Transformative Products and Processes: A Value Chain Assessment of the Australian Manufactured Housing Industry

Academic Report

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EXECUTIVE SUMMARY

Offsite manufacturing is a construction technique utilising prefabricated or standardised components manufactured in a controlled factory environment (either on- or off-site) and eventually assembled into the on-site structure. The benefits of OSM buildings are extensive - with improved quality, time and environmental performance resulting from the use of this construction practice. Despite extensive research, uptake of the use of OSM has remained languid across most of the world with numerous issues potentially contributing to the restriction of the observed uptake. The Supply Chain is a network of multiple businesses and relationships, which consists of different suppliers and distributors. Supply Chain Management is the concept of cooperation and integration of different companies' value chain. The strategic management of these chains has one major goal: the creation of value for both customers, in the form of high quality products and chain members in the form of increased profits.

The purpose of conducting the research is to develop modelling that would provide various opportunities to produce and quantify value across the OSM SC. Identifying, measuring and modelling value across all stakeholders in the SC is paramount to increase the adoption of OSM. In addition, increasing resilience of the OSM SC was required to ensure future risk mitigation of factors affecting the industry.

The research included a detailed industry assessment, academic consultation, industry consultation and the use of various model development techniques for both generation and verification. The project suggests that the developed outcomes should focus of OSM SC industry stakeholders to the improvement or consideration of key factors when creating value and resilience across the OSM SC.

1. INTRODUCTION

1.1 Project synopsis

The need for innovation in the building sector in Australia is growing with rising real-estate prices, increasing resource and utility costs, the need for achieving greater productivity and increased job opportunities. This project focuses on the offsite manufactured (OSM) building industry and undertakes a value chain assessment approach to identify specific areas within the Supply Chain (SC) that can be leveraged for greater value, and also how the SC as a whole can be made more resilient to a number of potential future influences.

The project investigates the transformative nature of products and processes associated with OSM buildings, and considers integrated SC practices that can build resilience against a range of probable future scenarios. The project extended on previous SBEnrc work in the area, and conducted an extensive background assessment incorporating previously published literature as well as academic and industry consultation. The outcomes informed the development of a detailed model designed to account for a range of causal relations and feedbacks along the OSM SC. The modelling sought to take into account scenarios that could influence value, its creation and the generation of resilience across a range of factors that may affect the OSM SC industry. The purpose of conducting the research was to provide modelling that would enable important recommendations and predictions as to how changes to key factors will affect the OSM SC and where various opportunities exist that may be targeted to support value creation across the OSM SC. The process involved the development of an industry wide modelling approach that was further refined through the production of detailed sub-models, specific to the relevant industry stakeholders. By providing better information about the factors affecting value in the OSM industry, along with a better understanding of the supply chain dynamics, public and private sector stakeholders in the housing market will be able to make more informed decisions.

1.2 Report aims and objectives

This report aims to provide an understanding of how to leverage greater value from the OSM industry and increase the robustness of the OSM SC. System dynamics modelling (SDM) was developed to forecast effects across the OSM SC. The output from the modelling provides important recommendations and predictions as to how changes to key factors will affect the SC and where various opportunities that arise can be targeted to support value creation in the OSM SC. The report communicates a detailed background assessment, research approach, justification and development of modelling to achieve this across the entire OSM SC. This was performed by the generation of an industry wide model and its refinement, through the development and use of specific sub-models, which focus on relevant OSM considerations. Due to the nature of the OSM SC and its identified key stakeholders (Figure 2), manufacturers and clients were selected to be the primary focus of this research. After identifying these key stakeholders – manufacturers and clients were determined to exhibit the greatest OSM SC perspective due to their input providing the key link across the OSM SC. Manufacturers are concerned with both process and product values due to their reliance on the process value for them to generate profit and the requirement for them to deliver quality products in order for demand to endure. Clients emphasis is primarily product value, providing an alternate perspective for consideration from the stakeholders identified (Figure 2). This justification was described in detail in Section 3.

Specifically, and through the broader aims and objectives discussed above, the project aims to inform the industrialisation of the residential housing industry through a shift to OSM buildings. The project aimed to investigate specific opportunities to create greater value across the OSM SC for OSM buildings and to increase the resilience of the entire SC by considering the following research questions:

I. How can greater value be created in the SC for OSM buildings in Australia?

II. How can the SC for OSM buildings be made more resilient to future risks associated with likely trends, events and potential crisis affecting the industry?

2. RESEARCH APPROACH

In order to appropriately consider relevant inputs and feedback surrounding the adopted research approach, numerous stages were incorporated throughout the duration of the project. This approach ensured continual feedback and critical review ensuring relevant outcomes were achieved. The research approach was summarised below (Figure 1), with detailed aspects of each stage presented. Milestone reports were delivered throughout the duration of the project, further detailing each of these research stages.

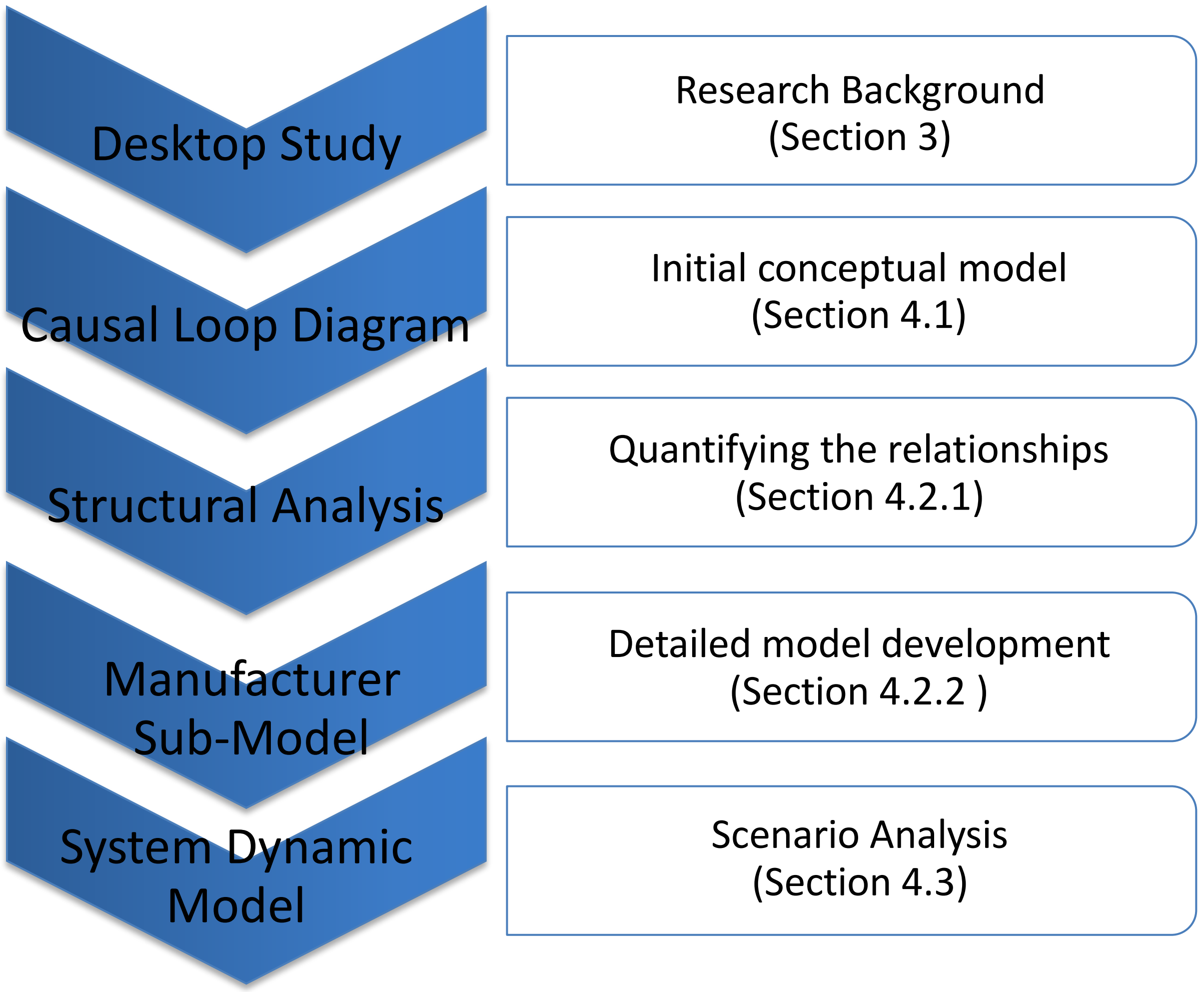


Figure 1: Research Overview

2.1 Desktop Study

The desktop study was conducted to obtain an understanding of the existing knowledge in the field. This assessment enabled the production of the Research Background (Section **Error! Reference source not found.**). The desktop study incorporated a detailed literature review as well as industry and academic consultation. This research phase resulted in the identification of key factors that would be incorporated into the modelling conducted. This was later verified by industry and academic consultation to both confirm the research approach and to endorse the suitability of the identified key factors. This research stage also incorporated the outcomes of earlier SBEnrc research, to include the SWOT analysis conducted for the identification of factors contributing to the current state of the OSM building industry.

2.2 Causal Loop Diagram

This stage incorporated the outcomes of the desktop study conducted above and specifically the identification of: 1) Key stakeholders and 2) Key factors effecting value creation in the OSM SC, enabling the generation of a proposed industry wide conceptual model using a causal loop diagram (CLD). This model distinguished the proposed research approach for partitioning both product and process value as key aspects providing alternate value creation perspectives to the key stakeholders across the OSM SC. The generated conceptual CLD is finalised using an iterative approach incorporating review and feedback from industry and academic representatives. The outcomes of this research stage are discussed in detail (Section 4.1).

2.3 Structural Analysis

Following the completion of the previous research stages, a detailed understanding and quantification of the modelled relationships is required to enable the development of the proposed modelling. This is conducted using a structural analysis matrix generated from the outcomes of the earlier research stages. A typical example of the utilised structural analysis matrix is presented for reference (Table 1). The outcome of this research stage is the identification of the influence and dependence of each of the key identified factors (Section 4.2.1), through industry participation.

Table 1: Example structural analysis matrix completed by participating industry representative

	Product Quality	Customer Satisfaction	Customer Perception	Production Flexibility	Supply Demand Gap	Sales	Initial Cost
Product Quality	0	3	3	1	2	3	2
Customer Satisfaction	3	0	3	2	2	3	1
Customer Perception	3	3	0	2	2	3	1
Production Flexibility	3	2	2	0	1	2	3
Supply Demand Gap	0	0	1	1	0	1	1
Sales	2	1	2	2	3	0	1
Initial Cost	2	1	0	2	1	1	0

2.4 Detailed Conceptual Model

Detailed models were generated enabling consideration of different parts of the OSM value creation process. The focus of this modelling was for the key identified stakeholder, manufacturers. Modelling considerations were developed to account for both product and process value. This stage involved developing a conceptual model (detailed CLD) as a tool for mapping a set of relationships forming the 'system'. The end result was a diagram showing causal links between key factors, which affect the system's behaviour and/or outcomes. The CLD reveals the systemic relationships underlying a complex system. The factors used in the CLD were both - quantitative (hard/measurable) or qualitative (soft). The outcomes of this research stage are presented in Section 4.2.2.

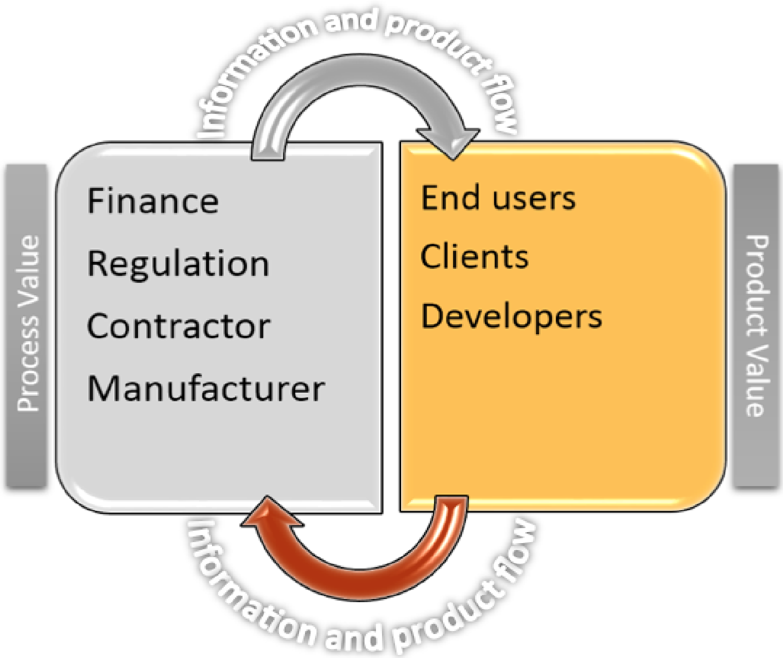
2.5 Systems Dynamic Approach

The SDM used in this research provided a robust platform for analysing the interactions between variables influencing value creation in the OSM SC, and for exploring the sensitivity of the results to the key identified factors. SDM is a powerful tool for informing all levels of SC members seeking to undertake long term planning of OSM related decisions. The strength of this modelling approach is that it enables the exploration of the sensitivity of the model to the baseline assumptions, such as: impact of quality, price level, effect of customer perception and satisfaction on demand and impact of profitability on new OSM investment decisions. Further, this modelling approach, incorporating sensitivity analysis, ensures that more informed decisions are possible in the context of long term planning for value creation across the OSM SC. The outcomes of this research stage are presented in Section 4.3.

