: Mass Customisation

As identified through the integrative literature review, the first theme that links PDM to the economic aspect is mass customisation. Mass customisation is then broken down to its base criteria, which are product variety, customised end product, inventory cost savings, and economies of scale. The next section will discuss the interpretation of the findings into weight inputs for the pairwise comparison matrices between the two case modules M1 versus M2 for each criterion.

5.5.1.1 Product Variety

The literature provided that there is a positive relationship between modularity in design and the ability of the company to increase its product variety. Product variety in turn is found to contribute to an increase in sales. This relationship therefore, focuses on PDM's ability to increase company profits through potential sales increase. The analysis for this relationship is based on the amount of sales that can be contributed by one module (M1), which is considered more modular in design, in comparison to another module (M2), which is considered more integral in design. This data was obtained from the sales record of the case company. The researcher categorised the washing machine models that shared M1 and obtained the total sales for those particular models over the 23 months period of analysis. The same process was done to calculate the total washing machine models sold, which shared the M2 module. The findings provided that M1 contributed to a total sale of 493,696 washing machine models, whereas M2 contributed to a total sale of 140,546 washing machine models over the 23 months period of analysis.

In order to input the finding into the AHP model, the researcher calculated the total sales of washing machines sold sharing M1 in comparison to washing machines sold sharing M2 as a ratio.

Ratio of M1 vs M2 for product variety = sum of sales for washing machine models sharing M1 / sum of sales for washing machine models sharing M2.

Based on the ratio it was identified that M1 leads to 3.67 times more sales than M2. The researcher then input these values into the AHP model with M1 being 3.67 times more preferable when compared to M2 for washing machine in terms of sales in units. The value for the comparison between M2 and M1 was input as the reciprocal value as shown in table 5.2 below.

Table 5.2: Product Variety Pairwise Comparison of M1 vs M2

Attribute Level	Product Variety	M1	M2
	M1	1	3.67
	M2	0.27	1
	Total	1.27	4.67

Through normalising the rows of the matrix, the researcher obtained the respective local weights (under the Row Average column) for M1 in comparison to M2 in the context of product variety as shown in table 5.3 below.

Table 5.3: Product Variety Local Weights

Product Variety	M1	M2	Row Average
M1	0.78	0.78	0.78
M2	0.21	0.21	0.21
Total	1	1	1

Accordingly, the consistency ratio of the weights was calculated as shown in Table 5.4. Saaty (1987) discussed that two by two matrices have 0 allowance in terms of inconsistency, meaning that the number of comparisons must equal the average matrix consistency.

Table 5.4: Product Variety CR

Product Variety	Consistency		Number of Comparisons	2
M1	2		Average Consistency	2
M2	2		CI	0
			RI	0
Total	4		Consistency Ratio	0
			Consistent	Yes

This process of calculating the local weight and the consistency for each of the bottom level criteria in the hierarchy is repeated for the remaining criteria. The remaining consistency ratio and local weight calculation tables are presented in Appendix VII to avoid repetition.

5.5.1.2 Customised End Product

The case company was found not to offer customised end products to the final customer. The company, nevertheless, was found to produce customised washing machines to other washing machine producers, who outsourced their production operations to the case company. Therefore, data inputs for this relationship are based on the unit sales of the customised washing machines exported to these specific customers. This relationship focuses on PDM's ability to increase company sales through the offering of a customised end product. The researcher calculated the total exports for the customised washing machines that shared M1 in comparison to the total exports of the customised washing machines sharing M2.

The findings provided that M1 was used in the sales of 177,281 customised washing machines for export; while M2 was used 44,716 exported washing machines. The same logic was followed as in the product variety relationship, where the researcher calculated these values as a ratio in order to input the values in the AHP model.

Ratio of M1 vs M2 for customised end product = sum of exported washing machines sold sharing M1 / sum of exported washing machines sold sharing M2

The ratio provided that for this relationship M1 contributed to 4.083 times more sales than M2. Accordingly, the value of 4.083 was input comparing M1 to M2 in the pairwise comparison matrix and the reciprocal of that value was input when comparing M2 to M1. Table 5.5 presents the pairwise comparison, local weights respectively.

Table 5.5: Customised End Product Pairwise Comparison M1 vs M2

Attribute Level	Customised End Product	M1	M2	Row Average
	M1	1	4.08	0.80
	M2	0.24	1	0.19
	Total	1.24	5.08	1

5.5.1.3 Inventory Cost Saving

As for inventory cost saving, PDM is seen to enhance cost savings through the inventory pooling effect (Zhang, et al., 2017). This relationship links PDM to the economic aspect through the possibility of supply chain cost reduction in terms of inventory cost savings. Modularity in design develops standardised modules, which leads to component commonality across a product family. The pooling effect is a result of more end items being dependent on a common module. Accordingly, to assess the different effect M1 has on inventory saving in comparison to M2, both M1 and M2 were calculated as an average of the number of washing machines dependent on them. Therefore, the total inventory of M1 was calculated and divided by the total number of washing machines, which share M1. Similarly, the total inventory of M2 was calculated and divided by the total number of washing machines, which share M2. As presented in the Findings Chapter, the case company was found to have 26,790 units of M1 on hand per washing machine model dependent on M1 and 74,628 units of M2 on hand per washing machine model dependent on M2. In order to input these values in the AHP model, the researcher calculated the findings as a ratio.

Ratio of M1 vs M2 for inventory cost savings = Average on hand inventory of M1 per washing machine sharing M1 / Average on hand inventory of M2 per washing machine sharing M2

From this ratio it is identified that the case company keeps 2.78 times more inventory for M2 than M1. Therefore, M1 results in 2.78 times inventory savings than M2. These values are input in the inventory cost saving pairwise comparison matrix and accordingly the local weights are calculated as shown in Table 5.6 below.

Table 5.6 Inventory Cost Saving Pairwise Comparison M1 vs M2

Attribute Level	Inventory Saving	M1	M2	Row Average
	M1	1	2.78	0.73
	M2	0.35	1	0.26
	Total	1.35	3.78	1

5.5.1.4 Economies of Scale

This relationship also links with the economic aspect from a cost perspective. PDM is seen to offer possible supply chain cost reductions through economies of scale in production or quantity discounts in purchases. By interpreting modularity in design as commonality in the product family modules this means that more end items are dependent on the same module. Hence, the company can capitalise on economies of scale in the production process or quantity discounts from the purchase of larger quantities of the same module from the supplier. For the case company this is present as is seen in the findings, where M1 and M2 are both purchased from the same supplier. The total purchase quantities for M1 over the period of analysis amounted to 449,769 units and for M2 154,953 units. The purchase price for M1 decreased by 1.57 Egyptian Pounds from 2015 to 2016, while for M2 it decreased from 1.37 Egyptian Pounds.

To input these values in the AHP model, the researcher calculated this in the form of a ratio.

Ratio of M1 vs M2 for economies of scale = purchase price reduction of M1 / purchase price reduction of M2

This resulted in M1 being slightly more preferable than M2 with a value of 1.17. This value was then input into the AHP model for M1 vs M2 and reciprocal value was input for M2 vs M1 as shown in table 5.7 below.

Table 5.7 Economies of Scale Pairwise Comparison M1 vs M2

Attribute Level	Economies of Scale	M1	M2	Row Average
	M1	1	1.17	0.53
	M2	0.85	1	0.46
	Total	1.85	2.17	1

5.5.2 Theme 2: Supply Chain Integration

The supply chain integration theme consists of four distinct relationships linking PDM to supply chain operational improvements through improving integration between supply chain members. Data for this theme was obtained through semi-structured interviews. For the relationships, supplier integration, manufacturing integration, and information integration, the interview was conducted with the supply chain manager of the case company due to his position being responsible for such operations as supplier selection, manufacturing strategies, and information system implementations. For the design integration relationship, the interview was conducted with the product design engineer.

Data obtained, however, related to product design methodologies in general without being specific to the case modules. Therefore, in order to obtain a pairwise comparison for the case modules the researcher conducted follow up phone interviews with the supply chain manager and product design engineer. The objective of these interviews was to obtain their expert opinion in terms of which module they preferred for each of the four relationships. Since the interviewees had signed the required ethical forms and already understood the overall aim of the research and the hierarchy of the relationships was already discussed with them during the initial semi structured interviews, the researcher thus was able to conduct the follow up phone interviews directly. For the phone interviews, the researcher opted for structured, closed ended questions instead of semi-structured interviews. The questions were structured in such a way so that the interviewee would provide a weight for

M1 vs M2 in respect to a particular relationship. The researcher explained that the weights should be assigned on a scale from 1 to 9, where 1 is when there is no difference between the modules and higher numbers on the scale would be considered multiples of how much preferable one module is to the other (Saaty, 1987). Therefore, the questions asked to the supply chain manager were:

- In terms of supply chain integration, can you provide your opinion, in the form of a weight on a scale from 1 to 9, for which module (M1 or M2) would you consider more preferable for improving supplier integration?

This question was then repeated for manufacturing integration and information integration.

The question asked to the product design engineer was:

- In terms of supply chain integration, can you provide your opinion, in the form of a weight on a scale from 1 to 9, for which module (M1 or M2) would you consider more preferable for improving design integration?

Accordingly, based on the answers provided, the researcher was able to input the weights assigned by the interviewees in the pairwise comparison between M1 and M2. The reciprocal value of the weights was hence input for M2 vs M1. The pairwise comparison for the supply chain integration theme and the local weights for M1 vs M2 for each respective relationship are provided in Table 5.8 below.

Table 5.8: Supply Chain Integration local weights

Supply Chain Integration		M1	M2	Row Average	
				M1	M2
	Supplier Integration	5	0.2	0.83	0.16
	Manufacturing Integration	7	0.14	0.87	0.12
	Information Integration	7	0.14	0.87	0.12
	Design Integration	3	0.33	0.75	0.25

5.5.3 Theme 3: Supply Chain Responsiveness

In terms of supply chain responsiveness, PDM is found to affect production cycle lead time and production scheduling. Supply chain responsiveness translates into the company's ability to meet changing market requirements through having the flexibility to control their production output in the form of product mix and quantity (Thatte, 2007). Improved supply chain responsiveness is linked with supply chain's being able to capitalise on opportunities for increasing profit and reducing cost (Holweg, 2005). Through standardising the modules within a product family, this means that the assembly process for that module is standardised. Through the findings in the case this was found to improve production efficiency through reducing production cycle lead-time.

PDM was also found to simplify production scheduling through reducing the number of suppliers the company must manage, reducing the number of components within a product family, and reducing forecasting discrepancies. Therefore, the production scheduling relationship is further broken down into three level four criteria: number of suppliers for a particular component, component percentage within a product family, and forecasting discrepancy ratio.

5.5.3.1 Production Cycle Lead-Time

For the production cycle lead time, the researcher obtained the production man minutes and machine hours required in production and assembly of all 39 washing machine models. The effect that M1 has on the overall production cycle lead time in comparison to M2 was analysed through comparing the man minute and machine hours used in installing M1 in actual units of washing machines produced over the 23 months period in comparison to M2. The total time for installing M1 was found to be 0.258 minutes and 0.281 minutes for M2. To input these values in the AHP model the ratio of installation time was calculated.

Ratio of M1 vs M2 production cycle lead time = installation time for M2 / Installation time for M1

The production cycle lead-time pairwise comparison and local weights are provided in Table 5.9.

Table 5.9: Production Cycle Lead-Time pair wise comparison and local weights

Production Lead Time	M1	M2	Row Average
M1	1	1.08	0.52
M2	0.91	1	0.47
Total	1.91	2.08	1

5.5.3.2 Simplified Production and Scheduling

Through implementing a modular design, the case company was able to use a common module across more end items within the same product family. Module commonality leads to reducing the total number of suppliers the case company has to manage, which simplifies the order processing; reducing the total number of components, which simplifies material requirement planning and inventory management; and reducing the forecast discrepancies, which reduces the risk of production stoppage.

5.5.3.2.1 Number of suppliers

Regarding the number of suppliers, the case company was found to import the both M1 and M2 from the same supplier. This is due to the modular design of the washing machines, which allowed the company to categorise its components and accordingly assign one or two main suppliers per category to capitalise on opportunities for economies of scale. Therefore, equal weights were input into the AHP model for M1 and M2 as shown in Table 5.10 below.

Table 5.10: Number of Suppliers Pairwise Comparison and Local Weights

No of Suppliers	M1	M2	Row Average
M1	1	1	0.5
M2	1	1	0.5
Total	2	2	1

5.5.3.2.2 Number of Components

To capture this relationship, the researcher compared between M1 and M2 by calculating the percentage of washing machines that depend on M1 compared to the percentage of washing machines that depend on M2. The findings provided that the motor module M1 covers the material requirement needs of 38% of the washing machines produced by the case company, while M2 covers 5%. The researcher then calculated the ratio of M1 compared to M2 in terms of number of components to input these values in the AHP model as shown in Table 5.11.