3. RESEARCH BACKGROUND

3.1 The supply chain network

The SC is a network of multiple businesses and relationships, which consists of different suppliers and distributors. In terms of product transformation, the SC is a procedure that converts goods from raw materials down to inventory, goods in progress and eventually finished goods. In other words, Supply Chain Management (SCM) is the concept of cooperation and integration of different companies' value chain. The strategic management of these chains has one **major goal: the creation of value** for both customers, in the form of high quality products and chain members in the form of increased profits [1]. The full potential of these benefits would be realised through generating and sustaining growth. The SC has been defined as: *"… a network of multiple businesses and relationships, which consists of different suppliers and distributors. The objective of SCM is to create possibly the highest value for the whole supply chain network from the point of origin to the end consumer"* [2]. Due to the focus of this research being on OSM buildings, an example of the relationships between product and process value considerations with respect to the OSM SC participants is presented (Figure 2a), as well as an appropriate example SC being defined to include key stakeholders at the macro-level (Figure 2b). Given the complexities present for any given SC, this example was proposed to be indicative only for the SC in OSM buildings. This SC representation has included aspects related product and process value perceptions by different SC members discussed in detail in Section 3.3.



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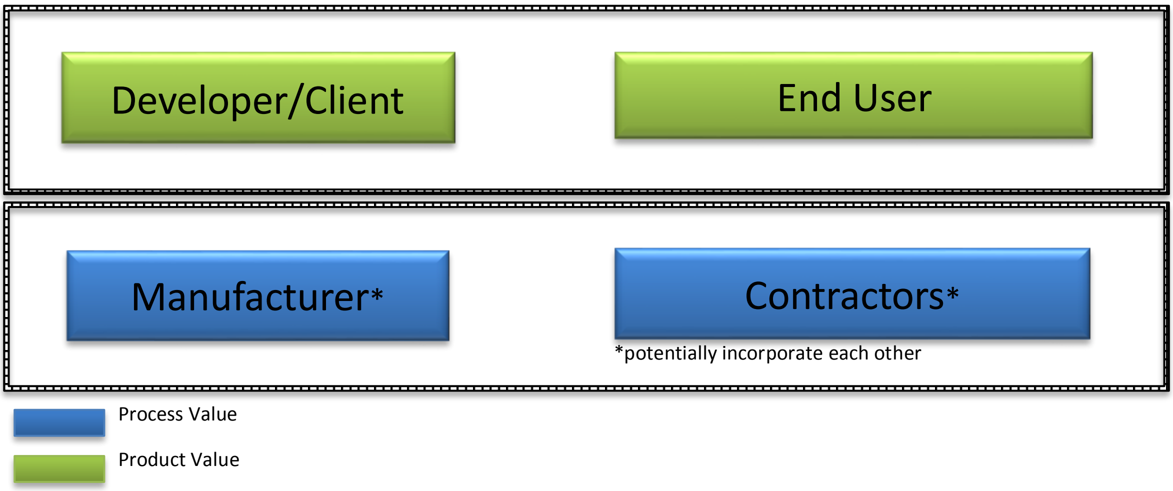

(b)

Figure 2: (a) Examples of the OSM SC stakeholder considerations; (b) Generic example OSM SC supply chain key stakeholders

Today the broader definition of SCM, determined by the Global Supply Chain Forum is the most widely accepted: *"Supply Chain Management (SCM) is the integration of key business processes from end user through original suppliers that provides products, services, and information that add value for customers and other stakeholders"* [3, 4]. SCM is still regarded as a synonym for logistics, supply and SC control. The purpose of SCM is to design the SC and to synchronize the key processes of the firm's suppliers and customers, so as to match the flow of services, materials and information with customer demand [5].

3.2 Off-site manufacturing

Off-site Manufacturing (OSM) (used inter-changeably here for: Off-site production (OSP), Off-site fabrication (OSF), Preassembly, Modularisation, and off-site fabrication (PMOF), Industrialised Building (IB) and Industrialised Building Systems (IBS)) is a construction technique utilising prefabricated or standardised components manufactured in a controlled factory environment (either on- or off-site) and eventually assembled into the on-site structure [6]. Extensive research has been conducted highlighting the benefits and potential improvements to the construction industry through the use of OSM as an alternative construction option to traditional approaches [6-13].

Previous research has principally focused on the barriers and benefits of OSM to the construction industry, with many of these studies citing the importance of the improvements in the uptake of OSM globally to improving the construction industry for all stakeholders [6, 14]. The UK has shown increasing trends in the use of OSM with its OSM industry increasing from £2.2 billion ($4.3 billion AUD equivalent) in 2004 up to £6 billion ($11.7 billion AUD equivalent) in 2006 [15, 16]. These previous trends were attributed to a catalytic government report, with a subsequent lull in the literature until a more recent renaissance [17]. Many other nations have highlighted the importance of increasing the adoption of OSM in the construction industry with Malaysia giving the use of OSM significant importance in its Construction Industry Master Plan 2006-2015 [6], Australia identifying OSM as a key vision for improving the industry in the coming decade [11], the USA department of Housing and Urban Development (HUD) confirming the benefits of OSM delivering more economical, faster and better homes [9] and research in China citing OSM as a potential viable alternative for improving sustainable practice of the industry [18].

Despite the extensive research, uptake of the use of OSM has remained languid across most of the world with numerous barriers identified for the restriction in uptake observed [8]. Identifying, measuring and modelling value across all stakeholders in the SC is paramount to increase the adoption of OSM. The purpose of this research was to develop mechanisms that appropriately achieve this.

3.2.1 Barriers and enablers to OSM

A detailed literature review was conducted to identify key barriers and enablers to the OSM industry. A 2014 study by researchers at the Barbara Hardy Institute in South Australia [8], assessed a total of 115 publications dated from 2002 to 2014 relevant to understanding the barriers and enablers to OSM buildings. The findings regarding the drivers and barriers related to OSM buildings were presented to enable comparison of the key aspects requiring research attention Table 2 and Figure 3.

Table 2: Summary of OSM drivers and barriers stated in the literature:

(Developed and adopted from [8])

Enablers										**Barriers**								
Customer preferences	*Logistics and process*	*Human skills*	*Waste removal*	*OS&H*	*Final product cost*	*Productivity*	*Environmental*	*Time*	*Quality*	*Leadership*	*Logistics and site operations*	*Process*	*Regulatory*	*Industry market and culture*	*Supply chain and procurement*	*Initial cost*	*Skills and knowledge*	**Source**
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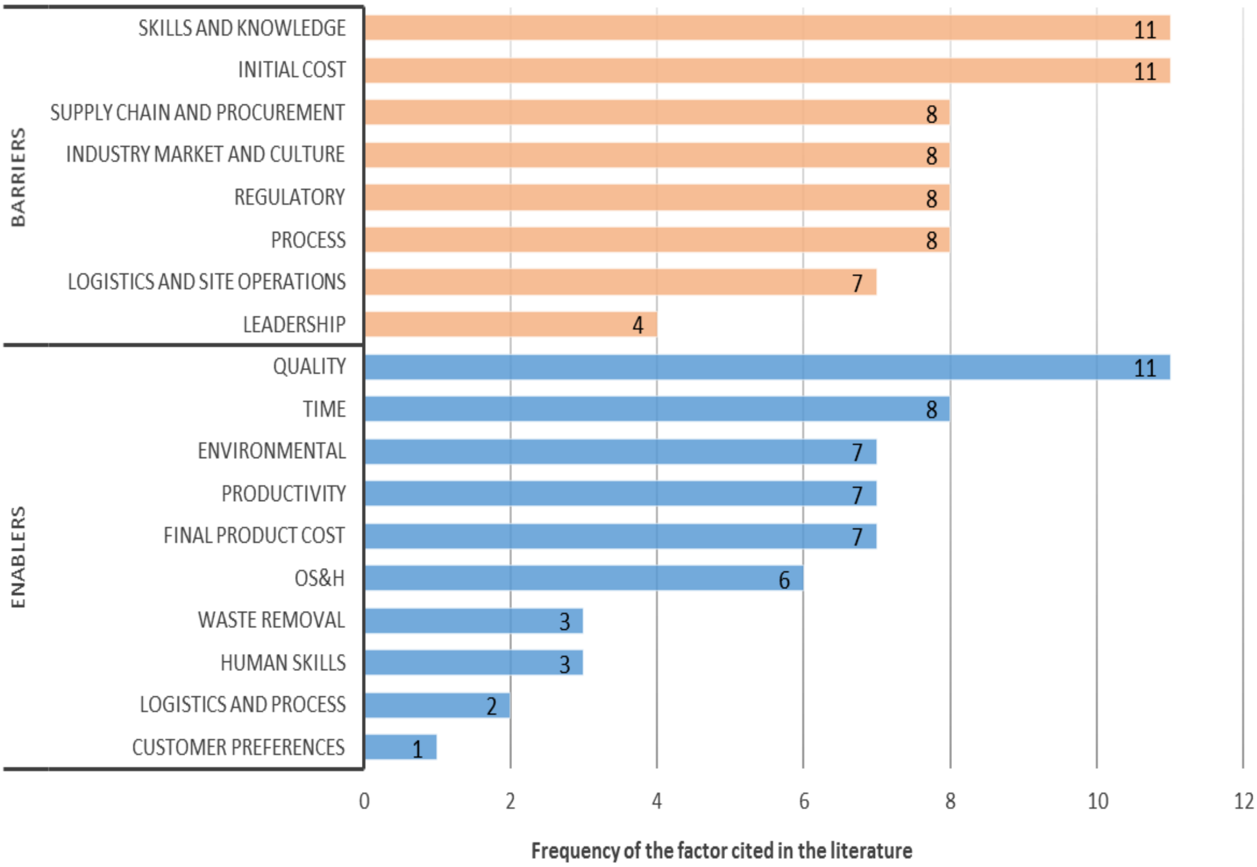


Figure 3: Summary of citation of OSM drivers and barriers in the literature

3.2.2 SWOT analysis

Prior to the development of SC value models, the outcomes of a previous SBEnrc research project [32], identifying key indicators influencing the performance of the OSM industry were investigated for relevance from a prior SWOT analysis. SWOT is a key tool for tackling complex strategic issues by decreasing the quantity of information to enhance decision making [33]. SWOT consist of factors describing the present and future trends of both internal and external industry environments, and is a convenient and promising way of conducting a situational assessment. Through combining the identification of relevant barriers and enablers to OSM (Section 3.2.1), with the outcomes of the previous SWOT analysis (Section 3.2.2 and [32]), key factors effecting the development of the OSM SC value models were presented (Figure 4). Figure 4 highlights how both: 1) the identified strengths and opportunities may lead to enablers which in turn contribute positive value creation in the OSM SC, while conversely 2) the weaknesses and threats link with the barriers thus detracting value creation in the OSM SC. These factors were used to guide the development of the modelling techniques later described (Section 4).