Ratio of M1 vs M2 for number of components = percentage of washing machines covered by M1 / percentage of washing machines covered by M2

Accordingly, M1 is found to cover the material requirement of washing machines 7.6 more times than M2. Or in other terms, M1 being more modular reduces the number of components within the motor module category 7.6 more times than M2.

Table 5.11 Number of Components Pairwise Comparison and Local Weights

No of Components	M1	M2	Row Average
M1	1	7.6	0.88
M2	0.13	1	0.11
Total	1.13	8.6	1

5.5.3.2.3 Forecasting Discrepancies

In terms of forecasting discrepancies, the relationship focused PDM's ability to reduce forecasting errors through the risk pooling effect. For this relationship PDM is seen to decrease forecasting errors due to the commonality of the components in the product family. Components that are shared across different end items can be reallocated to other end items depending on actual production needs in cases where forecasts for one model were overestimated and another model underestimated. Also, in cases where material needs were overestimated the components will not be obsolete and can be kept on hand and included in the next production period's opening inventory. Data for this relationship was obtained through comparing the forecasted material requirement, which is based on the forecasted production reports, and the actual on hand inventory of M1 and M2.

The researcher calculated the total on hand inventory of M1 and M2 in comparison to the total actual production of washing machines that depend on them. The findings presented that the company had an excess of 11,453 M1 motor modules and 31,780 M2 motor modules in inventory in comparison to their actual production needs. This discrepancy is further magnified when calculating the forecasting discrepancy per washing machine. The findings hence presented that for the washing machines that shared M1, the company has 763 excess units of M1; and for the washing machines that share M2 the company has 15,890 excess units of M2. These findings were calculated as a ratio to input into the AHP model.

Ratio of M1 vs M2 forecasting discrepancy = excess units of M2 / excess units of M1

The ratio provided that M1 reduces forecasting discrepancy 20.82 times more than M2. These values were hence input into the pairwise comparison table and the average local weights for this relationship were obtained as shown in Table 5.12 below.

Table 5.12 Forecasting Discrepancy Pairwise Comparison and Local Weights

Forecast Discrepancies	M1	M2	Row Average
M1	1	20.82	0.95
M2	0.04	1	0.04
Total	1.04	21.82	1

5.5.4 Theme 4: 6R Concept

Through the integrative literature review it was identified that PDM is used as a design strategy within three distinct processes that aim at improving environmental performance within a supply chain, which are: environmentally conscious manufacturing (ECM), design for the environment and recycling (DFE/DFR), life cycle assessment (LCA). These processes in particular were developed to integrate product and supply chain designs in order to improve the supply chain's environmental sustainability.

ECM aims to change manufacturing strategies from purely economic strategies, which focus on maximising optimisation and utilisation, to also include elements such as green sourcing, recycling, reuse, and reduce as part of the overall goals of manufacturing. DFE/DFR focus on product design strategies, which lead to less dependence on non-renewable material dependency in production, increased recycling, and more reuse. LCA evaluates a product's life cycle while developing options for the different life cycle stages. This is done with a view to elongate a product's life expectancy, facilitate product maintenance, repair and upgradability, and simplify disposal at end of life. All three processes (whether ECM, DFE/DFR, or LCA) include modularity in product design as a critical step towards their implementation. The findings chapter presented further validation, where interviews conducted with the product design engineer confirmed the use of PDM as a design strategy in the implementation of these processes.

The literature provided that the mechanism in which these processes lead to enhanced supply chain environmental performance is through improving one or more of the following operations within a supply chain: reuse, recycle, recover, reduce, redesign, remanufacture. These operations are identified in the literature as the 6R concept. The 6Rs are thus included as the bottom level criteria for evaluating the effect of PDM on a supply chain's environmental performance within the AHP model.

The data offered by the company, which was presented in the previous findings chapter, provided that the company does currently apply PDM as a design strategy within ECM, DFE/DFR, and LCA. The data also stipulated that PDM leads to enhanced environmental sustainability through increased components recovery, reuse, recycle, remanufacture within the washing machines product family. PDM was also used in product and component redesign with an overall aim of reducing dependence on non-renewable material. The data provided by the company, however, was not module or component specific and did not include number of recycled, reused, or remanufactured components. The data focused on the number of recovered end items and the sequence of operations that followed in order to repair or dispose of the product. The researcher therefore could not numerically compare between the effects of M1 vs M2 and instead opted for conducting a follow up phone interview with the product design engineer. The purpose of the follow up interview was to gain the engineer's expert opinion on the effect of M1 in comparison to M2 in terms of which one he considers better improves the company's recover, reuse, recycle remanufacture, redesign, and reduce operations. The researcher opted for structured, closed ended questions to obtain the pairwise weight values of M1 in comparison to M2 as per the product design engineer's opinion. Accordingly, the questions asked were:

- Can you provide your opinion, in the form of a weight on a scale from 1 to 9, for which module (M1 or M2) would you consider more preferable for improving component recovery?

The same question was then repeated for component reuse, remanufacture, recycle, redesign, and reduce operations. Table 5.13 presents the pairwise comparison and the local weights for each of the 6Rs when comparing M1 to M2.

Table 5.13 6Rs Concept Pairwise Comparison and Local Weights

6R Concept		M1	M2	Row Average	M1	M2
	Recover	5	0.2		0.83	0.16
	Redesign	9	0.11		0.9	0.1
	Remanufacture	7	0.14		0.87	0.12
	Reuse	7	0.14		0.87	0.12
	Reduce	5	0.2		0.83	0.16
	Recycle	1	1		0.5	0.5

5.5.5 Theme 5: 3 Dimensional Concurrent Engineering (3DCE)

As discussed in the previous chapter, the literature did not present a direct link between PDM and social sustainability. However, such a relationship can be induced when examining the effect of product design on process and supply chain designs. This relationship is therefore based on the 3DCE concept, which is defined as the integration of the planning phase for product, process, and supply chain designs (Fine, 1998). Accordingly, this integration of product design with process and supply chain design presents the basis for the effect of PDM on social sustainability in a supply chain.

To examine the effect of PDM on social sustainability certain issues needed to be addressed. First was the relationship between modularity in design and how it is generally considered a steppingstone towards achieving automation due to a standardised process design (Fixson, 2005). Second was the effect of product design on the development of industrial clusters and whether the development of an industrial cluster would lead to social sustainability (Thomsen and Pillay, 2012; Nadvi and Barrientos, 2004).

The researcher consequently assigned three main conditions, which need to be met first in order for PDM to be considered as a design strategy that leads towards social supply chain sustainability, which are:

4. The location of the industrial cluster should be in a developing country
5. The production output of the company is still below the level requiring automation of processes.
6. The supply chain process should be labour intensive.

For this case study all three conditions were met. The researcher accordingly deemed it important to include the social aspect in the research to provide a complete analysis of the effect of PDM on sustainability in supply chain management. The researcher hence examined the effect of PDM on process design and identified that due to PDM leading to work path simplification this can affect the social aspect positively through simplifying employee learning process for new skills and allowing workers to accumulate new skills easier within their work environment (Jacobs, Vickery and Droge, 2007; Liao, Tu and Marsillac, 2010). PDM was also seen to affect supply chain design through influencing the development of industrial clusters. Furthermore, industrial clusters are seen to be associated with increased job opportunities within the geographic area they operate in (Nadvi and Barrientos, 2004; Lei, 2009; Thomsen and Pillay, 2012).

Data obtained from the case findings support and validate the effect of PDM on both relationships. Where questions related to the effect of PDM on the development of industrial clusters and the creation of job opportunities were answered by the supply chain manager. Questions relating to the effect of PDM leading to work path simplification and workers abilities to gain and be proficient at new skills were asked to the product design engineer. However, as was the case with the supply chain integration and 6R concept themes the data provided was not specific to the case modules. The researcher consequently followed up with phone interviews with the supply chain manager and product design engineer. The questions were structured and closed ended with the purpose of obtaining comparative weights for M1 in respect to M2 for the effect of PDM on increasing job creation and on enhancing employee skills.

The supply chain manager was asked to provide a comparative weight on a scale of 1 to 9 for M1 in respect to M2 for which he considered more beneficial for creating more job opportunities.

The product design engineer was asked to provide a comparative weight on a scale of 1 to 9 for M1 in respect to M2 for which he considered more beneficial for work path simplification and improving employee skill learning.

Table 5.14 presents the pairwise comparison and the local weights for both relationships under the 3DCE theme.

Table 5.14 3DCE Pairwise Comparison and Local Weights

3DCE		M1	M2	Row Average	M1	M2
	Job Opportunities	5	0.2		0.83	0.16
	Skill Learning Curve	3	0.33		0.75	0.25

5.6 Discussion of Results

Tables 5.15 and 5.16 below present the final aggregated weights of M1 vs M2 and T1 vs T2 for all three aspects of sustainability. The way the model is structured allows for the calculation of comparative weights for the modules in terms of each of the aspects of sustainability. All three level 1 criteria are given equal weights in order to adhere to the definition of sustainability. The total aggregation of level 1 criteria, hence provides the effect of M1 in comparison to M2 regarding how they influence sustainability in supply chain management.

5.6.1 Model Contribution

Based on the data inputs from the findings, the model obtained that M1 was the better option for the economic, environmental and social aspects. Consequently, the final result of the AHP model presents that M1, as a modular component, enhances supply chain sustainability three more times than M2.

Table 5.15 Aggregated Weights for Economic, Environmental, and Social Aspects (M1 vs M2)

Total Weights on Aspect Level	Economic	Environmental	Social	Total Effect of M1 VS M2 on SSCM
M1	0.73	0.80	0.79	0.77
M2	0.26	0.19	0.20	0.22

Table 5.16 Aggregated Weights for Economic, Environmental, and Social Aspects (T1 vs T2)

Total Weights on Aspect Level	Economic	Environmental	Social	Total Effect of T1 VS T2 on SSCM
T1	0.76	0.80	0.79	0.79
T2	0.23	0.19	0.20	0.20

The environmental and social weights for both cases are identical due to the expert opinion obtained being the same. The data for the economic aspect for each case however was obtained through company operational records. What is noticeable is that T1 achieves an even higher economic weight than M1. This can be attributed to T1 being more modular than M1, where T1 is common in 20 washing machine models and M1 is common in 15 models. This shows that the degree of modularity, meaning how modular a component is also affects the economic performance.

The main objective of implementing AHP as an analytical tool within this research was to be able to integrate all the findings obtained and presented within the previous chapter, into one model to provide an aggregated answer to the main research question. The main research question for this thesis is 'How does PDM affect SSCM?' To answer this question, the researcher broke it down into three sub-questions each relating to how PDM affects the economic, environmental, and social supply chain aspects respectively. This part of the research was answered through the integrative literature review, where the effects of PDM on SSCM were categorised into five main themes summing up the relations integrating modularity in design to economic, environmental and social supply chain processes.

Based on the literature themes, the researcher was able to develop four propositions, which propose that PDM has a positive effect on each of the economic, environmental, and social aspects of sustainability.

Therefore, the next stage in the research was to ask whether PDM's effect on supply chain management leads to sustainable supply chain operations. For this stage, the research within this thesis is designed in such a way as to present a comparison between two product design methodologies, modularity and integrality. This is done with a view to evaluate the effect of these different design methodologies on the economic, environmental and social relationships, which were previously identified and eventually be able to answer which of the two designs enhances sustainable supply chain operations. The AHP model for this research is hence used as an analytical tool to develop pairwise comparisons between the case modules, with M1 representing the modular design and M2 representing the integral design. The case module choice focused on the commonality aspect of a specific module in a product family. Commonality here translates into how many end items depend on a common module. Such a module in this case would adhere to the definition of PDM, where according to Schilling (2000) a modular design allows for combinability, transferability and separability. A commonly shared module has all three design characteristics, where it can be transferred from one end item to another, easily separated, and easily combined to other end items. The researcher accordingly opted to choose the modules with each case module being at one extreme end of the product design spectrum. M1 was chosen for being the most commonly shared motor module within the washing machines product family to represent modularity in design and M2 was chosen for being the least commonly shared module within the same product family to represent integrality in design.

The AHP model presents an aggregated weight for the effect of M1 on SSCM in comparison to M2. The model also presents all the relationships linking PDM to supply chain operations across economic, environmental, and social aspects.