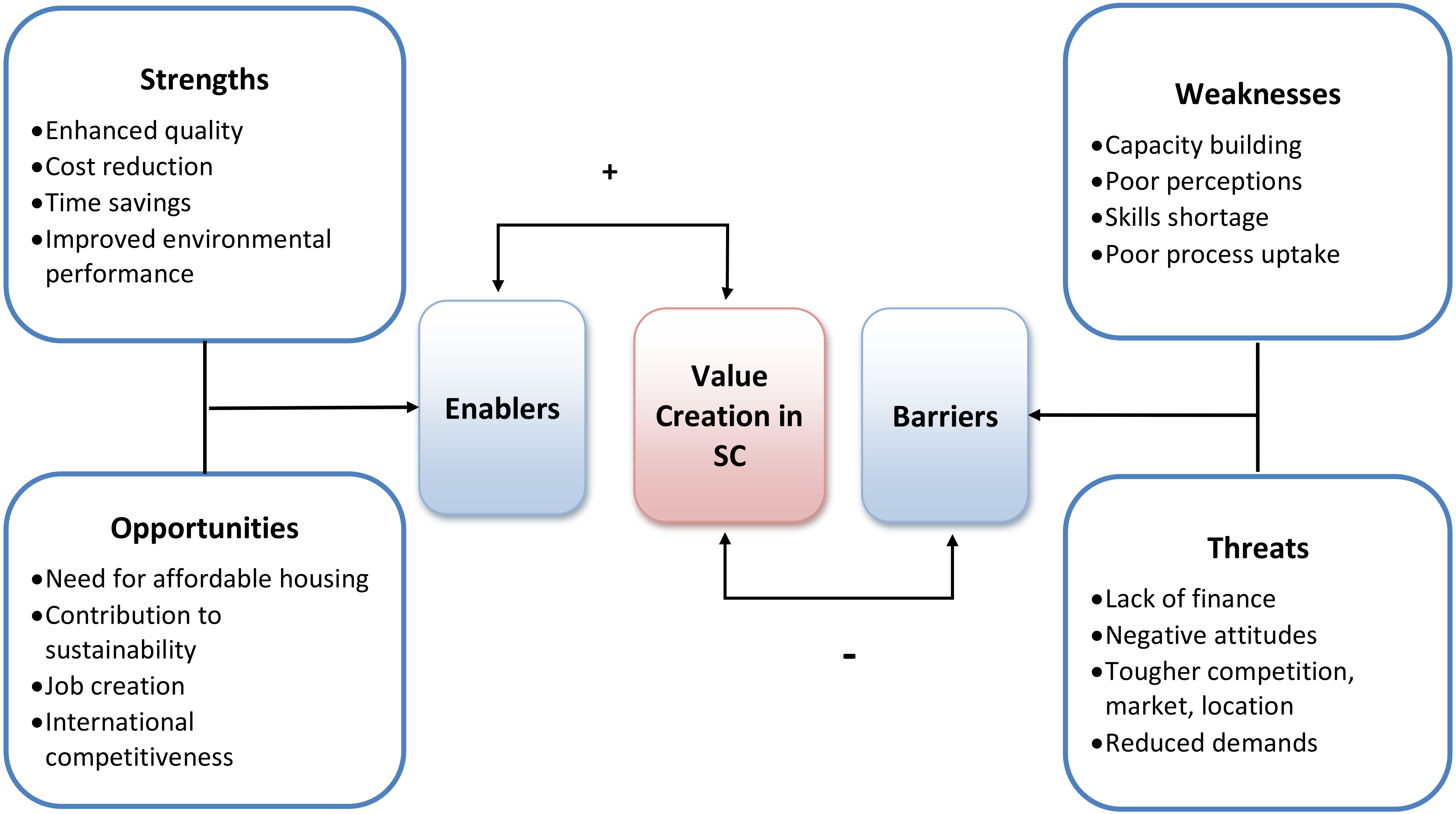


Figure 4: SWOT analysis report findings summary incorporated for model development [32]

3.3 Supply chain value in construction projects and its perception

Given the focus of this research being the identification of ***value*** in OSM and its associated SC, an understanding of its definition in the appropriate context is required. The concept of 'perceived value' emerged as the defining business issue of the 1990s, and has continued to receive extensive research interest to date. One of the most cited definitions of *value,* was that supplied by Zeithmal [34], who defined it as: *' . . . the consumer's overall assessment of the utility of a product based on perceptions of what is received and what is given'*. Broadly, the primary objective of the SC have been presented to contribute value [1]. The following was generated to assist in the conceptualisation of this process (Figure 5).

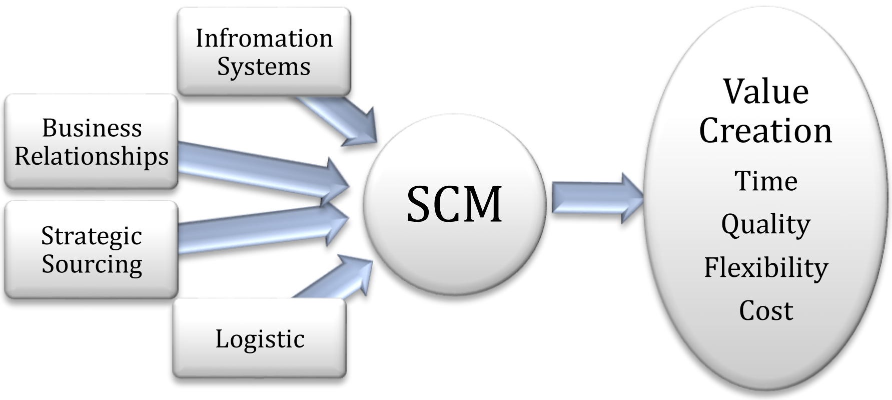


Figure 5: Conceptual process for value creation through SCM

(Created based on content available in [2])

This model was the basis through which the literature review outcomes were incorporated into the generation of value creation modelling (Section 4). The concept presented (Figure 5), details examples of the inputs required across the SCM - some examples being: information systems, business relationships, strategic sourcing and logistics. Each of these factors lead to value creation across the OSM SC through the key identified factors discussed in detail (Section 4.2.1). This concept was the basis for the generation of the standard value creation approach presented (Figure 13).

Wandahl and Bejder [35], specifically consider the values and their perceptions in regard to construction projects. The achievement of the values (needs/goals/expectations), determined by the construction client and sometimes the end-users, is always the primary objective for a construction project.

There are two variations of the described value:

Utility values: are associated with the technical and aesthetic construction and the use of the construction, e.g. brick type, top lighting, colour, usability, flexibility, etc.

Market value: is closely connected with the utility value. It describes the value of utility, quality in money and is closely related to demand.

Due to the described connection between these terms, the two values will be referred to only as *product value*.

The term value is often also connected with human/business behaviour, which in management philosophies is related to the process (process value) [35]. An overview of these concepts was presented from Wandahl and Bejder [35] (Figure 6).

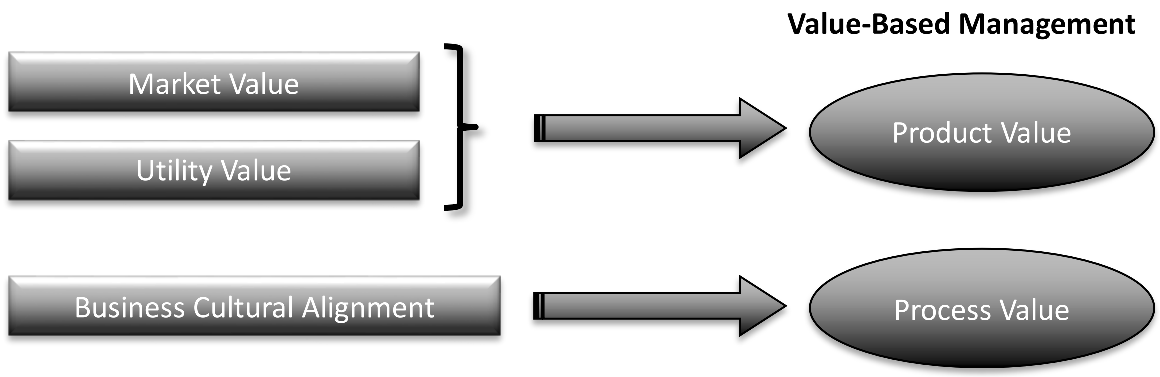
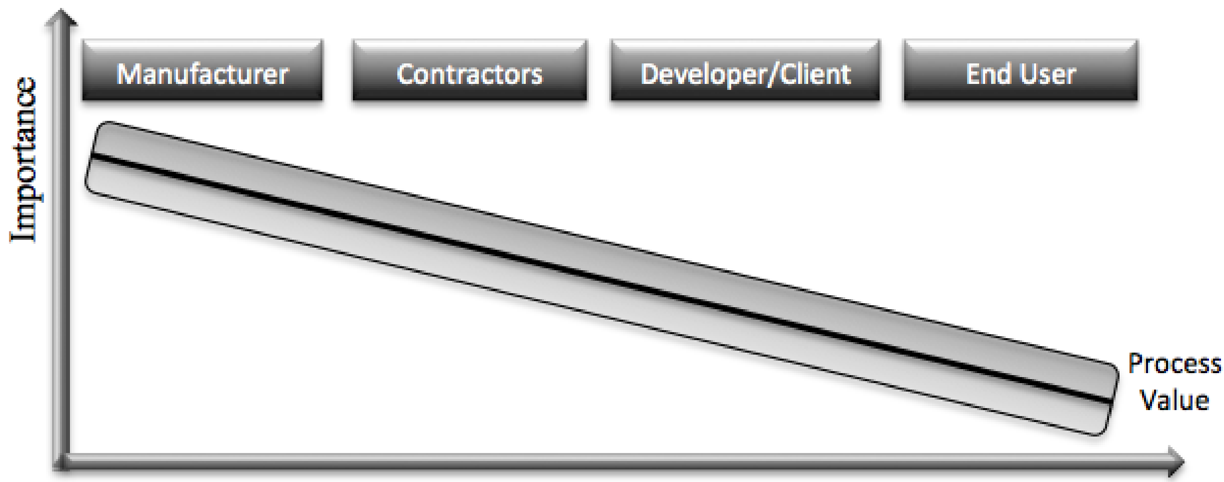


Figure 6: Value sets in value-based management (Adopted from: Wandahl and Bejder [35])

Manufacturers and contractors are more interested in process values (e.g. good cooperation, business relationships, information systems, and of course - their commercial benefit). While the clients and end-users will ultimately sell, live and/or work in the constructed buildings. Given this alternate focus, the latter two stakeholders are more interested in the final product values (e.g. quality, flexibility and economy). As process values are more subjective, the perception of them differs, with the importance of process and product values for different stakeholders being previously proposed by Wandahl and Bejder [35], which were modified and presented below for reference (Figure 7). The consideration of these factors and the importance of alternative value perceptions along different stages of the OSM SC was imperative to consider when developing the proposed value models. This approach has been incorporated for the modelling development presented. This distinction lead to the incorporation of outcomes from two alternate stakeholders throughout this research, to ensure different perspective was considered. These stakeholders were Manufacturers and Clients (Figure 2).



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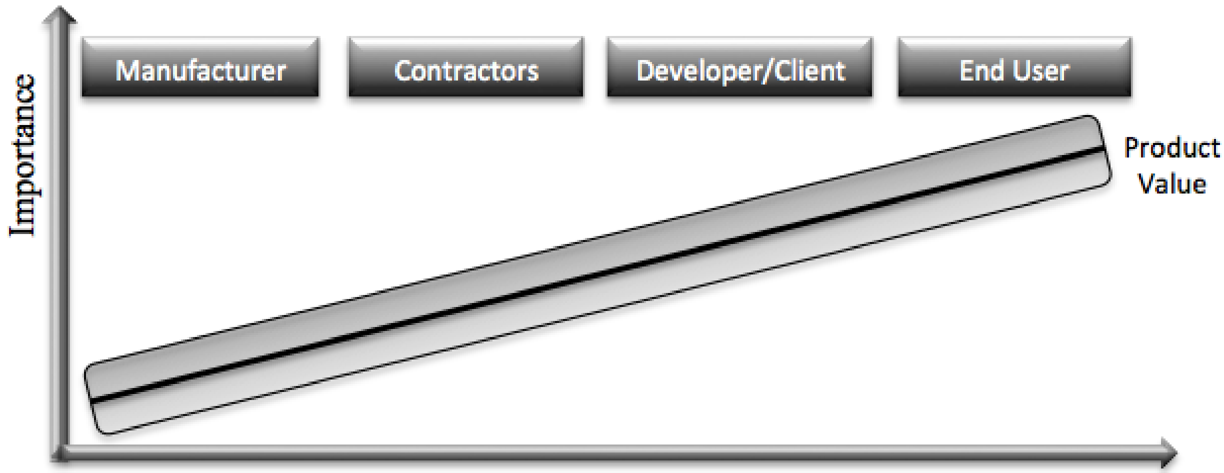

(b)

Figure 7: Difference in perception values (a) Process value and (b) Product value

(Adopted from Wandahl and Bejder [35])

Traditionally, the construction client is considered the customer of the construction process (the client is who defines the product values and finally pays for it). But the building industry as a trade, needs to do more than fulfilling buyer's needs; each company must secure their own future existence through ensuring net profits [35]. Value-based management uses the internal customer and the SC acts more like a strategic team by creating common process values, which all participants agree upon [36]. In terms of the importance placed on process value considerations, Figure 7(a) presents the manufacturers considering process value of highest importance through to the final end-user on the macro level considered. Conversely, Figure 7(b) details the alternate value based management measure highlighting the inverse for product value considerations of the identified key stakeholders. The product values are still defined to be the needs of the construction client, the final end users and in partnering projects also by other interested parties of the construction process.

Given the complexities of the SC in the OSM industry, the importance of considering different perspectives when developing models was required. Given the definition, measurement and perception of value being varied for each SC member [32, 34, 35], a systems approach was adopted to consider the OSM SC from different angles. Aspects related to the value chain proposed by Porter [37], as well as extended by Vrijhoef [38], were incorporated following these four theoretical perspectives: 1) Economic perspective, 2) Organisational perspective, 3) Production perspective and 4) Social perspective [38]. Varying aspects of these perspectives could be either complementary or conflicting. Due to the complexities present across the OSM SC, these factors are not able to be isolated and were therefore, not considered separately. Aspects relating to each of the above Incorporating, developing and understanding these properties and how they influence value was essential for improving the uptake of OSM in the building industry.