Even though the AHP model in this case was mainly used to evaluate the effect of modularity as a design methodology on SSCM, the model itself is seen to have another important use. The model can be used as an analytical tool, where product designers use it to compare between different modules in new product designs or for upgrading current product designs. The same model can be used to compare between a countless number of modules with each module given an aggregated weight as to the effect it has on economic, environmental, and social supply chain operations. Another use for this model can be to help supply chain managers rate the different criteria, which integrate between product design and supply chain design to enhance their overall sustainable operations. Giving each criterion a specific weight can help the company identify its current and future priorities in terms of its sustainable supply chain operations.

The relationships presented in the model can also be used as the basis for the development of measures, which evaluate the performance of a particular component's design in relation to others. The model therefore can be further developed into a performance measurement system with key performance indicators and benchmarks relating module design to economic, environmental and social supply chain operations.

5.6.2 Model Limitations

It is however important to note some of the shortcomings of the current model. A major obstacle the researcher faced during the entirety of this research was the sensitivity of the data requirements. Accordingly, the researcher had to adapt the model to best fit the available data. Even though the case company was quite helpful and allowed me permissions to obtain most of the data requirements set out in the research methodology chapter, some of the data was still considered too case sensitive to be divulged.

The first limitation in the model is that for the economic relationships of product variety and customised end product, the analysis was conducted as a comparison between sales in units and does not include sales value as part of the comparison. This is due to the company only giving the researcher access to their sales records in the form of units without the value of the end item models being included. Hence, this model can be further enhanced to include both sales in units and sales in value for the product variety and customised end product relationships to give an indication of the monetary profit achieved from each module design.

The second limitation is that the environmental data is based on subjective opinions. Even though the opinions are obtained from experts who are directly responsible for the operations in the 6R relationships, the model would provide a more accurate result from objective quantitative inputs based on how many times each module was reused, recovered, recycled, remanufactured, redesigned, or reduced. The case company however did not follow such a reporting system, which obliged the researcher to opt for basing the comparative weights on opinions from expert subject matter instead.

The third limitation is that the model assumes that all three pre-set conditions of social sustainability are already present. The two relationships of creation of job opportunities and employee skill learning can still nonetheless be used as evaluative criteria for assessing the effect of a particular module design on social sustainability. For the purpose of providing evidence as to PDM having a positive effect on sustainability however, these conditions must be met prior to the analysis.

The fourth limitation is that this model is designed to analyse modules and components within a product design, therefore it is mainly for industries where there is an option for modularity in product design planning. The automotive and electronics industries are prime examples where this model can be used to provide an evaluation for the sustainability of their components as well as assist in the decision making process to identify the most sustainable module choice. Industries that are heavily reliant on make to order production with highly customised end products where no standardisation can be implemented at any of the stages of production are out of the scope of this research.

5.7 Chapter Summary

This chapter focused on providing an analytical tool able to combine all the data sets obtained from Chapter 4 into one model. The objective of the analytical model is to integrate and present the data sets from the economic, environmental and social and provide a means to calculate which module design achieves better performance. The AHP model presented in this chapter provided such a solution, where the conceptual framework presented at the end of Chapter 2 is transformed into the hierarchical model. The first level in the hierarchy would be the three main pillars of sustainability. The subsequent criteria as presented are the specific supply chain processes where a product's design is seen to have an effect on the performance of the supply chain whether from an economic, environmental or social perspective. The model is used to assess the performance of M1 in comparison to M2 and then again for T1 in comparison to T2. This was done through inputting the data sets obtained from the company and presented in chapter 4 as the value inputs for the alternatives within the model. In each case the module with the more modular design was seen to achieve better performance across all three pillars of modularity. This model can therefore be used as a tool to help supply chain managers and product design engineers come up with the most sustainable module alternative through comparing the performance of each module based on the identified criteria. The model also presents an overall sustainability measure which can easily be broken down into an economic, environmental and social measures. This can help the company better match its strategic, supply chain, and sustainability objectives through giving a higher weight to the criteria the company wishes to help improve.

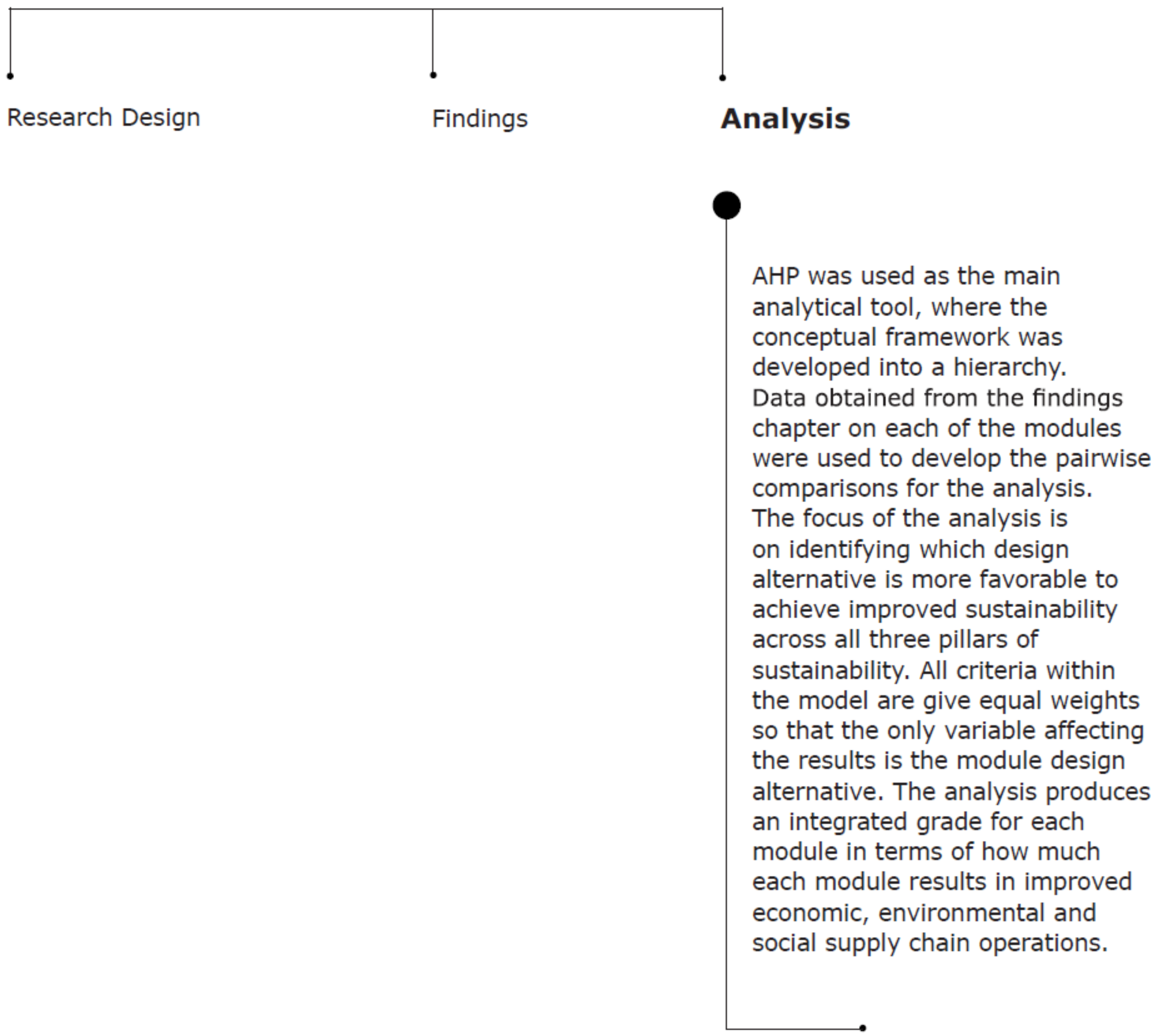


Figure 5.2 Analysis Chapter Summary

Chapter 6 Conclusion

6.1 Conclusion and Discussion

The purpose of this thesis was to assess the effect modularity in design has on the sustainability of supply chain operations. Propositions were presented in Part B of the literature review claiming that PDM leads to enhancing economic, environmental, and social performance of a supply chain. The research that followed provided a methodology to test these propositions (P1, P2, P3, P4).

The developed methodology was in the form of a comparative study, which focused on two modules within a product family that were at extreme ends of the product design spectrum. One component was at the modular end of the product design spectrum and the other was at the integral end. The findings obtained were based on empirical evidence through the case company, where data was collected on the modular component and the integral component as presented in Chapter Four. This data was then used as the basis for the pairwise comparison weight inputs for the AHP model in Chapter Five.

The first two research propositions (P1, P2) focused on the effect modularity in design has on improving economic performance in a supply chain. This economic effect was translated into PDM having either a potential for increasing profit or reducing costs within the identified supply processes.

As modularity in design was initially developed to solve supply chain trade-offs between efficiency and effectiveness in manufacturing (Kong, et al., 2010), the integrative review provided that a majority of the literature on PDM discussed the effect of modularity on enhancing operational performance of a supply chain (Table 2.6). Three major themes were identified in the literature providing a total of ten relationships where modularity in design was seen to have an economic effect on supply chain operations (Figure 2.13). Table 6.1 and 6.2 present the findings for the economic effect of PDM on the economic performance of the case company.

Table 6.1 M1 vs M2

Economic Effect of PDM on SSCM						
Mass Customisation		Product Variety	Customised End Product	Inventory Saving	Economies of Scale	Total Weight for MC
	M1	0.78	0.80	0.73	0.53	0.71
	M2	0.21	0.19	0.26	0.46	0.28
SCI		SI	MI	II	DI	Total Weight for SCI
	M1	0.83	0.87	0.87	0.75	0.83
	M2	0.16	0.12	0.12	0.25	0.16
SCR		Simplified Production Scheduling		Production Lead Time		Total Weight for SCR
	M1	0.77		0.52		0.65
	M2	0.22		0.47		0.34

Table 6.2 T1 vs T2

Economic Effect of PDM on SSCM						
Mass Customisation		Product Variety	Customised End Product	Inventory Saving	Economies of Scale	Total Weight for MC
	T1	0.60	0.72	0.73	0.9	0.75
	T2	0.39	0.27	0.26	0.1	0.24
SCI		SI	MI	II	DI	Total Weight for SCI
	T1	0.83	0.87	0.87	0.75	0.83
	T2	0.16	0.125	0.125	0.25	0.16
SCR		Simplified Production Scheduling		Production Lead Time		Total Weight for SCR
	T1	0.71		0.52		0.61
	T2	0.28		0.47		0.38

The findings supported the propositions, where in both cases the modular component (M1, T1) was found to enhance the economic performance within the identified supply chain process in comparison to the integral component (M2, T2). The modular components were found to improve the company's economic performance through a number of factors:

- Increasing the range of product offerings within the washing machines product family and by doing so increasing the sales in units for the case company.

- Allowing the company to offer customised washing machines to other white electronic goods producers that were looking to outsource their production and by doing so increased the exports in units for the case company.
- Enabling the company to save operational costs through reducing holding inventory of the modular components due to the risk pooling effect.
- Reducing operational costs through economies of scale achieved from purchase quantity discounts of the modular components.
- Enhancing supply chain integration through supplier, manufacturing, information, and design integration. Hence allowing the company to increase profit making potential and reduce supply chain operational costs through streamlining processes such as information sharing, manufacturing and design synchronisation, supplier selection, and responsibility division between supply chain entities.
- Increasing supply chain responsiveness by reducing production cycle lead-time and simplified production and scheduling. Hence, the company is more adept to respond to market opportunities and mitigate risks arising from changes in market demand.

Starting from the 1980's sustainability began to be an increasingly researched topic (Carter and Rogers, 2008). Accordingly, more literature began to investigate the relationship between PDM and its effect on environmental sustainability in particular. PDM was integrated into supply chain processes, which dealt with design of green products, disposal of products at end of life, maintenance, repair, upgradability, and waste reduction (Table 2.8). A majority of the identified literature concentrated on PDM's ability to enhance six supply chain processes specifically: reduce, recover, reuse, recycle, remanufacture, and redesign. Therefore, the effect of PDM on environmental performance was assessed based on PDM's ability to reduce environmental harm resulting from supply chain operations (P3). Table 6.3 provides the findings of the M1 vs M2 case and T1 vs T2, which for this case were found to be identical.

Table 6.3 M1 vs M2 and T1 vs T2

Environmental Effect of PDM on SSCM							
6R Concept	Recover	Redesign	Remanufacture	Reuse	Reduce	Recycle	Total Weight
M1/T1	0.83	0.9	0.87	0.87	0.83	0.5	0.80
M2/T2	0.16	0.1	0.12	0.12	0.16	0.5	0.19

The environmental relationship between PDM and SSCM was based on semi-structured interviews and the expert opinion of the supply chain manager and product design engineer, therefore the data obtained to validate the relationship was qualitative in nature. This was due to the company's reporting system not being designed to monitor these processes on a component level. The results for both cases were identical due to the supply chain manager and product design engineer providing the same comparative weights when asked regarding each case. The findings support the third proposition, where the modular component was found to enhance the company's environmental performance in a number of areas:

- The company was found to implement PDM with the objective of reducing their dependence on non-renewable resources in their product design.
- The company also was found to rely on PDM to develop the product choices for maintenance, repair, upgradability, and disposal throughout the washing machines' life cycle. By focusing on modularity in design the company was able to provide substantially better after sales service to its customers and elongate the washing machines' life span.
- Modularity in design was also identified as a key factor in the company's product recovery and recycling processes. The company was found to depend on modular product design to allow for the easy disassembly of the washing machines into separate components with specific channels for the recovery, recycling, reuse, and remanufacture of the components to reduce overall byproduct waste.

As discussed previously in chapter two, the literature provided a limited number of articles that discuss the effect of PDM on social sustainability (Table 2.10). However, in order to present a holistic model integrating PDM to SSCM, a social relationship was induced through PDM's effect on supply chain design and on process design through the concept of three-dimensional concurrent engineering. The social connection between PDM and supply chain sustainability for this case took a narrower focus by concentrating on only one stakeholder in the supply chain, which were the line workers of the case company. Accordingly, PDM was also recognised to influence the social wellbeing of employees in a supply chain (P4). Table 6.4 below provides the findings from both cases.

Table 6.4 M1 vs M2 and T1 vs T2

Social Effect of PDM on SSCM	Job Opportunities	Skill Learning Curve	Total Weight
M1/T1	0.83	0.75	0.79
M2/T2	0.16	0.25	0.20

For the social aspect as well, the data to validate this relationship was qualitative in nature due to the lack of numeric reports provided by the company that can quantify increase in job opportunities or skills acquired by employees. Nevertheless, PDM was found to have a direct relationship improving social wellbeing for the line workers of the company from two perspectives:

- From a supply chain design perspective, modularity in design is considered a main influence in the development of industrial clusters (Thomsen and Pillay, 2012). Furthermore, industrial clusters were linked to increasing job opportunities in the geographic locations where they operate. The case company currently operates within such an industrial cluster with a number of similar white electronic goods manufacturers operating in the same area. The company currently employs 80 full time line workers and hires seasonal workers during high seasons.
- From a process design perspective, PDM results in a simplified work path due the standardisation of component interfaces (Brandenburg, et al., 2014). A simplified work path is further connected to an employees' ability to acquire and become proficient with new skills. The case company was found to run quarterly training sessions for its employees to maintain and enhance their operational accuracy.

The findings presented in this research therefore supported that a modular design leads to more sustainable supply chain operations. Data sets from both cases provided that the modular components (M1 and T1) achieved higher scores across the economic, environmental, and social aspects of the supply chain in comparison to the integral components (M1 and T2).

Even though modularity in design is not a new concept and research on the topic has been dated as early as the 1960's (Kong, et al., 2010), SSCM is still considered an emerging topic. So far it has faced a number of obstacles mainly regarding the implementation of practical sustainable initiatives in supply chains (Kremer, et al., 2016). The integration of PDM and supply chain design decisions with the objective of enhancing sustainability provided new perceptions and solutions towards improving supply chain sustainability. Research within this thesis offered a new approach to integrate sustainability in supply chain management through a focus on product design. This research reasoned that sustainability considerations for a supply chain needed to be made as early as the product design stage. Integrating product design and supply chain design decisions allows a supply chain to be sufficiently flexible to make changes, which would otherwise be difficult to make if a supply chain was already operational.

The conceptual framework (Figure 2.13) offered a cause and effect relationship between modularity in design and economic, environmental, and social supply chain performance, which clarified the effect product design decisions have on SSCM. Furthermore, through identifying the areas in the supply chain that are directly affected by product design decisions, supply chains can have more control on the sustainability of their operations. By opting for a more modular or an integral design, the economic, environmental, and social performance of a supply chain can be altered.

Modularity in design is already used to solve a number of major trade-offs in supply chain management when it comes to balancing between increasing product variety and reducing manufacturing costs. However, PDM was yet to be considered for solving the trade-offs in SSCM. Hoffman and Bazerman (2005) argued that a major issue in sustainability is that not all initiatives for reducing environmental harm and improving social wellbeing are economically beneficial for a supply chain. This research provided confirmation that modularity in design achieved improved economic, environmental, and social performance simultaneously within the case company without facing the need to trade-off the economic aspect of sustainability against the environmental and social aspects.

The research also recognises that from the multitude of methods available for developing SSCM, AHP provides a systematic mean for criteria development across all three sustainability aspects. The benefit of AHP in this case was the ease of customisation to fit the specific needs to answer the research question. AHP also focuses on a hierarchy approach where the criteria can further be aggregated to demonstrate economic, environmental, and social supply chain performance.

6.2 Academic Contribution

This research acknowledges and builds on previous literature discussions on the major issues identified in the field of SSCM.

Reefke and Sundaram (2016) argued that one of the main difficulties in research on SSCM is the broad scope of the field. Pagell and Shevchenko (2014) discussed that this broad scope is due to the various stakeholders in a supply chain that can affect and are affected by sustainability. Another factor is that sustainability cannot be taken as a stand-alone initiative by one member in a supply chain and needs to be coordinated as an overall objective for all supply chain members (Carter and Rogers, 2008). All these factors add to the problem of implementing sustainability within supply chains, where major trade-offs between economic, environmental, and social objectives arise across the entirety of the supply chain (Hoffman and Bazerman, 2005). This thesis took such obstacles into consideration and developed an integrated view between product design decisions and SSCM. This thesis argued that considerations for supply chain sustainability should be made at the product design stage through integrating product design and supply chain design decisions. Product design decisions widely affect supply chain decisions such as supplier selection, transportation networks, inventory management, and further affect the degree of supply chain integration between supply chain members (Zhuo, San, and Seng, 2008). Therefore, by integrating product design with supply chain design decisions the resulting supply chain design will have overreaching effects on the supply chain entities operating within the supply chain.

Furthermore, by concentrating the research to the effect modularity in design has on SSCM, this thesis was able to develop the relationship between PDM and SSCM across economic, environmental, and social aspects of sustainability simultaneously to demonstrate a holistic representation of SSCM. Even though this research identified very limited research linking PDM to social supply chain sustainability (Table 2.10). This research induced such a relationship, however taking a narrower scope through focusing on one stakeholder only in the supply chain, which is the line worker of the case company. Two criteria were presented, which demonstrated a relationship between PDM and the line worker's standard of living based on two criteria: the availability of job opportunities, which was based on the relation between PDM and the development of industrial clusters (Thomsen and Pillay, 2012); and the line workers ability to acquire and become proficient at new skills, which was linked with PDM resulting in simplified work paths in process designs (Jacobs, et al., 2011).

Another major issue found in SSCM was the abundance of research presenting theoretical solutions in comparison to research offering practical initiatives for the implementation of sustainable initiatives in supply chains (Kumar and Garg, 2017). Therefore, research within this thesis focused on developing a conceptual framework integrating PDM and SSCM (Figure 2.13), but more importantly on providing empirical evidence to validate this conceptual framework in practice. Accordingly, in Chapter Four data from the case company was presented portraying the effect a modular design had on each of the supply chain processes identified within the conceptual framework. Hence, this research provided both, a conceptual framework integrating PDM and SSCM, and validation for the framework and the theoretical relationships presented within it in practice. Furthermore, this research presented PDM as a solution towards enhancing supply chain sustainability, which supply chains can implement in practice.

This thesis also offered a systematic methodology, which supply chains can adopt to identify the most suitable product design to improve their economic, environmental and social performance to become more sustainable. The methodology within this research employed a comparative study investigating the effect a modular component design in comparison to an integral component design has on economic, environmental, and social supply chain performance. The comparison focused on the performance of the supply chain in the specific processes, which were identified in the conceptual framework. The methodology also employed analytical hierarchy processing (AHP) to aggregate the effects the case components had on the supply chain operations to obtain a weight value for the effect the modular component in comparison to the integral component had on sustainable performance in the supply chain. The supply chain processes were based on the relational criteria presented in the conceptual framework linking modularity in product design to SSCM. This same methodology can be used to compare between two or more modules. The data required for the AHP model can be actual data to compare between components already present in the product family or forecasted data evaluating between components that the company is considering to make or buy. Supply chains can therefore model different scenarios for different component designs to choose the design that will be most suitable to enhance their sustainable performance.

Also considered a significant issue in research on SSCM has been the absence of a standardised accounting system to measure the effect of supply chain operations from a sustainable perspective (Hassini, Surti & Searcy, 2012). Formentini and Taticchi (2016) also discussed the difficulty in developing a sustainable supply chain performance measurement system that can be generalised. This was mainly attributed to the broad range of criteria that would need to be included in order to give a holistic representation to sustainable supply chain management. Another reason was the difficulty in developing benchmarks for sustainable performance due to the different nature and industry of the supply chains. Taticchi, Tonelli and Pasqualino (2013) presented a review of the most common supply chain sustainability performance measurement systems and identified that a majority of the models were based on Elkington’s (1994) triple bottom line accounting (TBL) concept.

Research within this thesis therefore followed the TBL concept and attempted to present a holistic view on the economic, environmental, and social performance of the supply chain. However, instead of focusing on the development of a sustainable supply chain performance measurement system, this research focused on the development of a methodology that can be customised depending on the different criteria each supply chain uses to measure the sustainability of their operations. This research argued that AHP could be used as an analytical tool that is easily customisable with different criteria to measure sustainable supply chain performance from different perspectives and across different industries. Accordingly, this research presented an AHP model, which focused on the sustainability of supply chain operations from the perspective of product design for supply chain industries manufacturing products with a degree of modularity, such as electronics and automotive industries.

6.3 Practical Contribution

There are two main outputs from this research that can assist supply chains in practice to become more sustainable. First is the conceptual framework, which presented the relational criteria of supply chain processes affected by modularity in product design. Second is the AHP model, which offers supply chains a tool to compare between current components within a product family or future components that the company plans to make or source. Both the conceptual framework and the AHP model work together to offer a clear cause and effect relationship between how changes in product design lead to changes in the sustainability of the supply chain operations. The research presented a guide, which could be implemented in practice that allows supply chains to control the sustainability of their operations through product design decisions.

The research also provided empirical evidence validating the effect modularity in design has on supply chain sustainability. Hence, this research presented PDM as a practical initiative that allows supply chains to improve their economic, environmental, and social performance simultaneously.

The AHP model demonstrated how changes in product design affect supply chain sustainability through impacting processes that affected economic, environmental, and social performance of the supply chain. The model therefore has a number of practical uses:

1. The model can be used to test how changes in the module designs within a product family can affect the sustainability of supply chain operations without purchasing or manufacturing the model.
2. The model can be used to help product designers choose the best module from among a set of module alternatives to obtain the most sustainable product design option.
3. The model provides criteria upon which designers can evaluate and monitor product design upgrades and new product designs will have on the sustainability of the supply chain operations.

6.4 Limitations

The main limitation for this research was the sensitivity of the data required for the validation of the relationships. The researcher visited 12 different industrial facilities in Egypt, before gaining approval and access to the data required. The companies were chosen based on the applicability of modularity in their operations. The researcher targeted manufacturing facilities either in the automotive or the electronics section. The sensitivity of the data stems from the ability of the data to be used by competitors to identify critical sales and supplier information that could affect the competitiveness of the company. Even though the researcher did explain the principles of the confidentiality agreement, only one company allowed access to the information required. In some of the cases the company had already provided the data, however refused to sign the required ethical forms required under the university regulations.

Another limitation, which was a result of the difficulty in obtaining the data, was that this research considers one company and one product family only. The validity and reliability of the data could have been further enhanced if more than one company was considered.

The research also did not consider cases from various industries that apply modularity in design such automotive and various other electronic industries, which could have added to the robustness of the findings.

The only data available for the economic and social criteria was qualitative in nature based on the expert opinion of the supply chain manager and the product design engineer. This data however, can be numerical as well if the company altered its data recording from a focus on end items to a focus on the specific modules recovered, reused, remanufactured, and recycled. This could have provided a more objective relationship between modularity and the environmental aspect. As for the social aspect this research takes a narrow scope regarding the effect of PDM on social supply chain sustainability. The research only considers one stakeholder (line workers) in this study, which is affected by changes in product design. The research also identified certain conditions, which need to be met in order for PDM to affect the social aspect positively.