3.4 OSM SC lessons from alternate manufacturing industries

Prior to the development of modelling approaches for the determination of value in the OSM industry, experiences were investigated from other manufacturing industries. The idea of improving the performance of the construction industry through utilising experiences from other manufacturing industries is not a new approach. Comparisons can be made between numerous manufacturing sectors and the OSM industry. In research conducted by Vrijhoef [38], comparisons are investigated between the OSM industry and several other manufacturing industries incorporating SC. Vrijhoef [38] identified that OSM should move away from its ingrained time and budget focus and pursue higher levels of speed, innovation, product development and customer focus observed in other manufacturing sectors [38]. The research also included aspects related to the lessons available for the OSM industry with regard to SC management and identified a required shift to a more centrally controlled SC accepting potential negative ramifications and adopt more repetitive product solutions in favour of one-off projects [38]. On an OSM industry wide scale, the use of repetitive solutions enables the most achievable application of lean SC management concepts. This is an approach developed originally in the automotive manufacturing industry to minimise waste and is increasingly achievable with repetitive solutions [10]. The agile concept promotes flexibility and customisation and in the OSM context is in contradiction to the lean framework. It was identified that no explicit lean and agile assimilation approach for OSM in Australia exists [10], with the combination of these management concepts proposed by Purvis et al. [39], across the whole SC using a developed concept known as *"leagile"* [39]. This generally separates the SC into lean concepts in OSM based activities, with the agile concepts present at the construction site. The ability to add value to the SC and relevant OSM stakeholders through the use of these concepts and lessons from existing manufacturing industries was included during the development of systematic OSM value modelling.

3.5 Supply chain metrics

The broad goal of this research was to develop mechanisms through which obtaining the manifold benefits of improving the adoption of OSM could be achieved. In order to develop these, measurable metrics were investigated through aspects of the SC to ensure reliable, quantifiable and qualifiable outcomes would be achieved. Investigations into SC metrics identified previous research defining appropriate performance measures for SC considerations. SC performance measurement can be defined as the process of qualifying the efficiency and effectiveness of SC action [5]. A performance measure is defined as a metric used to quantify the efficiency and/or effectiveness of an action. This performance measurement provides the necessary feedback for management to make informed decisions [5]. Performance measurement provides an approach to identifying the success and potential of management strategies, and facilitating the understanding of the situation. It assists in directing management attention, revising company goals, and re-engineering business processes.

SC performance measurement is a system that provides a formal definition of SC performance models based on mutually agreed upon goals, measures, measurement methods that specify procedures, responsibilities and accountability of SC participants and the regulation of the measurement system by SC participants [5]. Shepherd and Günter [40] and Sillanpää [5] categorize SC performance measures into five SC processes: plan, source, make, deliver and return or customer satisfaction, whether they measure cost, time, quality, flexibility and innovativeness and whether they are quantitative or qualitative measures. The categories including the corresponding method of measurement are presented below with the findings summarized (Table 3). These measures can also be categorized into different management levels as required.

Table 3: The SC processes and performance measurements (adopted from Sillanpaa [5] and Shepherd and Günter [40])

Supply Stage [40]	Base * [5]	SC measurement (creating relative values)
Plan	Cost (QN)	Total cost, sales, profit, ROI, IRR,
	Time (QN)	SC response time, SC cycle time, order lead time, customer response time, development, total cash flow time
	Quality (QL)	Satisfaction with developer, fill rate, forecast accuracy, planning accuracy, order fulfilment
	Flexibility (QL)	Order flexibility, number of new products
Source	Cost (QN)	Wrong delivery percentage
	Time (QN)	Supplier lead time, purchase order cycle time
	Quality (QL)	Manufactured product quality, information accuracy, information availability
	Flexibility (QL)	Problem responsiveness
Make	Cost (QN)	Resources cost, inventory cost, inventory utilization, disposal cost, number of items produced
	Time (QN)	Process cycle time, manufacturing lead time
	Quality (QL)	Built product quality, wrong products percentage, inventory accuracy
	Flexibility (QL)	Inventory range, production flexibility, capacity flexibility
Deliver	Cost (QN)	Logistics cost, distribution cost,
	Time (QN)	Delivery lead time, frequency of delivery, order lateness
	Quality (QL)	Delivery reliability, documentation quality
	Flexibility (QL)	Delivery flexibility, delivery responsiveness
Return	Cost (QN)	Warranty processing cost
	Time (QN)	Customer query time
	Quality (QL)	Final product quality, customer complaints
	Flexibility (QL)	Product customization, service system flexibility,

* QN = Quantitative, QL = Qualitative

The determination of appropriate performance measures to incorporate for the modelling development and refinement included those presented (Table 3). In addition, discussions with relevant industry and academic representatives were conducted, who provided agreement with this approach.

4. MODELLING OUTCOMES

4.1 Industry wide approach

After detailed assessment and consideration of the literature, barriers and enablers to the OSM industry and SWOT analysis outcomes (Section 3.2.2), a generic conceptual model was developed for the SC in OSM (Figure 8). As presented, Speller (et al.) [1] noted that a SC has one major goal - being to add *'value'*. The output from the system dynamics modelling will provide predictions to guide decision makers and identify opportunities to increase value creation in the OSM SC. Despite the extensive research examined, there exists general acceptance that no specific value assessment models encompass all aspects of SC management and specifically the OSM SC. There was consideration of all aspects presented above and inclusion of key principles to the development of the conceptual value assessment model proposed (Figure 8). This model was developed as a new approach to the assessment of value in the OSM SC.

To achieve the developed model for value creation in an OSM SC, two (2) key outcomes were included. These were presented below for the conceptual model overview of the entire OSM industry based on the identified key stakeholders (Figure 2). Customer satisfaction and profit were considered the key outcomes influencing all stakeholders in an OSM SC. The determination of these key factors was based on the literature review and industry assessment (Section 3), industry consultation, academic consultation, the consideration of barriers and enablers to OSM (Table 2 and Figure 3), SWOT findings (Figure 4) and performance measures (Table 3). From a theoretical perspective, the simplification of this model based on the literature findings would incorporate the product and process values previously presented (Figure 6 and Figure 7), where *'Customer Satisfaction'* and *'Profit'* (Figure 8), equated broadly to product and process value respectively.

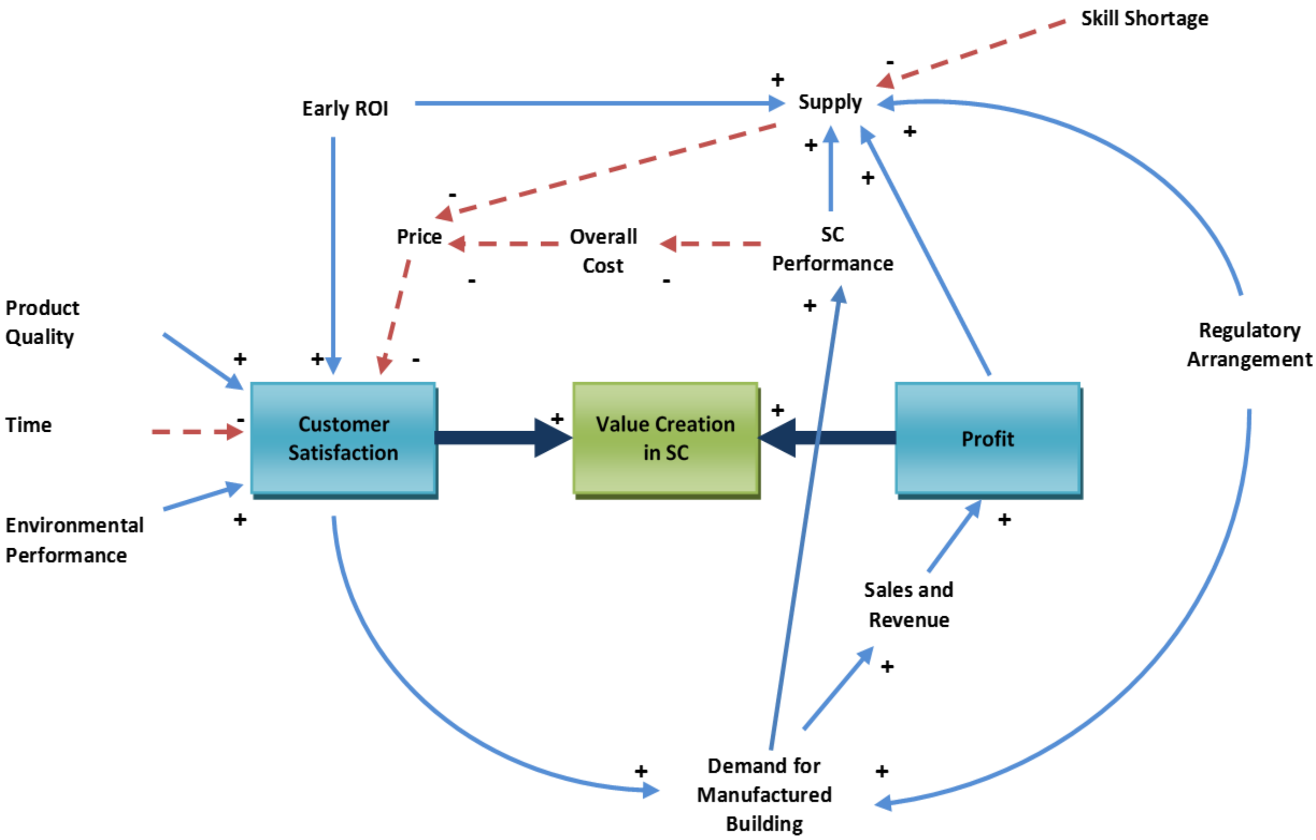

Figure 8: OSM SC value creation model overview – All industry stakeholders

4.1.1 Model verification

The industry wide modelling approach proposed (Section 4.1), was developed by the research team and required verification prior to its implementation. Verification was conducted through academic and industry consultation throughout model development. This verification included the structural analysis approach for the stakeholder specific modelling described (Section 4.2).

4.2 Stakeholder modelling

In order to refine the outcomes achievable through the System Dynamic Modelling (SDM) proposed, a detailed modelling approach for one specific industry stakeholder was developed to promote feedback and discussion. Given the importance of Manufacturers in the OSM SC process (Figure 2), they were selected for the focus of the initial stakeholder sub-model development. The intention was to enable critical review, reflection and feedback on the generation of the generic industry wide model (Figure 8) and the manufacturer stakeholder model (Figure 17), prior to the development of models for other key industry stakeholders (Figure 2). After verification of the research approach adopted for the Manufacturer sub-model development, this process was repeated for the Client sub-model development. This approach ensured alternate perspectives were sought in accordance with the outcomes of the literature assessment conducted (Section 3).

4.2.1 Structural analysis

Structural analysis was used, particularly for the analytical integration of culpable system parts and to identify causal feedback loops (both direct and indirect) between factors. Further, the Influence – Dependence mapping (

Figure 9 and Figure 10) from this method, was used for enhancing the dynamics of the resultant analysis to allow for a likely scenario. The maps represent the direct influences and dependences between the SC model factors from alternate stakeholder perspectives. The coordinates of the factors correspond to the sums of the influences and dependences, calculated based on matrix MDI-Matrix of Direct Influences. The Matrix of Direct Influences (MDI) describes the relations of direct influences between factors defining the system. To provide stakeholder relevant outcomes, as part of the detailed consultation with the participating industry representatives, a detailed matrix was provided for completion based on the ranking system presented (Table 4). The outcomes of these results were later used to validate the SDM approach

The first step of the sub-model development and verification involved a structural analysis of the conceptual model. Structural analysis is a methodology utilised to link up ideas, allowing stakeholders/ researchers to describe the system using a matrix linking all its constitutive elements. By studying these relations, the methodology enables us to underline the variables that are essential to the system's evolution. It has the advantage of stimulating reflection within the group, and leading it to think about certain aspects, which are sometimes counterintuitive. It applies to the qualitative study of extremely different systems. The system under study comes in the form of a group of interrelated elements (variables/factors). In this instance, structural analysis was to identify key factors and their influences on each other [41]. These elements' interrelations web constitutes the key of its dynamics and remains quite permanent [42].

In this phase of the research, a structural analysis model was provided initially for critical review by participating academic and industry representatives. The original structural analysis matrix included the consideration of 33 different factors and their importance to the OSM SC. After agreement and satisfaction on the research approach was obtained, a simplified matrix was provided to the manufacturing representatives for completion based on their experiences (Section 2.3). This simplified matrix included a reduction in the number of factors considered from 33 to 16 based on the input and details provided by the research participants (Figure 9). Similarly, due to the nature of a number of the factors being specific to the manufacturers perspective, further refinement resulted in the presentation of 10 relevant factors to the client stakeholders for consideration and response (Figure 10).

The outcomes of the industry participation resulted in generation of the following Influence/Dependence mapping enabling the enhancement of the dynamics of the resultant analysis to allow for various likely scenario analyses for both Manufacturers and Clients perspective respectively (

Figure 9 and Figure 10).