As discussed previously, PDM was only considered to positively affect social supply chain performance under certain conditions. Accordingly, if these conditions are not present PDM might have a negative effect on social sustainability.

The criteria within the AHP model were all given equal weights because the scope of this research was not on analysing the importance of the criteria, but on the effect a particular design can have on the sustainability of the supply chain operations. However, this is also considered a limitation, because the findings of the research could have been altered depending on the importance of each criterion from the perspective of the case company.

This research does not consider the effect modules with varying degrees of modularity can have on the sustainability of supply chain operations. Instead this research offered a comparison between two modules, with each module being on one end of the product design spectrum. In this case M1 and T1 were chosen based on their commonality factor, where M1 and T1 were the most commonly shared motor and timer modules respectively for the washing machine product family representing the modular components. M2 and T2 were the least shared modules in their module categories; therefore, they were chosen to represent the integral end of the product design spectrum.

6.5 Recommendations for Future Work

A number of research points were identified as having potential to be developed further a result of research carried out within this thesis.

The first point is the relationship between product design decisions and supply chain design decisions, which needs to be investigated across different industries. With each industry having a different supply chain model and structure it would be interesting to assess the effect product design decisions have on the sustainability of supply chain operations of one industry compared to another. Such research can build on the relationships already identified within this thesis (Figure 2.4 conceptual framework) to demonstrate the effect changes in product design can have on the sustainability of supply chain operations. The purpose of such research would be to allow supply chains to have more control on the economic, environmental, and social performance of their supply chains through their product design decisions.

The second point is balancing supply chain decisions in order to effectively improve the economic, environmental, and social performances simultaneously, which still presents a major research gap for SSCM. This research provided a step forward towards presenting practical solutions for the integration of sustainability and supply chain management across all three aspects. Nevertheless, much work in this field is still required to present further solutions for the implementation of sustainability across all three aspects simultaneously. Research in this area is required to overcome the problems that arise in supply chains when shifting from a focus on economic performance to including environmental and social performance as well to the measurement criteria of a supply chain’s performance.

The third point is the relationship between PDM and social supply chain sustainability. This research provided evidence for the basis for such a relationship considering the effect product design has on the standard of living of the line workers in the case company. More research is required, however, to identify the full impact product design can have on other stakeholders such as customers for example from a social perspective.

The fourth point is the relationship between product design and supply chain network structure. Product design can affect the distribution of value adding responsibilities within the supply chain between the supply chain members. Therefore, product design decisions can affect the entire network structure of a supply chain from supplier selection to the transportation routes to the mode of transport, etc. Therefore, further research is required to investigate this relationship to allow supply chains to have more control over the distribution of value adding responsibilities through product design decisions.

The fifth point is the AHP model, which can also be further developed by adding more criteria depending on the specific nature of the operations of a supply chain. Comparative weights can also be given to each criterion depending on how each supply chain values each specific criterion. The methodology for creating the model can be further developed to be easily customisable for different industries to adopt and use to measure the sustainability of their supply chain’s operations.

Classification and categorisation of articles included in the integrative literature review.

Appendix I

Author	Aspect	Relationship
Zhang, et al. (2017)	Economic	Mass Customisation, Supply Chain Integration
Aydinliyim and Murthy (2016)	Environmental	Closed loop supply chain, recycle, reduce, refurbish, reuse
Kristianto and Helo (2015)	Environmental	Reuse, remanufacture, renewable resources, waste management, Recovery, Refurbishing
Beske and Seuring (2014)	Environmental	Life Cycle Assessment through product design
Brandenburg, et al. (2014)	Environmental, Social	reverse logistics, close loop supply chains, employment, learning curve
Chiu and Okudan (2014)	Economic	Mass Customisation
Bask, et al. (2013)	Environmental	Closed loop supply chain, reuse, redesign, refurbish, recycle abilities of the modules

Danese and Filippini (2013)	Economic	Supplier Integration, New product development, Product Variety, Mass Customisation, Lead time
Seuring (2013)	Environmental	Reverse Logistics, Closed loop supply chains, Life cycle assessment through sustainable product design
Taticchi, Tonelli and Pasqualino (2013)	Environmental	Closed loop supply chain, remanufacture, refurbishing, recycling
Yan and Feng (2013)	Environmental	6R Concept
Huang, et al. (2012)	Environmental	3R Concept
Nepal, Monplaisir and Famuyiwa (2012)	Economic	Mass Customisation, supplier integration
Shamsuzzoha (2011)	Economic, Environmental	Mass Customisation, outsourcing, simplified planning and scheduling, reuse, MRO
Danese, Romano, and Bartolotti (2011)	Economic	Supplier integration
Jacob, et al. (2011)	Economic	Mass Customisation

Ulku and Schmidt (2011)	Economic	Supplier integration
Yu, et al. (2011)	Environmental	Life Cycle Assessment through product design, reverse engineering, reuse, recycle
Lau, et al. (2010)	Economic	Supplier integration
Ilgin and Gupta (2010)	Environmental	Environmentally conscious product design, reverse and closed-loop supply chains, remanufacturing, and disassembly. Finally,
Bush, Tiwana, and Rai (2010)	Economic	Supply Chain Responsiveness, Mass Customisation, product variety, Information integration
Liau, Tu and Marsillac (2010)	Economic, Social	Mass Customisation, Supply Chain Integration, Employee learning curve

Lau, Yam and Tang (2010)	Economic	Supply chain integration, Mass Customisation, Simplified planning and scheduling, economies of scale, Inventory cost reduction, MRO, NPD
Pero, et al. (2010)	Economic	NPD, Mass Customisation (product variety), supply chain integration, simplified planning and scheduling
Kong, et al. (2010)	Economic	Economies of scale, Mass Customisation, NPD
Kuik, Nagalingam, and Amer (2010)	Environmental	6R Concept
Jayal, et al. (2010)	Environmental	6R Concept
Tseng, Chang, and Cheng (2010)	Environmental	Recycling
Brun and Zorzini (2009)	Economic	Mass Customisation, Postponement, Economies of scale, inventory cost saving
Antonio, Richard and Tang (2009)	Economic	Supply Chain Integration
Khan and Creazza (2009)	Economic	Simplified Planning and Scheduling

Qian and Zhang (2009)	Environmental	DFE, DFR
Tseng, Chang and Li (2008)	Environmental	Green Life Cycle Engineering, DFR, DFE, Reuse, Recycle, MRO
Umeda, et al. (2008)	Environmental	Life Cycle Assessment through product design, reverse engineering, reuse, recycle, MRO
Zhou, San and Seng (2008)	Economic	Mass Customisation, Economies of Scale
Zhang, Huang and Rungtusnatham (2008)	Economic	Economies of Scale, Mass Customisation, Product Variety, Inventory Pooling
Jacobs, Vickery and Droge (2007)	Economic, Social	Economies of Scale, Learning Curve, Inventory pooling, Improved forecasting, Simplified Planning and Scheduling, Mass Customisation, Product Variety, Supplier Integration,

		Design Integration
Lau, Yam and Tang (2007) a	Economic	Supply Chain Integration, Mass Customisation, Cycle time reduction
Lau, Yam and Tang (2007) b	Economic	Mass Customisation, Cycle time reduction
Howard and Squire (2007)	Economic	Supplier integration
Jiao, Simpson and Siddique (2007)	Economic	Mass Customisation, Outsourcing
Doran, et al. (2007)	Economic	Supplier integration, Outsourcing
Ro, Liker and Fixson (2007)	Economic	Mass Customisation, Outsourcing, NPD, Supply Chain Integration, Cycle time reduction, Product Variety, Economies of Scale

Kasarda, et al. (2007)	Environmental	Life Cycle Assessment through product design, DFR
Ijomah, et al. (2007)	Environmental	DFE, Remanufacturing
Voordijk, Meijboom and Haan (2006)	Economic	Supply Chain Integration
Sharifi, Ismail and Reid (2006)	Economic	Supply Chain Responsiveness
Lau and Yam (2005)	Economic	Outsourcing, Supplier Integration, NPD
Doran and Roome (2005)	Economic	Supply Chain Integration, Outsourcing
Fixson (2005)	Economic	Cycle time reduction, Mass Customisation
Huang, Zhang and Liang (2005)	Economic	Inventory Pooling, Inventory cost saving, Outsourcing, Cycle time reduction, Mass Customisation
Jose and Tollenaere (2005)	Economic	Product Variety, Mass Customisation, Simplified Planning and Scheduling
Kumar (2005)	Economic	Mass Customisation, Economies of Scale, Product Variety

Gershenson, Prasad and Zhang (2004)	Economic, Environmental	Product Variety, LCA, Recycling, Reuse
Mikkola and Gassmann (2003)	Economic	NPD, Product Variety, Economies of Scale, Inventory Cost Saving, Simplified Planning and Scheduling, Outsourcing
Newcomb, Rosen and Bras (2003)	Environmental	LCA, Recycling, DFR
Doran (2003)	Economic	Supply Chain Integration, Outsourcing, Simplified Planning and Scheduling
Cantamessa and Rafele (2002)	Economic	Outsourcing, Supply Chain Integration
Kusiak (2002)	Economic	Product Variety, Economies of Scale, Simplified Planning and Scheduling, Inventory Cost Saving, Cycle time reduction, MRO
Salvador, Forza and Rungtusanatham (2002)	Economic	Product Variety, Outsourcing, Cycle time reduction, Inventory Cost

		Saving, Supply Chain Integration
Novak and Eppinger (2001)	Economic	Outsourcing
Ernst and Kamrad (2000)	Economic	Supply Chain Integration, Outsourcing, Inventory Cost Saving, Product Variety, Mass Customisation
Duray, et al. (2000)	Economic	Mass Customisation, Product Variety, Economies of Scale, Inventory Cost Saving, Cycle time reduction, Simplified Planning and Scheduling
Gershenson, Prasad and Allamneni (1999)	Environmental	LCA, Recycling, DFR
Hsuan (1999)	Economic	Supply Chain Integration, Outsourcing
Gu and Sosale (1999)	Environmental	LCA, Recycling Reuse, Remanufacture, DFR
Hoek and Weken (1998)	Economic	Product Variety, Simplified Planning and Scheduelling,

		Supply Chain Integration
Gershenson and Prasad (1997)	Economic	Simplified Planning and Scheduling, Economies of Scale, NPD, Cycle time reduction, Product Variety
Ulrich (1995)	Economic	Product Variety, Mass Customisation, Economies of Scale

Information Sheet

Appendix II

The Effect of Product Design Modularity on Sustainable Supply Chain Management

INFORMATION SHEET

You are being invited to take part in a study about how product design modularity can affect economic, environmental, and social aspects of a supply chain. This study is conducted by Ahmed Tarek El-Said, a PhD researcher at the University of Huddersfield and is supervised by Dr Nicoleta Tipi. Before you decide to take part it is important that you understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it me if you wish. Please do not hesitate to ask if there is anything that is not clear or if you would like more information.

What is the study about?
The purpose of this study is to assess and evaluate through empirical research the relationship between product design modularity and its effect on economic, environmental, and social aspects of a supply chain. For the economic aspect the assessment will be based on how product design modularity can affect the profit or cost structure of supply chain. This assessment will focus on how product design modularity is used to develop product ranges and how this helps in the sales and profit of the company. Also how product design modularity helps in the planning and scheduling of production, inventory pooling and cost saving, supplier integration, and order processing. As for the environmental aspect, the assessment will focus on the relationship between product design modularity and the ability to reuse, recycle, refurbish, recover, redesign, and reduce the use of resources used within manufacturing. Finally for the social aspect the assessment will focus on the effect product design modularity has on the learning curve of employees and how this affects employees' employment and standard of living.

Why I have been approached?

You are kindly invited to participate because your organisation produces a range of modular products and through this study an assessment of your product design can be analysed with a view to understanding its effect on the sustainability of your supply chain.

Do I have to take part?

It is your decision whether or not you take part. If you decide to take part you will be asked to sign a consent form, and you will be free to withdraw at any time and without giving a reason.

What will I need to do?

If you agree to take part in the research you will be asked to provide information on a product family (range of products) produced by your organisation. Including the bill of material for the products within that product family and their product structure tree, inventory records in units for the components used in the manufacturing of products within that product family, the sales in units of the end items sold within that product family, the orders in units for the components used in the manufacturing of products within that product family; the items returned, recycled, refurbished, and recovered of products or components from that product family; access to conduct focus group interviews with employees in the manufacturing process.

Will my identity be disclosed?

All information disclosed within the study will be kept confidential, unless you indicate that you or anyone else is at risk of serious harm, in which case I would need to pass this information to… *(this may need adapting depending on the particular reasons for any limits to confidentiality)*

What will happen to the information?

All information collected from you during this research will be kept secure and any identifying material, such as names will be removed in order to ensure anonymity. It is anticipated that the research may, at some point, be published in a journal or report. However, should this happen, your anonymity will be ensured, although it may be necessary to use your words in the presentation of the findings and your permission for this is included in the consent form.

Who can I contact for further information?

If you require any further information about the research, please contact me on:

Researcher Name: Ahmed Tarek El-Said

E-mail: ahmed.el-said@hud.ac.uk
Supervisor Name: Dr Nicoleta Tipi
Email: n.tipi@hud.ac.uk

Organisational Consent Form

Appendix III

University of Huddersfield
Business School Research Ethics Committee
Sample organisational participation consent form (E5)
(required for submission with application for ethical approval)

This form is to be used when consent is sought from those responsible for an organisation or institution for research to be carried out with participants within that organisation or institution. This may include schools, colleges or youth work facilities.

Title of Research Study:

Name of Researcher:

School/College/organisation:

Describe i) the purpose of the research study

ii) the data collection methods to be used

iii) which pupils/groups/classes will be selected for this study.

I ☐ ıfirm that I give permission for this research to be carried out and that permission from all participants will be gained in line within my organisation's policy.

Name and position of senior manager:

………………………………………………………………………………………

Signature of senior manager:….……………………………………………

Date: …………………………

Name of Researcher: ……………………………………………………………

Signature of Researcher: ……………………………………………………

Date: …………………….

Participant Consent Form

Appendix IV

University of
HUDDERSFIELD
Inspiring tomorrow's professionals

CONSENT FORM

(this is an example – this form should be modified to be appropriate to your study)

Title of Research Project:

It is important that you read, understand and sign the consent form. Your contribution to this research is entirely voluntary and you are not obliged in any way to participate, if you require any further details please contact your researcher.

I have been fully informed of the nature and aims of this study as outlined in the information sheet version X, dated 00:00:00	□
I consent to taking part in this the study	□
I understand that I have the right to withdraw from the research …. (*you should outline the withdrawal arrangements)*	□
I give permission for my words to be quoted (by use of pseudonym	□
I understand that the information collected will be in kept secure conditions for a period of ___ years at the University of Huddersfield	□
I understand that no person other than the researcher/s and facilitator/s will have access to the information provided	□
I understand that my identity will be protected by the use of pseudonym in the report and that no written information that could lead to my being identified will be included in any report	□

If you are satisfied that you understand the information and are happy to take part in this project please put a tick in the box aligned to each sentence and print and sign below.

Signature of Participant:	Signature of Researcher:
Print:	Print:
Date:	Date:

(one copy to be retained by Participant / one copy to be retained by Researcher)

Appendix V

Article 37:

a- Open burning of garbage and solid waste shall be absolutely prohibited.

b- The persons responsible for collecting and transporting garbage shall be allowed to throw, sort or treat garbage and solid waste only in the sites designated for such purpose, away from residential, industrial, agricultural areas and waterways. The Executive Regulation of this law shall determine specifications, regulations and the minimum distance of such sites from these areas.

c- Municipal administrative units shall, in agreement with The Egyptian Environmental Affairs Agency EEAA, designate the sites for throwing, sorting and treating of garbage and solid waste according to provisions of this law and its Executive Regulation. These units shall also designate containers or dumps inside cities and villages for collecting and transporting garbage and solid waste and fixing appropriate timing for that; otherwise the responsible person shall be accounted administratively.

d- Throwing garbage and solid waste in places other than such containers and dumps shall be prohibited. Garbage and solid waste collectors and transporters shall maintain cleanliness of garbage containers and transport vehicles. Garbage collection containers should also be tightly covered, and garbage should be collected and transported at suitable intervals provided that the quantity of which shall not exceed the actual capacity of such containers.

Article 39:

All organizations and individuals shall be held, when carrying out exploration, excavation, construction or demolition works or when transporting the resultant waste or debris, to take the necessary precautions to secure the safe storage or transportation thereof to prevent loose particles from escaping into the air, in accordance with the provisions of the executive regulations.

Article 69:
It is prohibited for all establishments, including public places and commercial, industrial, touristic and service establishments, to discharge or throw any untreated substances, wastes or liquids which may cause pollution along the Egyptian sea shores or adjoining waters either directly or indirectly, intentionally or unintentionally. Each day of such prohibited discharge shall be considered as a separate violation.

Article 70: No building permits shall be granted for establishments or public places on or near the sea shore, which would result in the discharge of polluting substances in violation of the provisions of this Law and the decrees issued in implementation thereof unless the applicant for such permit conducts environmental impact studies and undertakes to provide waste treatment units and to operate them as soon as the establishment commences work.

Article 71: The executive regulations of this Law shall define the specifications and criteria which must be observed by industrial establishments allowed to discharge degradable polluted substances after they have been treated. The administrative authority, specified in the said executive regulations, shall conduct periodic analysis of samples of the treated liquid waste in its laboratories and notify the competent administrative authorities of the results. In case of violations, the party concerned shall be granted a grace period of one month to treat the waste and render it compatible with the said specifications and standards. If treatment is not completed within the grace period as aforesaid or if the tests carried out during such period prove that continued discharge would result in severe harm to the water environment, discharge shall be halted by administrative means and the establishment license shall be revoked without prejudice to the penalties prescribed in this Law. In addition, the executive regulations shall specify the non-degradable polluting substances which industrial establishments are prohibited from discharging in the water environment.

Article 72: Taking into consideration provisions of Article (96) of this law, the person in charge of managing the establishments, mentioned in Article (69) of this law, discharging in the water environment, shall be held responsible for any acts committed by his employees in violation of provisions of the said article, if his full knowledge of such violation is proven and if the crimes was committed due to negligence of his duties, in which case he shall be penalized as per Article (84 Bis) of this law.

Ministry of State for Environmental Affairs. (2009). Law No. 9 of 2009. *Promulgating the Environment Law.*

Appendix VI

Ministry of Commerce and Industry

General Authority for Industrial Development

Space Area of Industrial Zones in Governorates - 2012

	Sr.	Governorate	Sr.	Zone Name	Industrial Reference	Arae (Acre)
1- Greater Cairo Region	1	Cairo	1	Industrial Zone at Egypt - Ismailia Dessert Rd. - Nozha District	Governorate	
			2	Industrial Zone at Al Salam City	Governorate	33
			3	Industrial Zone at Al Marj district	Governorate	
			4	Industrial Zone at Sharabia district	Governorate	101.34
			5	Industrial Zone at the zone of Maadi Company for Development and Construction	Governorate	95.59
			6	Nasr City Public Free Zone	Free Zones	168
			Total			397.93

	2	Helwan	7	Industrial Zone at Turrah and Shaq Al Thoban	Governorate	1000
			8	Industrial Zone at Qatamiya	Governorate	164
			9	Industrial Zone at Shaq Al Thoban (adverse possession)	Governorate	290
			10	Industrial Zone at South Helwan	Governorate	7
			11	Industrial Zone at Maasara	Governorate	15
			12	Industrial Zone at Al Roubeky	Governorate	500
			13	New Cairo	New Cities	1090
			14	Shourouk City	New Cities	0
			15	15th May City	New Cities	371.49
			16	Badr City	New Cities	2316
				Badr City (Developers Zone)	Developers	720.64
			Total			6474.13
	3	Giza	There is no Industrial Zones			
	4	6th of October	17	Abo Rawash and its extensions	Governorate	1468
			18	6th October	New Cities	8902
				Developers Zone at 6th October	Developers	2186.05
			19	Wahat (Heavy)	Heavy	272119.3
			20	Media Public Free Zone	Free Zones	714
			Total			284675.35
	5	Qalyubia	21	Shourouk Industrial Zone (Abo Zaabal)	Governorate	137
			22	Safa Industrial Zone for Foundries (Al Zahar district)	Governorate	142
			23	Industrial Zone at Al Akrasha	Governorate	428

			24	Abour City	New Cities	4066
			Total			4773
2- Delta Region	6	Monufia	25	Mubark Industrial Zone and its extension	Governorate	307
			26	Kafr Dawood Industria Zone (Mubark extensions)	Governorate	96.1
			27	Sadat City	New Cities	4395
				Developers Zone at Sadat	Developers	2619.05
			28	Shibin Al Koom Public Free Zone	Free Zones	48
			Total			7465.15
	7	Kafr El Sheikh	29	Industrial Zone at Baltim	Governorate	114
			30	Industrial Zone at Motobas and its extension	Governorate	1660
			31	Industrial Zone at Menesy saltworks in Al Shabiya Zone	Governorate	417
			Total			2191
	8	Damietta	32	New Damietta	New Cities	545
			33	Damietta Public Free Zone	Free Zones	190
			Total			735
	9	Al Gharbia	There is no industrial Zones			
	10	Al Dakahlia	34	Industrial Zone at South West Gamasa	Governorate	727
			35	Industrial Zone at El Asafra (small industries compound)	Governorate	60
			36	Ivestment Zone at Mit Ghamr	Investment	17.71
			Total			804.71
3- Suez Canal	11	Al Sharqia	37	Industrial Zone at Belbeis (Belbeis - 10th Ramadan Rd. at Km 5)	Governorate	270
			38	New Salhia	New Cities	722
			39	10th of Ramadan	New Cities	9524

				Developers Zone at 10th of Ramadan	Developers	10476.19
				Salughterhouses Zone at 10th of Ramadan (Developers)		476.2
			Total			21468.39
	12	Port Said	40	Industrial Zone C1	Governorate	67
			41	Industrial Zone C6	Governorate	4.3
			42	Industrial Zone C11 (Trade housing and workshops)	Governorate	2
			43	Industrial Zone at North West Portex Factory	Governorate	25.5
			44	Industrial Zone at South Port Said - Roswa	Governorate	1153
			45	East Port Said Industrial Zone	New Cities	23574
			46	Port Said Free Zone	Free Zones	235.5
			47	Free Zone at Port Said East port.	Free Zones	8429
			Total			33490.3
	13	Ismailia	48	Industrial Zone at East Qanrara	Governorate	910
			49	First Industrial Zone	Governorate	365
			50	Technology Valley	Governorate	16500
			51	Second Industrial Zone	Governorate	145
			52	Industrial Zone at Wadi Khalefa and its extension	Governorate	1101
			53	Industrial Zone at Wadi Khalefa (sugar factory)	Governorate	169
			54	Ismailia Public Free Zone	Free Zones	77.38
			Total			19267.38
	14	Suez	55	Light industries Zone	Governorate	595
			56	Ataqa and its extensions	New Cities	1168

			57	Petrochemicals Industrial Zone - South Sumed Pipeline	New Cities	4142
			58	Free Zone (Adabia Port - Port Tawfiq)	Free Zones	77
			59	Economic Zone North West Suez Gulf	Economic	48333
			60	North Ataqa (Heavy)	Heavy	18896.4
			61	West Ataqa (Heavy)	Heavy	37337.1
			Total			110548.5
	15	North Sinai	62	Industrial Zone at Bir Alabd	Governorate	238
			63	Literal Industrial Zone at Al Masaeed	Governorate	368
			64	Industrial Zone of construction materila at Al Arish	Governorate	60
			Total			666
	16	South Sinai	There is no Industrial Zones			
4- Alexandria Region	17	Al Beheira	65	Industrial Zone at Wadi Natrun	Governorate	517
			66	Industrial Zone at Bosely desert	Governorate	200
			67	New Nubaria	New Cities	235
			Total			952
	18	Alexandria	68	Industrial Zone at New Mansheyah	Governorate	843.5
			69	Industrial Zone at Nasria	Governorate	168
			70	Industrial Zone at Margham (North and South)	Governorate	3576
			71	Industrial Zone at desert rd. km 31	Governorate	814
			72	Industrial Zone at SIBCO	Governorate	160
			73	Agami - South Bitash	Governorate	3
			74	Industrial Revival Zone and its extensions	Governorate	4611
			75	Industrial Zone at Om Zaghio	Governorate	2851