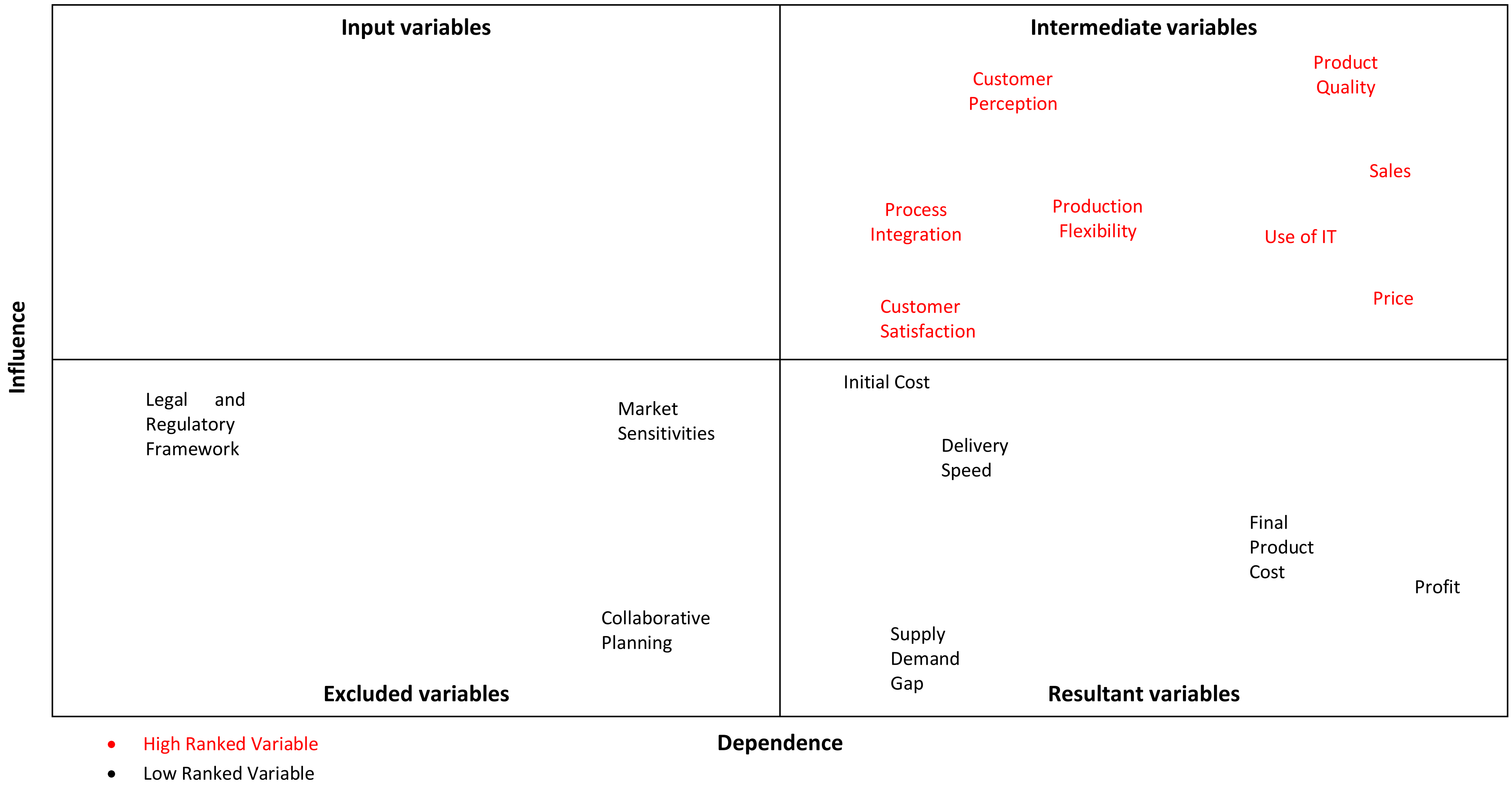

Figure 9: Direct influence and dependence map of the model variables in the Manufacturer stakeholder OSM SC

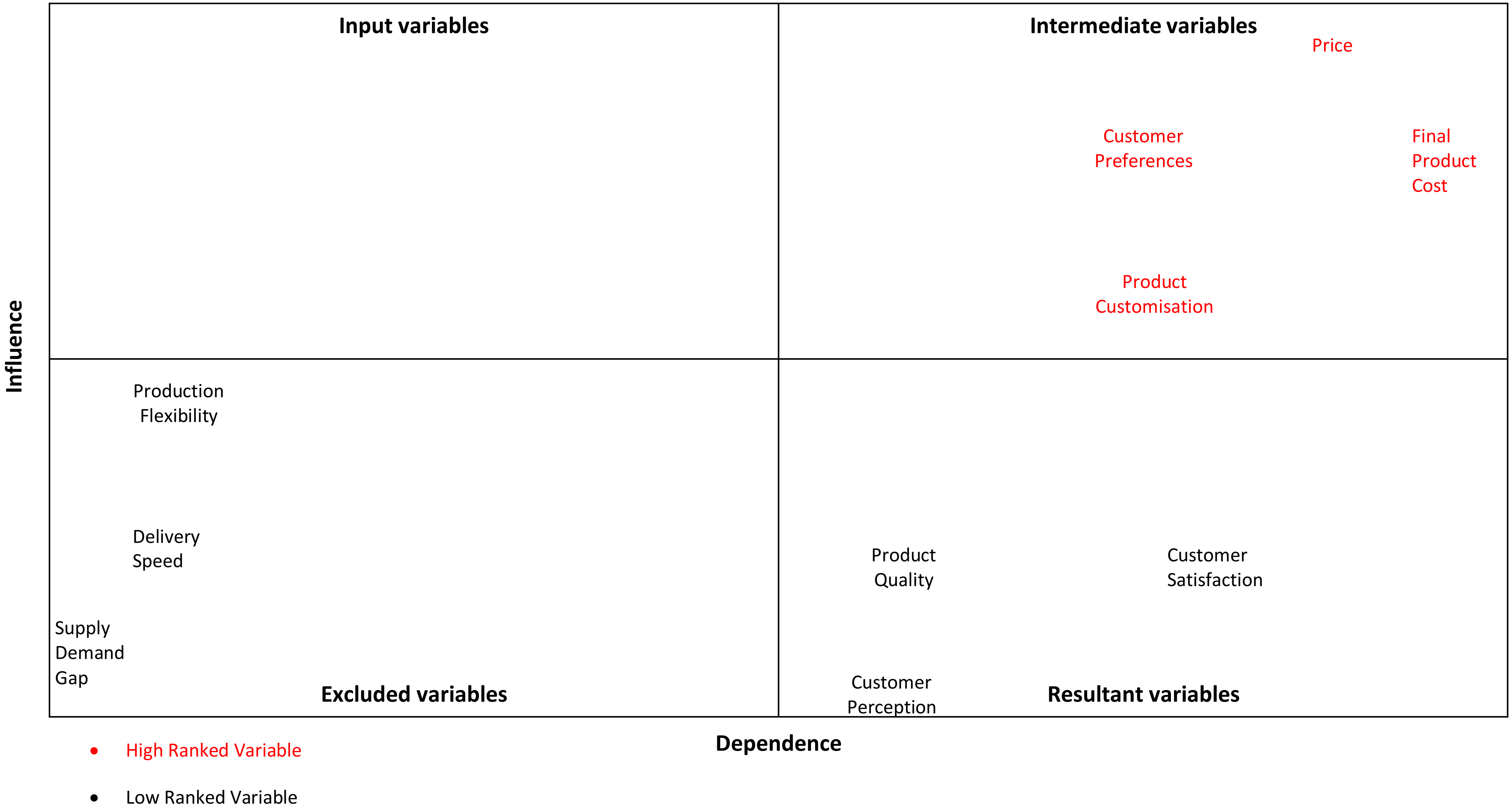

Figure 10: Direct influence and dependence map of the model variables in Client stakeholder OSM SC

The Influence/Dependence map (

Figure 9 and Figure 10) represents the direct influences and dependencies among the SC model factors. The factors are plotted on a two-dimensional matrix whose axes are defined as influence and dependence. The grid is divided in four quadrants representing four types of factors. The differences between factors lie in the value for the influence and dependence. Therefore, each factor was defined by these two criteria according to its position on the matrix.

(1) The input factors are highly influential and also independent. These factors tend to describe the system under study and condition the system's dynamic. When at all possible, these factors must be considered a priority when considering strategic plans of action. The outcomes of this research identified no such factors.

(2) At the intermediate, factors are both highly influential and highly dependent. Thus, they are, by their nature, unstable. Any action taken on these factors will cascade throughout the rest of the system, profoundly affecting the system's dynamic (High Ranked Variables – Figure 9 and Figure 10).

(3) The resultant factors are not influential but very dependent. Their behaviour therefore explains the impacts resulting from other factors, principally input and intermediate factors.

(4) Excluded factors are neither influential nor dependent. These factors are the less important ones in terms of dependency and influence. Therefore, they have little impact on the system under study. Often, these factors simply describe inertial or prevailing trends that change little over time. Other times, these factors are simply autonomous, and therefore have little impact on the system. For example, Figure 9 includes "legal and regulatory framework" in this quadrant. While it is accepted these factors may effect value creation across the OSM SC, these are beyond any ability of control or influence by any related parties.

These results show the key factors of the system but do not exclude the rest of factors that work in the system. The Influence/Dependence map communicates the "key factors" on which greater attention should be placed relative to each stakeholder specific perspective.

Significantly and in agreement with the outcomes of the background assessment conducted (Figure 5, Table 3 and Section 3), four key factors were identified as both highly important from the previously published literature and were also present in the same quadrant of the influence dependence map as a result of the conducted structural analysis from a manufacturers perspective (

Figure 9). These outcomes detail highly influential and independent factors. From the clients perspective (Figure 10), cost and quality ranked highly of these four consideration which is in accordance with the outcomes of the background assessment conducted highlighting this stakeholders focus on product quality metrics (Figure 2).

In addition, these key factors also ranked highly in the outcomes of the individual levels of influence or/dependence in value creation of the OSM SC (Figure 11 and Figure 12). Given the consistent classification of these factors through the literature assessment as well as both stakeholder assessment perspectives conducted, they were selected as the focus of the remainder of the modelling approach. The four key factors identified were: 1) Time, 2) Cost, 3) Quality and 4) Flexibility.

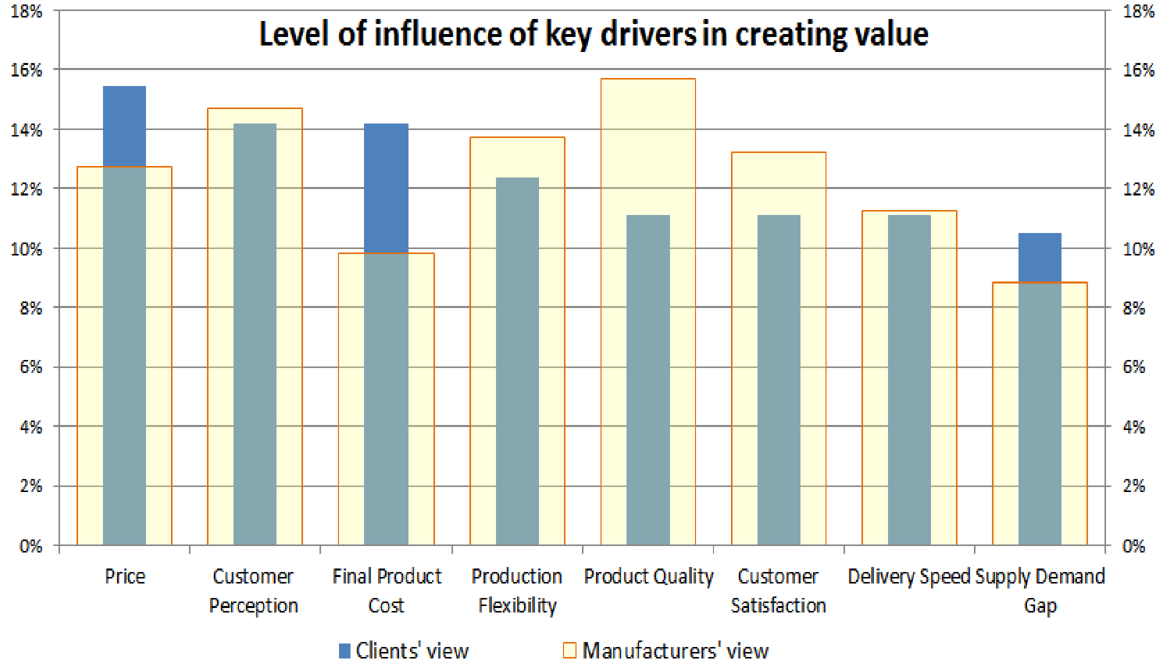

Figure 11: Level of influence of key factors across the OSM SC from alternate stakeholder perspectives

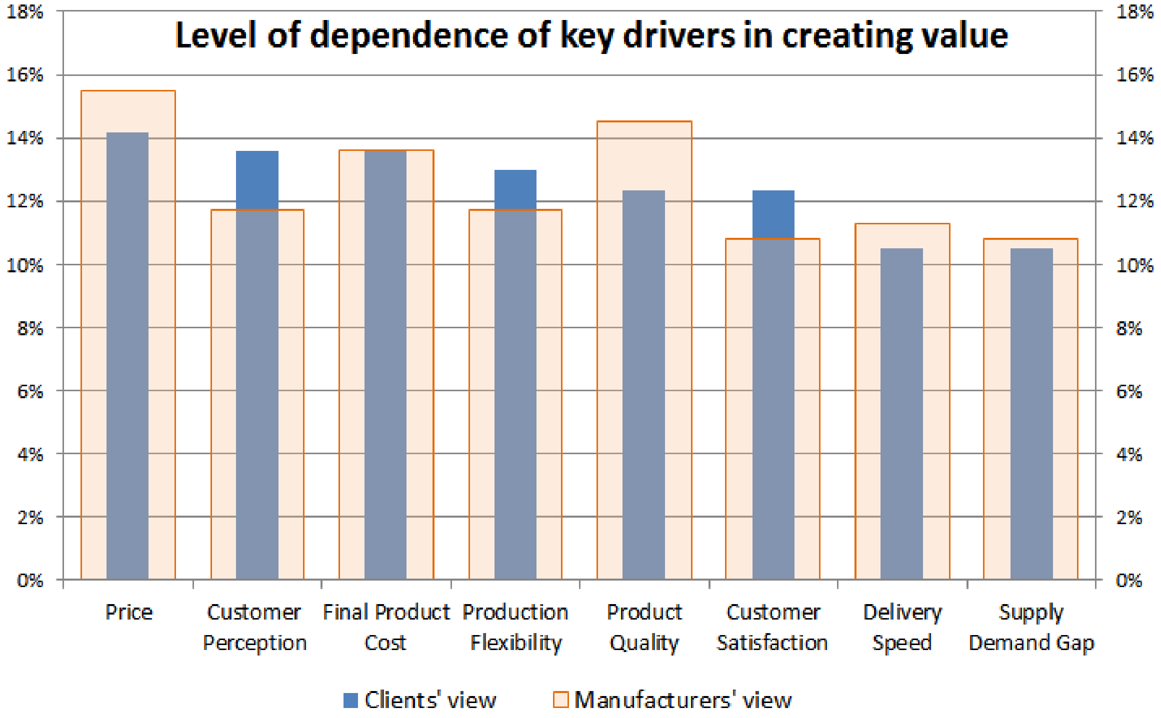

Figure 12: Level of dependence of key factors across the OSM SC from alternate stakeholder perspectives

The identification of these outcomes as a result of the structural analysis approach enabled the further simplification of the utilised structural analysis matrix to 4 variables (Figure 13). For the purposes of this research, each of these four key factors included a range of sub-factors, for example: "Cost" included a range of sub-factors which influence cost based on model development understanding including; 1) Initial Cost, 2) Investment, 3) Price, 4) Promotion, 5) Process Integration and 5) Final Product Cost. The same approach was adopted for the remaining three (3) key factors.

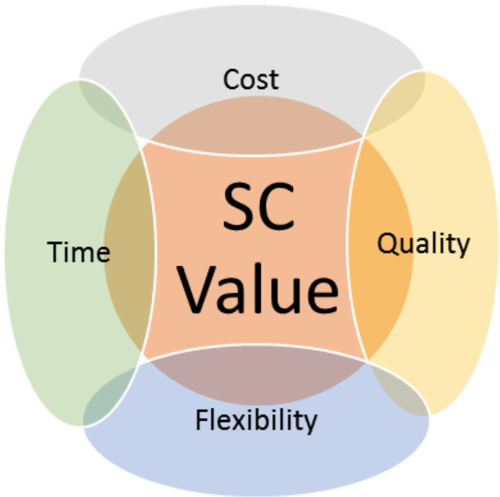

Figure 13: Supply Chain value creation process and performance measurements

4.2.2 Causal loop diagram

The second stage of the modelling involved developing a conceptual model (causal loop diagram (CLD) as a tool for mapping a set of relationships forming a 'system'. The CLD reveals the systemic relationships underlying a complex system. The factors used in a CLD are both quantitative (hard/measurable) or qualitative (soft). While 'soft' factors, such as trust, confidence, and collaboration do not generally lend themselves to direct measurement; their inclusion adds considerable power and realism to the model. The structural analysis outcomes were incorporated, particularly for the analytical integration of culpable system parts and to identify causal feedback loops (both direct and indirect) between variables.

In a CLD, the variables are linked together by arrows. An arrow (link) between two variables indicates a causal relationship, or direct influence or change. A causal link between two variables implies polarity or the direction of change between the cause and effect pairs. These polarity signs have the following meanings:

(1) A causal link from one element (e.g.: A) to another (e.g.: B) element is positive, denoted by (S). That is, either (a) A adds to B, or (b) a change in A produces a change in B in the same direction.
(2) A causal link from one element A to another element B is negative, denoted by (O). That is, either (a) A subtracts from B or (b) a change in A produces a change in B in the opposite direction.

That is, the polarity is 'S' when two variables move up or down together and polarity is 'O' when one variable moves up while the other moves down, and vice versa.

For example, in Figure 14 below, the link between Customer satisfaction and Customer perceptions indicates change (or movement) in the same direction. In contrast, an increase in Price may reduce the customer satisfaction level; hence it is a change in the opposite direction.

To enable detailed feedback and verification of the modelling approach, CLD were prepared based on the distinction between factors having a greater influence on product value or process value in accordance with the definitions previously supplied (Figure 6 and Figure 7). These CLD diagrams were verified through industry and academic participation and have been presented for reference below. Figure 14 presents the identified factors and their relationships in accordance with the perspective of product value considerations. Similarly, Figure 15 illustrates the identified factors and their relationships from the perspective of product value considerations.

Figure 16 represents integrated SC management dynamics showing how to manage the whole SC in an integrated manner to benefit collectively. The OSM manufacturer may choose to employ a *Collaborative Planning* approach by involving other SC members. As a result, this approach would influence both *Delivery Speed* and *Quality*, which has an influence on the state of *Lead Time*, *Uncertainty* and ultimately *Final Product Cost*, which would provide manufactures sufficient room to adjust their price level to improve the resulting customer satisfaction level as shown (Figure 16). Thus, incorporating this integrated dynamics into *Profitability* would provide a complete picture for understanding the whole dynamics.

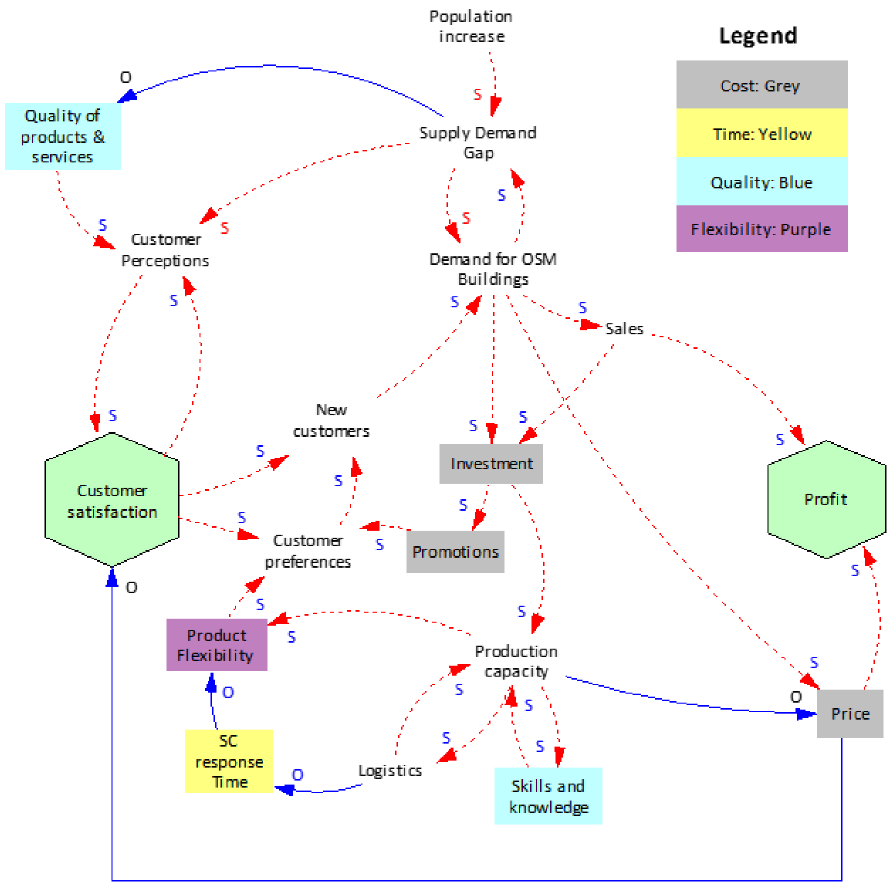

Figure 14: CLD representing the Customer Satisfaction (Product Value) dynamics

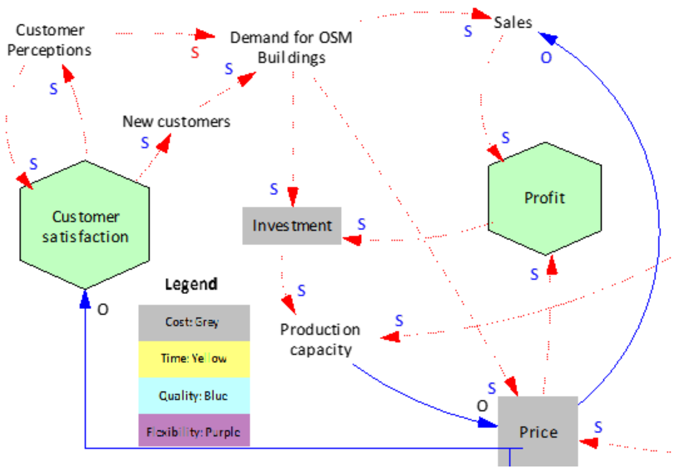

Figure 15: CLD representing the Profitability (Process Value) dynamics

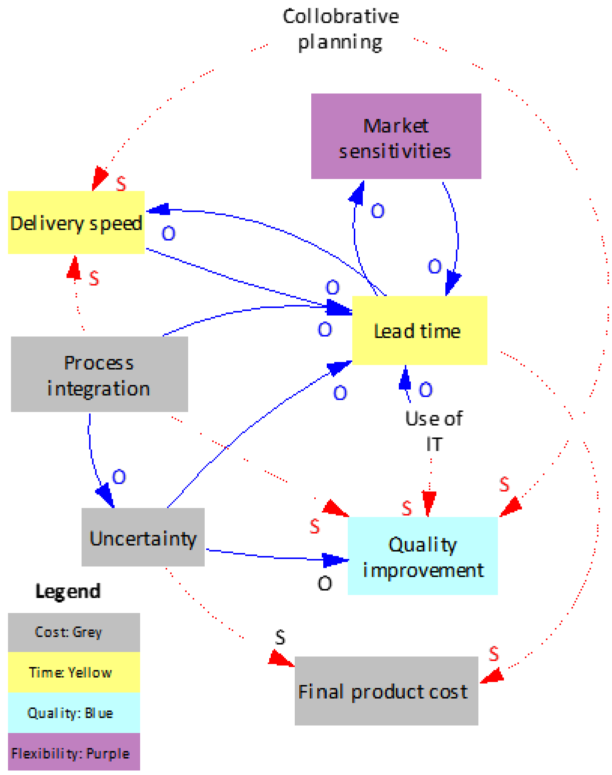

Figure 16: CLD representing integrated SCM dynamics

After the development of these detailed CLD presented (Figure 14 – Figure 16), these CLD and models were combined to provide a comprehensive CLD to consider all aspects related to value creation across the OSM SC from a manufacturers perspective (Figure 17)