			76	Alexandria Public Free Zone	Free Zones	1357.14
			77	New Burg Al Arab	New Cities	5465
				Burg Al Arab (Developers Zone)	Developers	2838.26
			Total			22686.9
	19	Matrouh	78	km 26 South Esat Matrouh Rd.	Governorate	803
			Total			803
5- North Upper Egypt Region	20	Faiyum	79	Industrial Zone at Kom Oshim	Governorate	1102
			80	Industrial Zone at Kom Oshim extension - North Faiyum	Governorate	7872
			81	Industrial Zone at Kota	Governorate	2000
			82	Industrial Zone at New Faiyum	New Cities	
			Total			10974
	21	Beni Suef	83	Industrial Zone at Bayad Al Arab	Governorate	1379
			84	Industrial Zone at Kom Abo Rady	Governorate	655
			85	Industrial Zone 1/31	Governorate	6428.57
			86	Industrial Zone 2/31	Governorate	3582
			87	Industrial Zone 3/31	Governorate	3110
			88	Industrial Zone 4/31	Governorate	2857.14
			89	New Beni Suef	New Cities	1652
			90	Industrial Zone at Gabal Ghorab (Heavy)	Heavy	161373.6
			Total			181037.31
	22	Minya	91	Industrial Zone at Al Matahra east Nile	Governorate	2215.01
			92	New Minya	New Cities	140
			93	Wadi Sarira (Heavy)	Heavy	22676.4

			Total			25031.41
6- Middle Upper Egypt Region	23	Asyut	94	Industrial Zone at Arab Awamer	Governorate	614
			95	Industrial Zone at Zarabi (Abutig)	Governorate	63.47
			96	Industrial Zone at Safa (Beni Ghalib)	Governorate	424
			97	Industrial Zone at Sahel Saleem (Small industries)	Governorate	48
			98	Industrial Zone at Dashlout in Dayrout	Governorate	109
			99	Industrial Zone at Al Badari	Governorate	40
			100	New Asyut	New Cities	200
			Total			1498.47
	24	New Valley	101	Industrial Zone at Kharga	Governorate	180
			102	Industrial Zone at Mout	Governorate	71
			103	Industrial Zone at Dakhla (Heavy)	Heavy	298043.1
			104	Industrial Zone at West wadi Daaer (Heavy)	Heavy	231157.6
			Total			529451.7
7- South Upper Egypt Region	25	Sohag	105	Industrial Zone at Al Kawthar	Governorate	500
			106	Industrial Zone at Al Ahayouh	Governorate	250
			107	Industrial Zone at Beit Dawood - West Girga	Governorate	1086
			108	Industrial Zone at West Tahta	Governorate	912
			109	New Sohag	New Cities	188
			110	Investment Zone at Al Matameer	Investment	52278.6
			Total			55214.6
	26	Qena	111	Industrial Zone at Kalaheen - District of Qaft	Governorate	354

			112	Industrial Zone at Hou district	Governorate	500
			113	Free Zone at Kalaheen	Free Zones	216
			114	Investment Zone at Gabal Al Geer	Investment	60530
			Total			61600
	27	Luxor	115	New Thebes	New Cities	370
			116	Al Baghdadi	Governorate	200
			Total			570
	28	Red Sea	117	Industrial Zone at Berenice 1 (Heavy)	Heavy	120485.2
			118	Industrial Zone at Berenice 2 (Heavy)	Heavy	89615.8
			119	Industrial Zone at Al Alaqy 1 (Heavy)	Heavy	61840.7
			120	Industrial Zone at Al Alaqy 2 (Heavy)	Heavy	306749.7
			Total			578691.4
	29	Aswan	121	Shalalat, Wadi Al Alaqy Rd.	Governorate	223
			Total			223
General Total						1961690.63

Source: Industrial Development Authority (6/2012)

Analytical Hierarchy Processing Model Excel Calculations

Appendix VII

Level 1				
	Criteria	Economic	Environmental	Social
	Economic	1	1	1
	Environmental	1	1	1
	Social	1	1	1
	Total	3	3	3

Comparison of Level 1 Criteria	Economic	Environmental	Social	Row Average
Economic	0.333333333	0.333333333	0.333333333	0.333333333
Environmental	0.333333333	0.333333333	0.333333333	0.333333333
Social	0.333333333	0.333333333	0.333333333	0.333333333
Total	1	1	1	1

Comparison of Level 1 Criteria	Consistency		Number of Comparisons	3
Economic	3		Average Consistency	3
Environmental	3		CI	0
Social	3		RI	0.58
			Consistency	0
Total	9		Consistent	YES

Economic

Level 2				
	Criteria	MC	SCI	SCR
	MC	1	1	1
	SCI	1	1	1
	SCR	1	1	1
	Total	3	3	3

Comparison of Economic Criteria	MC	SCI	SCR	Row Average
MC	0.333333333	0.333333333	0.333333333	0.333333333
SCI	0.333333333	0.333333333	0.333333333	0.333333333
SCR	0.333333333	0.333333333	0.333333333	0.333333333
Total	1	1	1	1

Comparison of Level 2 Criteria	Consistency	Number of Comparisons	3
MC	3	Average Consistency	3
SCI	3	CI	0
SCR	3	RI	0.58
		Consistency	0
Total	9	Consistent	YES

MC					
Level 3					
	Criteria	Product Variety	Customised End Product	Inv. Cost Saving	Economies of Scale
	Product Variety	1	1	1	1
	Customised End Product	1	1	1	1
	Inv. Cost Saving	1	1	1	1
	Economies of Scale	1	1	1	1
	Total	4	4	4	4

Comparison of MC Criteria	Product Variety	Customised End Product	Inv. Cost Saving	Economies of Scale	Row Average
Product Variety	0.25	0.25	0.25	0.25	0.25
Customised End Product	0.25	0.25	0.25	0.25	0.25
Inv. Cost Saving	0.25	0.25	0.25	0.25	0.25
Economies of Scale	0.25	0.25	0.25	0.25	0.25
Total	1	1	1	1	1

Comparison of MC Criteria	Consistency	Number of Comparisons	4
Product Variety	4	Average Consistency	4
Customised End Product	4	CI	0
Inv. Cost Saving	4	RI	0.9
Economies of Scale	4	Consistency	0
		Consistent	Yes

SCI					
Level 3					
	Criteria	SI	MI	II	DI
	SI	1	1	1	1
	MI	1	1	1	1
	II	1	1	1	1
	DI	1	1	1	1
	Total	4	4	4	4

Comparison of SCI Criteria	SI	MI	II	DI	Row Average
SI	0.25	0.25	0.25	0.25	0.25
MI	0.25	0.25	0.25	0.25	0.25
II	0.25	0.25	0.25	0.25	0.25
DI	0.25	0.25	0.25	0.25	0.25
Total	1	1	1	1	1

Comparison of SCI Criteria	Consistency	Number of Comparisons	4
SI	4	Average Consistency	4
MI	4	CI	0
II	4	RI	0.9
DI	4	Consistency	0
		Consistent	Yes
Total	16		

SCR			
Level 3			
	Criteria	Simplified Production Schdeuling	Reduced Production Lead Time
	Simplified Production Schdeuling	1	1
	Reduced Production Lead Time	1	1
	Total	2	2

Comparison of SCR Criteria	Simplified Production Schdeuling	Reduced Production Lead Time	Row Average
Simplified Production Schdeuling	0.5	0.5	0.5
Reduced Production Lead Time	0.5	0.5	0.5
Total	1	1	1

Comparison of SCR Criteria	Consistency	Number of Comparison	2	
Simplified Production Scheduling	2	Average Consistency	2	
Reduced Production Lead Time	2	CI	0	
		RI	0	
Total	4	Consistency	0	
		Consistent	Yes	

Simp. Prod. Sched.				
Level 4				
	Criteria	No of Suppliers	No of Components	Reduced Discrepancies
	No of Suppliers	1	1	1
	No of Components	1	1	1
	Reduced Discrepancies	1	1	1
	Total	3	3	3

Comparison of Simplified Prod. Sched. Critera	No of Suppliers	No of Components	Reduced Discrepancies	Row Average
No of Suppliers	0.333333333	0.333333333	0.333333333	0.333333333
No of Components	0.333333333	0.333333333	0.333333333	0.333333333
Reduced Discrepancies	0.333333333	0.333333333	0.333333333	0.333333333
Total	1	1	1	1

Comparison of Simplified Prod. Sched. Criteria	Consistency	Number of Comparison	3
No of Suppliers	3	Average Consistency	3
No of Components	3	CI	0
Reduced Discrepancies	3	RI	0.58
		Consistency	0
Total	9	Consistent	Yes

Environmental							
6Rs							
Level 2							
	Criteria	Recover	Redesign	Remanufacture	Reuse	Reduce	Recycle
	Recover	1	1	1	1	1	1
	Redesign	1	1	1	1	1	1
	Remanufacture	1	1	1	1	1	1
	Reuse	1	1	1	1	1	1
	Reduce	1	1	1	1	1	1
	Recycle	1	1	1	1	1	1
	Total	6	6	6	6	6	6

Comparison of 6Rs Criteria	Recover	Redesign	Remanufacture	Reuse	Reduce	Recycle	Row Average
Recover	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667
Redesign	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667
Remanufacture	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667
Reuse	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667
Reduce	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667
Recycle	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667	0.166666667
Total	1	1	1	1	1	1	1

Comparison of 6Rs Criteria	Consistency	No of Comparisons	6
Recover	6	Average Consistency	6
Redesign	6	CI	0
Remanufacture	6	RI	1.24
Reuse	6	Consistency	0
Reduce	6	Consistent	Yes
Recycle	6		
Total	36		

Social

Level 2			
	Criteria	Job Opportunities	Skill Learning Curve
	Job Opportunities	1	1
	Skill Learning Curve	1	1
	Total	2	2

Comparison of Social Criteria	Job Opportunities	Skill Learning Curve	Row Average
Job Opportunities	0.5	0.5	0.5
Skill Learning Curve	0.5	0.5	0.5
Total	1	1	1

Comparison of Social Criteria	Consistency	Number of Comparisons	2
Job Opportunities	2	Average Consistency	2
Skill Learning Curve	2	CI	0
		RI	0
Total	4	Consistency	0
		Consistent	YES

MC Criteria

Attribute Level	Product Variety	M1	M2	Product Varitey	M1	M2	Row Average	Product Variety	Consistency	Number of Comparisons	2
	M1	1	3.67	M1	0.785867238	0.785867238	0.785867238	M1	2	Average Consistency	2
	M2	0.272479564	1	M2	0.214132762	0.214132762	0.214132762	M2	2	CI	0
										RI	0
	Total	1.272479564	4.67	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Customised End Product	M1	M2	Customised End Product	M1	M2	Row Average	Customised End Product	Consistency	Number of Comparisons	2
	M1	1	4.083	M1	0.803265788	0.803265788	0.803265788	M1	2	Average Consistency	2
	M2	0.244917952	1	M2	0.196734212	0.196734212	0.196734212	M2	2	CI	0
										RI	0
	Total	1.244917952	5.083	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Inventory Saving	M1	M2	Inventory Saving	M1	M2	Row Average	Inventory Saving	Consistency	Number of Comparisons	2
	M1	1	2.786	M1	0.735868991	0.735868991	0.735868991	M1	2	Average Consistency	2
	M2	0.358937545	1	M2	0.264131009	0.264131009	0.264131009	M2	2	CI	0
										RI	0
	Total	1.358937545	3.786	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Economies of Scale	M1	M2	Economies of Scale	M1	M2	Row Average	Economies of Scale	Consistency	Number of Comparisons	2
	M1	1	1.171	M1	0.539382773	0.539382773	0.539382773	M1	2	Average Consistency	2
	M2	0.853970965	1	M2	0.460617227	0.460617227	0.460617227	M2	2	CI	0
										RI	0
	Total	1.853970965	2.171	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

SCI Criteria											
Attribute Level	Supplier Integration	M1	M2	Supplier Integration	M1	M2	Row Average	Supplier Integration	Consistency	Number of Comparisons	2
	M1	1	5	M1	0.833333333	0.833333333	0.833333333	M1	2	Average Consistency	2
	M2	0.2	1	M2	0.166666667	0.166666667	0.166666667	M2	2	CI	0
										RI	0
	Total	1.2	6	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Manufacturing Integration	M1	M2	Manufacturing Integration	M1	M2	Row Average	Manufacturing Integration	Consistency	Number of Comparisons	2
	M1	1	7	M1	0.875	0.875	0.875	M1	2	Average Consistency	2
	M2	0.142857143	1	M2	0.125	0.125	0.125	M2	2	CI	0
										RI	0
	Total	1.142857143	8	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Information Integration	M1	M2	Information Integration	M1	M2	Row Average	Information Integration	Consistency	Number of Comparisons	2
	M1	1	7	M1	0.875	0.875	0.875	M1	2	Average Consistency	2
	M2	0.142857143	1	M2	0.125	0.125	0.125	M2	2	CI	0
										RI	0
	Total	1.142857143	8	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Design Integration	M1	M2	Design Integration	M1	M2	Row Average	Design Integration	Consistency	Number of Comparisons	2
	M1	1	3	M1	0.75	0.75	0.75	M1	2	Average Consistency	2
	M2	0.333333333	1	M2	0.25	0.25	0.25	M2	2	CI	0
										RI	0
	Total	1.333333333	4	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