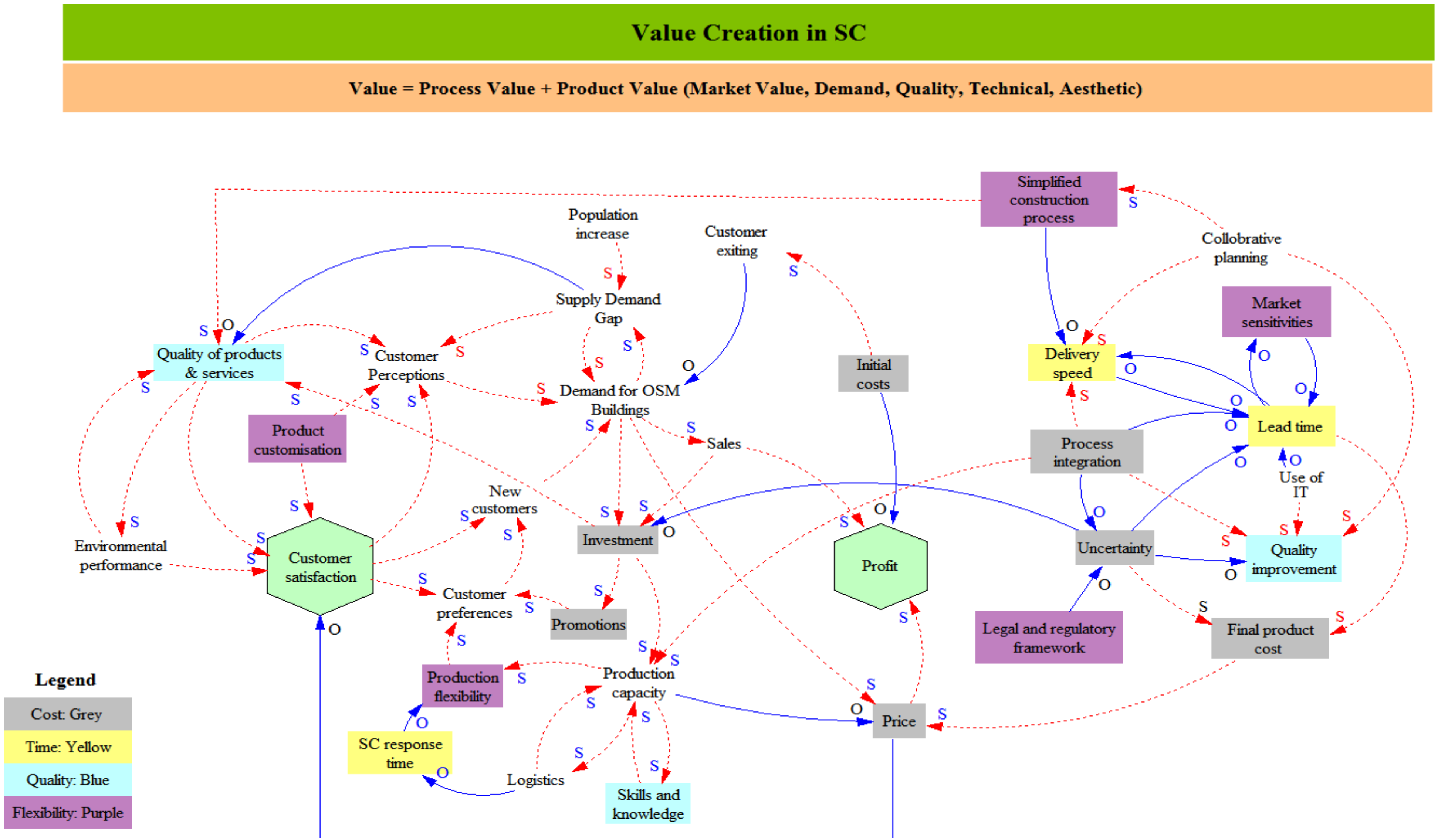

Figure 17: Value creation in the SC - A manufacturers perspective

4.2.3 Dealing with uncertainty: sensitivity and analysis

A key intention of the model development was to allow flexibility, rather than limit users to predefined scenarios. The SDM was capable of simulating a very large number of permutations, based on user choice and the multivariate Monte Carlo simulation technique. This technique is widely used for completing sensitivity analyses that are commonly applied in risk assessments under uncertainty. Therefore, rather than limiting the users to a set of predefined scenarios, a flexible scenario development approach was employed, enabling users to modify key variables to accurately assess solution alternatives by applying various scenario parameters (Table 2 and Table 3).

Based on these scenarios, over a prescribed time frame, the Customer Satisfaction level (Product Value), the Profitability (Process Value), and therefore the complete value in the OSM SC were simulated. Since sensitivity analysis, for even a modest number of parameters, will generate a large number of simulations (1220 in our case), we performed the '*Latin Grid*' search approach, which ignored the number of simulations specified. However, this method has enabled an adequate number of simulations to examine every possible combination of parameters. Among these scenarios, three (Best, Moderate, and Worst) were selected to compare with the scenario (OSM Industry scenario) envisaged by the industry representatives as shown in (Table 4). This was the adopted approach provided for the completion of the supplied structural analysis matrix detailed (Section 2.3).

Table 4: Key variable parameters for Monte Carlo simulation scenarios

Scenarios	**Sensitivity of demand on Customer Satisfaction** 0-100%	**Flexibility level** 1=Low 2=Moderate 3=High	**Quality level** 1=Low 2=Moderate 3=High	**Price level** 1=Low 2=Moderate 3=High
Best	70%	3	3	3
Moderate	60%	1	1	1
Worst	100%	1	1	1
OSM Industry	100%	2	3	3

4.3 Scenario analysis: SDM outcomes

The SDM, was conducted using the Vensim® DSS [43]. This SDM was built by identifying key variables, estimating assumed relationships between these variables and finally parameterising these relationships. In building the SD model, a participatory modelling approach was employed. Participatory model development can focus on portraying system structure through stakeholder consultation, while model simulations reveal system behaviour, which is less intuitive and often the source of confusion [44-46]. The SDM utilised in this research was developed from the results of the structural analysis (Section 2.3). This was conducted to be able to present scenario-based outcomes to communicate what influence certain levels of changes in the relevant variables had on overall OSM SC value.

By improving customer satisfaction and consequently increasing value in the OSM SC process, the probability of a new customer using OSM product and services (increasing demand and sales) depended on the quality of the products enjoyed by the existing users, price, product customisation (flexibility) and delivery speed (time).

To understand the effects of the dynamics of *Customer Satisfaction* and *Profitability*, a SDM was developed (Figure 18). Using this model, two sensitivity analyses were run in tandem to determine how different qualifiers (Best, Moderate and Worst) of these four key variables (*Quality, Cost, Flexibility*, and *Time*) will impact *Customer Satisfaction* and *Profitability* and consequently the value creation across the OSM SC under a given set of assumptions. Sensitivity analysis is very useful when attempting to determine the impact the actual outcome of a particular variable will have if it differs from what was previously assumed. This also helps to increase our understanding of the causal relationships between factors in a SC system. The sensitivity analysis was also used to identify and rank the importance of these key parameters.

Therefore, the cause and effect relationships and feedbacks among these factors across the OSM SC were clearly defined in order to identify which feedback was dominant. The outcomes assist the OSM SC members to make informed decision when attempting to create value effectively. To achieve this, the entire SC value creation process was mapped (Figure 17). The mapped process (Figure 17) was then deconstructed back into two sub-models (Figure 14 and Figure 15) to explore the underlying dynamic mechanism influencing OSM SC value creation. These sub-models were explained in detail below, being: Customer Satisfaction (Section 4.3.1) and Profit (Section 4.3.2).

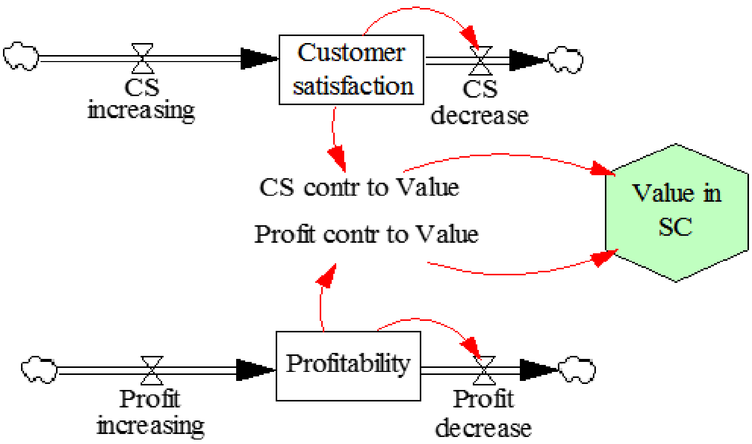

Figure 18: SDM for simulating the effects of *Customer Satisfaction* and *Profitability* on value creation across the OSM SC.

4.3.1 Customer satisfaction (Product Value) sub-model

The concept of customer satisfaction is topical across all industries. Therefore, companies often include customer satisfaction as an important strategic objective within their long term planning in order to obtain an advantage and financial gain. With this sub-model the links between customer satisfaction and value creation were explored by examining the impact of key factors such as Quality, Flexibility, Time and Cost. Usually, linkages between customer satisfaction and profitability in creating value in a SC are consider linear, that is:

Customer Satisfaction → Customer Retention → Increased Sales → Profitability → Value

However, this approach ignores interactions (interdependencies) and feedback influences among factors. In reality, changes in customer satisfaction may/would affect (either negatively or positively) other organisational strategies, which influence financial decisions (eg investment), and ultimately customer satisfaction (Figure 17). The influence diagram (Figure 18) emphasises the complexity of customer satisfaction and profitability relationships in creating value through OSM SC feedback loops.

The customer satisfaction (Product Value) model was a function of many factors - the most important being previously identified as: *Quality*, *Cost*, *Flexibility*, and *Time*. The relationships were previously illustrated in the CLD (Section 4.2.2). To provide reference for the logic applied, an example scenario analysis would include improvement in the *Quality of Product & Services* resulting in an increase in the *Customers' Perception.* As result, the *Customer Satisfaction* level would increase. This, in return, would attract more *New Customers* by positively influencing *Customer Preferences*. Increased customers would raise *Demand for OSM Buildings.* This would consequently affect the *Supply Demand Gap*. Additionally, the increase in the number of customers would likely affect the quality level negatively as manufacturers try to satisfy the increased demand by stretching their production capacity. The widening gap (between actual and expected quality) would lead to a decrease in *Customer Satisfaction* level. This, as a result of dissatisfied customers, would leads to a decline in the total number of customers. Consequently, manufacturers would experience more financial loss and/or stress. To break this cycle and close the gap, the manufacturers would adopt/develop new strategies, such as marketing campaigns, investment to improve production capacity and reduce delivery time. Likewise, the investment to improve the quality would put pressure on the cost causing an increase in the price level of the products. Higher product prices would then raise expectations, which in turn widen the gap again. The quantitative effect depends on price elasticity of demand as explained in the Profitability (Process value) sub-model below (Section 4.3.2).

The outcomes of the sensitivity analysis conducted for the customer satisfaction perspective across the OSM SC highlighted the significant consideration of this provided from the manufacturers perspective. Figure 19 presents the outcomes of the present consideration of *Customer Satisfaction* (red line), being well in excess of the average from the various scenario analysis conducted (black line). The current perception is approaching the 'best' case scenario (upper blue boundary), and as such was not considered a key perception requiring further detailed analysis.

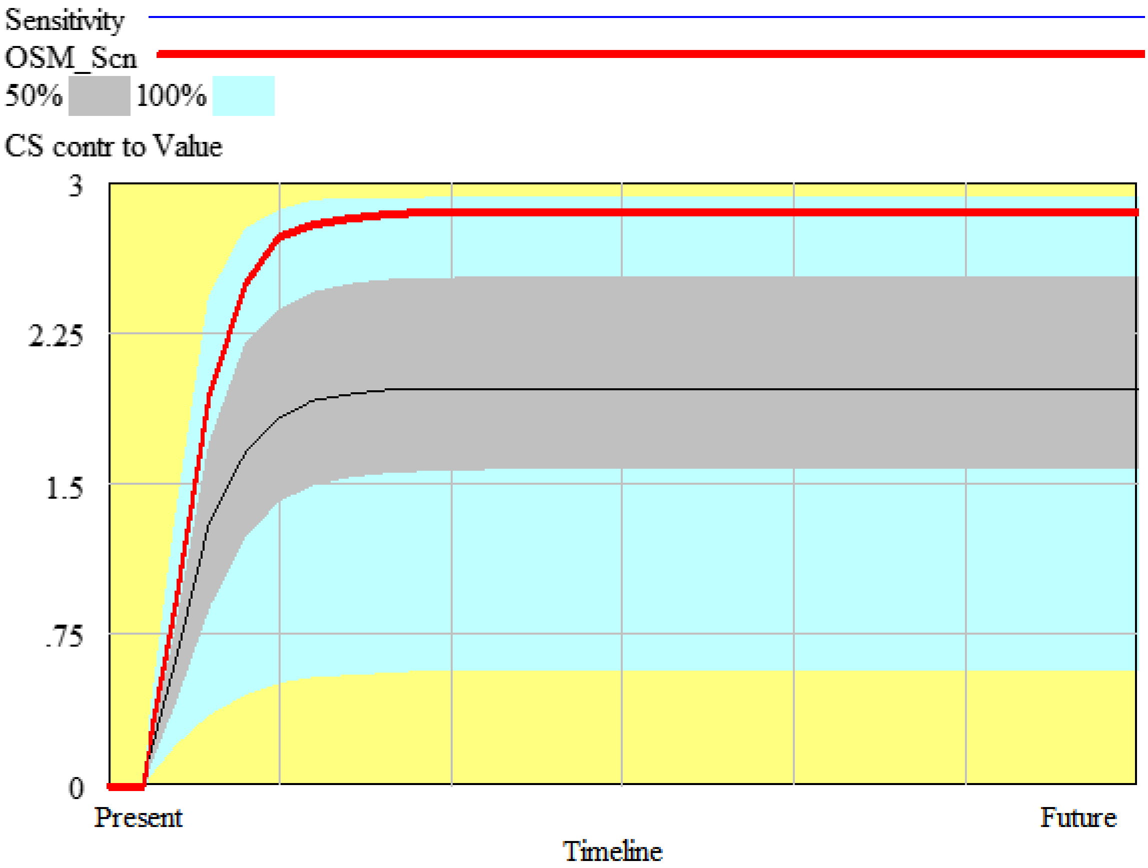

Figure 19: Scenario analysis outcomes for Customer Satisfaction of SDM value creation

4.3.2 Profitability (Process Value) sub-model

The price has at least two effects on profit. It determines how much profit is generated per sale and the quantity of sales [47]. That is, higher prices reduce sales. In this case, the price elasticity of demand determines the level of demand fluctuation. If demand was insensitive to price, then price raises profit levels more than the net effect of an Increase in price would have on increased profits. On the contrary, if customers are price-sensitive, the increase in profit per sale would reduce sales, so the eventual effect of a price increase would be a fall in profit. However, these changes would be realised over a period of time. Therefore, a time lag would exist between a change in price and a change in sales, whereas there would be very little time lag in the effect of price on profit.

To reduce the impact of cost on price increase, and resulting customer dissatisfaction, the manufacturers may seek/investigate new strategies, such as implementing an integrated SC management by involving other SC members as illustrated (Figure 16).