SCR Criteria

Attribute Level	Production Lead Time	M1	M2	Production Lead Time	M1	M2	Row Average	Production Lead Time	Consistency	Number of Comparisons	2
	M1	1	1.088	M1	0.521072797	0.521072797	0.521072797	M1	2	Average Consistency	2
	M2	0.919117647	1	M2	0.478927203	0.478927203	0.478927203	M2	2	CI	0
										RI	0
	Total	1.919117647	2.088	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Simplified Production and Scheduling Criteria

Attribute Level	No of Suppliers	M1	M2	No of Suppliers	M1	M2	Row Average	No of Suppliers	Consistency	Number of Comparisons	2
	M1	1	1	M1	0.5	0.5	0.5	M1	2	Average Consistency	2
	M2	1	1	M2	0.5	0.5	0.5	M2	2	CI	0
										RI	0
	Total	2	2	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	No of Components	M1	M2	No of Components	M1	M2	Row Average	No of Components	Consistency	Number of Comparisons	2
	M1	1	7.6	M1	0.88372093	0.88372093	0.88372093	M1	2	Average Consistency	2
	M2	0.131578947	1	M2	0.11627907	0.11627907	0.11627907	M2	2	CI	0
										RI	0
	Total	1.131578947	8.6	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Forecast Discrepancies	M1	M2	Forecast Discrepancies	M1	M2	Row Average	Forecast Discrepancies	Consistency	Number of Comparisons	2
	M1	1	20.82	M1	0.954170486	0.954170486	0.954170486	M1	2	Average Consistency	2
	M2	0.04803074	1	M2	0.045829514	0.045829514	0.045829514	M2	2	CI	0
										RI	0
	Total	1.04803074	21.82	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

6Rs Criteria

Attribute Level	Recover	M1	M2	Recover	M1	M2	Row Average	Recover	Consistency	Number of Comparisons	2
	M1	1	5	M1	0.833333333	0.833333333	0.833333333	M1	2	Average Consistency	2
	M2	0.2	1	M2	0.166666667	0.166666667	0.166666667	M2	2	CI	0
										RI	0
	Total	1.2	6	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Redesign	M1	M2	Redesign	M1	M2	Row Average	Redesign	Consistency	Number of Comparisons	2
	M1	1	9	M1	0.9	0.9	0.9	M1	2	Average Consistency	2
	M2	0.111111111	1	M2	0.1	0.1	0.1	M2	2	CI	0
										RI	0
	Total	1.111111111	10	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Remanufacture	M1	M2	Remanufacture	M1	M2	Row Average	Remanufacture	Consistency	Number of Comparisons	2
	M1	1	7	M1	0.875	0.875	0.875	M1	2	Average Consistency	2
	M2	0.142857143	1	M2	0.125	0.125	0.125	M2	2	CI	0
										RI	0
	Total	1.142857143	8	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Reuse	M1	M2	Reuse	M1	M2	Row Average	Reuse	Consistency	Number of Comparisons	2
	M1	1	7	M1	0.875	0.875	0.875	M1	2	Average Consistency	2
	M2	0.142857143	1	M2	0.125	0.125	0.125	M2	2	CI	0
										RI	0
	Total	1.142857143	8	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Reduce	M1	M2	Reduce	M1	M2	Row Average	Reduce	Consistency	Number of Comparisons	2
	M1	1	5	M1	0.833333333	0.833333333	0.833333333	M1	2	Average Consistency	2
	M2	0.2	1	M2	0.166666667	0.166666667	0.166666667	M2	2	CI	0
										RI	0
	Total	1.2	6	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Recycle	M1	M2	Recycle	M1	M2	Row Average	Recycle	Consistency	Number of Comparisons	2
	M1	1	1	M1	0.5	0.5	0.5	M1	2	Average Consistency	2
	M2	1	1	M2	0.5	0.5	0.5	M2	2	CI	0
										RI	0
	Total	2	2	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Social Criteria (3DCE)

Attribute Level	Job Opportunities	M1	M2	Job Opportunities	M1	M2	Row Average	Job Opportunities	Consistency	Number of Comparisons	2
	M1	1	5	M1	0.833333333	0.833333333	0.833333333	M1	2	Average Consistency	2
	M2	0.2	1	M2	0.166666667	0.166666667	0.166666667	M2	2	CI	0
										RI	0
	Total	1.2	6	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Skill Learning Curve	M1	M2	Skill Learning Curve	M1	M2	Row Average	Skill Learning Curve	Consistency	Number of Comparisons	2
	M1	1	3	M1	0.75	0.75	0.75	M1	2	Average Consistency	2
	M2	0.333333333	1	M2	0.25	0.25	0.25	M2	2	CI	0
										RI	0
	Total	1.333333333	4	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

MC Criteria

Attribute Level	Product Variety	T1	T2	Product Varitey	T1	T2	Row Average	Product Variety	Consistency	Number of Comparisons	2
	T1	1	1.52	T1	0.603174603	0.603174603	0.603174603	T1	2	Average Consistency	2
	T2	0.657894737	1	T2	0.396825397	0.396825397	0.396825397	T2	2	CI	0
										RI	0
	Total	1.657894737	2.52	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Customised End Product	T1	T2	Customised End Product	T1	T2	Row Average	Customised End Product	Consistency	Number of Comparisons	2
	T1	1	2.65	T1	0.726027397	0.726027397	0.726027397	T1	2	Average Consistency	2
	T2	0.377358491	1	T2	0.273972603	0.273972603	0.273972603	T2	2	CI	0
										RI	0
	Total	1.377358491	3.65	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Inventory Saving	T1	T2	Inventory Saving	T1	T2	Row Average	Inventory Saving	Consistency	Number of Comparisons	2
	T1	1	4.14	T1	0.805447471	0.805447471	0.805447471	T1	2	Average Consistency	2
	T2	0.241545894	1	T2	0.194552529	0.194552529	0.194552529	T2	2	CI	0
										RI	0
	Total	1.241545894	5.14	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Economies of Scale	T1	T2	Economies of Scale	T1	T2	Row Average	Economies of Scale	Consistency	Number of Comparisons	2
	T1	1	9	T1	0.9	0.9	0.9	T1	2	Average Consistency	2
	T2	0.111111111	1	T2	0.1	0.1	0.1	T2	2	CI	0
										RI	0
	Total	1.111111111	10	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

SCI Criteria											
Attribute Level	Supplier Integration	T1	T2	Supplier Integration	T1	T2	Row Average	Supplier Integration	Consistency	Number of Comparisons	2
	T1	1	5	T1	0.833333333	0.833333333	0.833333333	T1	2	Average Consistency	2
	T2	0.2	1	T2	0.166666667	0.166666667	0.166666667	T2	2	CI	0
										RI	0
	Total	1.2	6	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Manufacturing Integration	T1	T2	Manufacturing Integration	T1	T2	Row Average	Manufacturing Integration	Consistency	Number of Comparisons	2
	T1	1	7	T1	0.875	0.875	0.875	T1	2	Average Consistency	2
	T2	0.142857143	1	T2	0.125	0.125	0.125	T2	2	CI	0
										RI	0
	Total	1.142857143	8	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Information Integration	T1	T2	Information Integration	T1	T2	Row Average	Information Integration	Consistency	Number of Comparisons	2
	T1	1	7	T1	0.875	0.875	0.875	T1	2	Average Consistency	2
	T2	0.142857143	1	T2	0.125	0.125	0.125	T2	2	CI	0
										RI	0
	Total	1.142857143	8	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Design Integration	T1	T2	Design Integration	T1	T2	Row Average	Design Integration	Consistency	Number of Comparisons	2
	T1	1	3	T1	0.75	0.75	0.75	T1	2	Average Consistency	2
	T2	0.333333333	1	T2	0.25	0.25	0.25	T2	2	CI	0
										RI	0
	Total	1.333333333	4	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

SCR Criteria

Attribute Level	Production Lead Time	T1	T2	Production Lead Time	T1	T2	Row Average	Production Lead Time	Consistency	Number of Comparisons	2
	T1	1	1.088	T1	0.521072797	0.521072797	0.521072797	T1	2	Average Consistency	2
	T2	0.919117647	1	T2	0.478927203	0.478927203	0.478927203	T2	2	CI	0
										RI	0
	Total	1.919117647	2.088	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Simplified Production and Scheduling Criteria											
Attribute Level	No of Suppliers	T1	T2	No of Suppliers	T1	T2	Row Average	No of Suppliers	Consistency	Number of Comparisons	2
	T1	1	1	T1	0.5	0.5	0.5	T1	2	Average Consistency	2
	T2	1	1	T2	0.5	0.5	0.5	T2	2	CI	0
										RI	0
	Total	2	2	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	No of Components	T1	T2	No of Components	T1	T2	Row Average	No of Components	Consistency	Number of Comparisons	2
	T1	1	9.66	T1	0.90619137	0.90619137	0.90619137	T1	2	Average Consistency	2
	T2	0.103519669	1	T2	0.09380863	0.09380863	0.09380863	T2	2	CI	0
										RI	0
	Total	1.103519669	10.66	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Forecast Discrepancies	T1	T2	Forecast Discrepancies	T1	T2	Row Average	Forecast Discrepancies	Consistency	Number of Comparisons	2
	T1	1	2.96	T1	0.747474747	0.747474747	0.747474747	T1	2	Average Consistency	2
	T2	0.337837838	1	T2	0.252525253	0.252525253	0.252525253	T2	2	CI	0
										RI	0
	Total	1.337837838	3.96	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

6Rs Criteria

Attribute Level	Recover	T1	T2	Recover	T1	T2	Row Average	Recover	Consistency	Number of Comparisons	2
	T1	1	5	T1	0.833333333	0.833333333	0.833333333	T1	2	Average Consistency	2
	T2	0.2	1	T2	0.166666667	0.166666667	0.166666667	T2	2	CI	0
										RI	0
	Total	1.2	6	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Redesign	T1	T2	Redesign	T1	T2	Row Average	Redesign	Consistency	Number of Comparisons	2
	T1	1	9	T1	0.9	0.9	0.9	T1	2	Average Consistency	2
	T2	0.111111111	1	T2	0.1	0.1	0.1	T2	2	CI	0
										RI	0
	Total	1.111111111	10	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Remanufacture	T1	T2	Remanufacture	T1	T2	Row Average	Remanufacture	Consistency	Number of Comparisons	2
	T1	1	7	T1	0.875	0.875	0.875	T1	2	Average Consistency	2
	T2	0.142857143	1	T2	0.125	0.125	0.125	T2	2	CI	0
										RI	0
	Total	1.142857143	8	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Reuse	T1	T2	Reuse	T1	T2	Row Average	Reuse	Consistency	Number of Comparisons	2
	T1	1	7	T1	0.875	0.875	0.875	T1	2	Average Consistency	2
	T2	0.142857143	1	T2	0.125	0.125	0.125	T2	2	CI	0
										RI	0
	Total	1.142857143	8	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Reduce	T1	T2	Reduce	T1	T2	Row Average	Reduce	Consistency	Number of Comparisons	2
	T1	1	5	T1	0.833333333	0.833333333	0.833333333	T1	2	Average Consistency	2
	T2	0.2	1	T2	0.166666667	0.166666667	0.166666667	T2	2	CI	0
										RI	0
	Total	1.2	6	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Recycle	T1	T2	Recycle	T1	T2	Row Average	Recycle	Consistency	Number of Comparisons	2
	T1	1	1	T1	0.5	0.5	0.5	T1	2	Average Consistency	2
	T2	1	1	T2	0.5	0.5	0.5	T2	2	CI	0
										RI	0
	Total	2	2	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Social Criteria (3DCE)

Attribute Level	Job Opportunities	M1	M2	Job Opportunities	M1	M2	Row Average	Job Opportunities	Consistency	Number of Comparisons	2
	M1	1	5	M1	0.833333333	0.833333333	0.833333333	M1	2	Average Consistency	2
	M2	0.2	1	M2	0.166666667	0.166666667	0.166666667	M2	2	CI	0
										RI	0
	Total	1.2	6	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

Attribute Level	Skill Learning Curve	M1	M2	Skill Learning Curve	M1	M2	Row Average	Skill Learning Curve	Consistency	Number of Comparisons	2
	M1	1	3	M1	0.75	0.75	0.75	M1	2	Average Consistency	2
	M2	0.33 3333 333	1	M2	0.25	0.25	0.25	M2	2	CI	0
										RI	0
	Total	1.33 3333 333	4	Total	1	1	1	Total	4	Consistency	0
										Consistent	Yes

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