Figure 20 illustrates the outcomes when the four key factors were simulated under all possible scenarios by varying the values of each factor. The initial simulation was run under the assumption made by OSM manufactures that Impact of *Quality* and *Price* are “high” on changing customer perceptions, while *Flexibility* and *Time* were “moderate”. If an OSM manufacturer achieved high level product quality and offer a competitive price, they would have a greater capability for improving Customer Satisfaction, and therefore, Profitability. The red line (Figure 20), represents the contribution level of Profitability (Process Value) over time if their assumptions were implemented. Although their view generates a result better than the average (black line), it doesn’t provide the ‘best’ outcomes (upper blue bound).

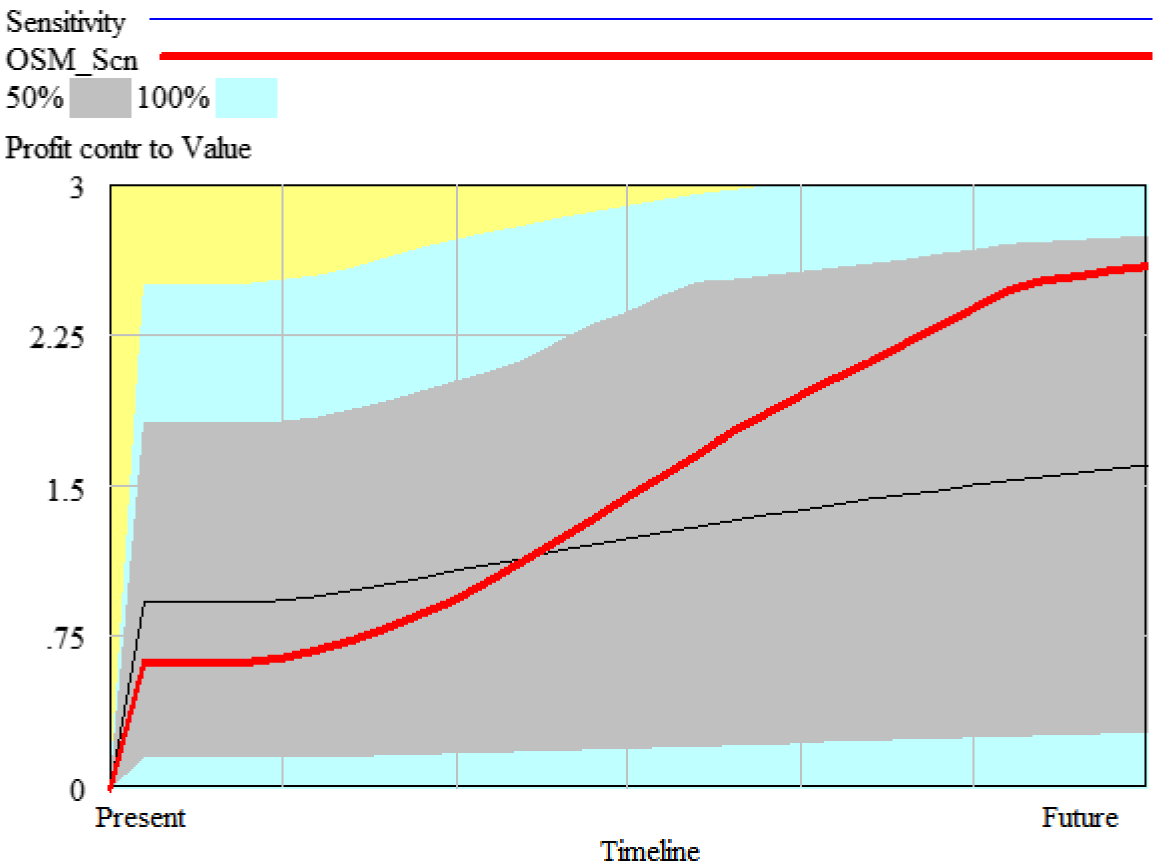

Figure 20: Scenario analysis outcomes for profitability of SDM value creation

4.3.3 Scenario analysis of the primary key factors

After completion of the research conducted, the following detailed scenario analysis were conducted to present key findings with respect to the factors consider from the outcomes of this research to be the most important. These analyses were conducted by varying the outcomes of both price and quality. Figure 21 presents the outcomes from 1) overall OSM SC value creation, 2) Product Value and 3) Process Value perspectives by altering the price accordingly. The blue line presented below details the findings from the current OSM SC structural analysis results, while the red and green lines highlight the changes achievable through a corresponding change in price according to Figure 21.

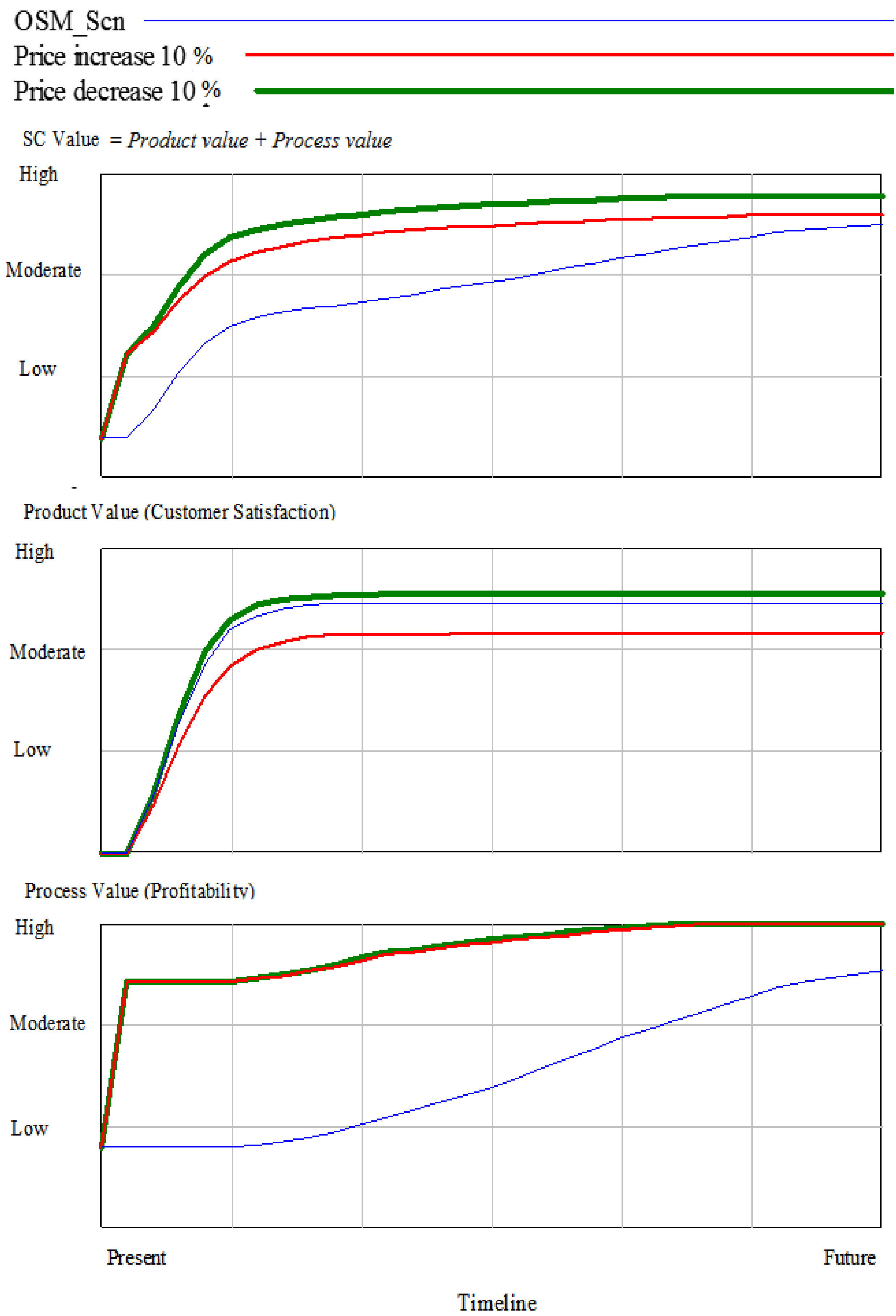

Figure 21: Value creation based on price variations across the OSM SC

Similarly, the second detailed scenario analysis was conducted to present key findings with respect to variations in product quality outputs. The analysis highlighted that by varying the outcomes of product quality (Figure 22), value creation outcomes were reduced (green and red line), when compared to the current perceptions of product quality as a result of the structural analysis conducted during this research (blue line).

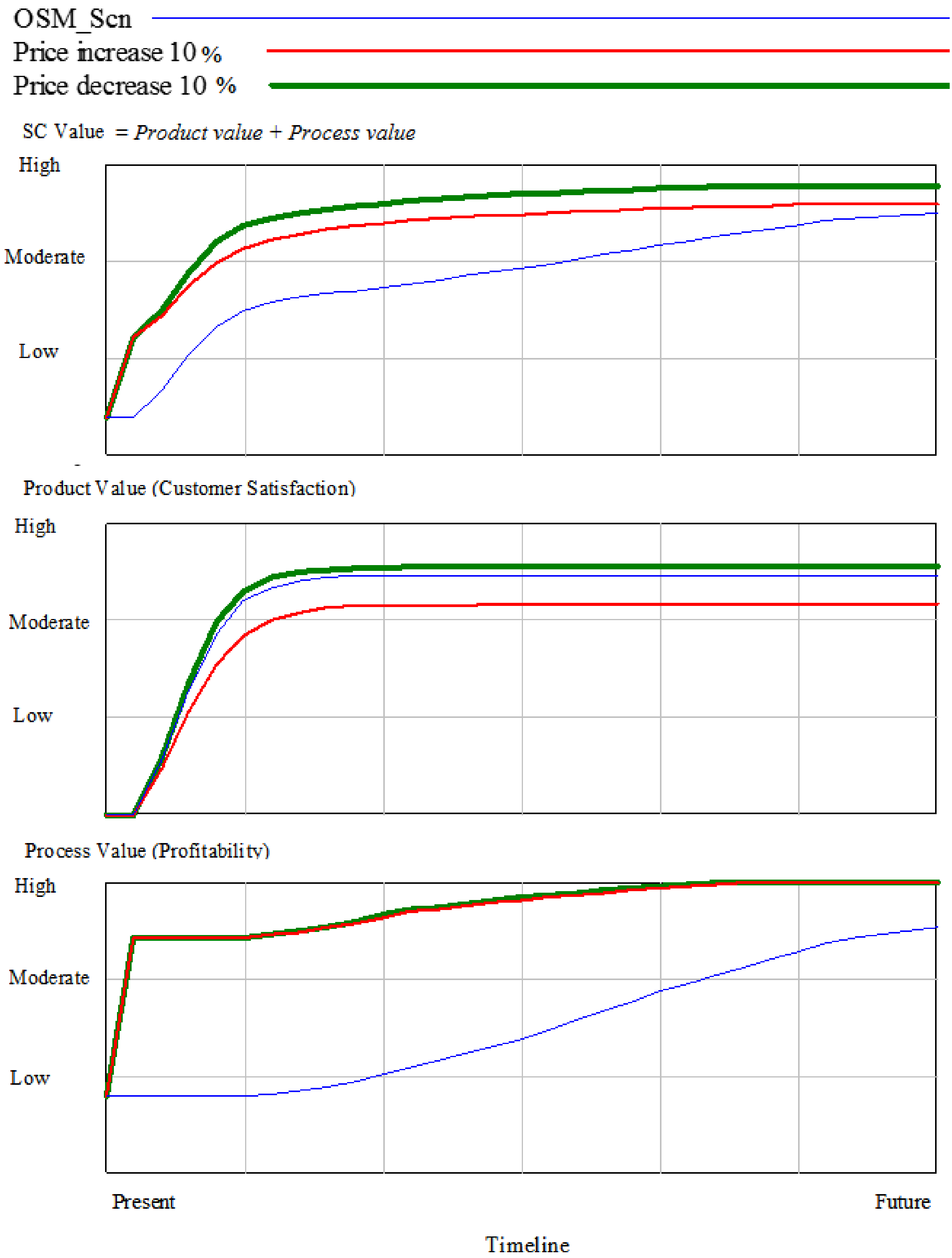

Figure 22: Value creation based on quality variations across the OSM SC

5. RESILIENCE

In addition to modelling the creation of value across the OSM SC, this research also investigated the ability of the industry to increase its resilience to future risks associated with likely trends, events and potential crisis. In order to appropriately consider resilience across the OSM SC a suitable definition was required. Previously published literature does not present a widely accepted definition with the interdisciplinary nature of the OSM SC and SCM.

Hohenstein et al. [48] stated that a suitable multi-faceted, multi-disciplinary definition does not exist. The earliest attempts to define resilience across a SC was presented by Rice and Caniato [49] who regarded it as the ability to react to an unexpected disruption, such as one caused by a terrorist attack or a natural disaster, and restore normal operations. Others have included in the definition the ability of a system to withstand external shocks and quickly restore or even exceed the earlier state in the aftermath of a disturbance [50, 51]. The first multi-disciplinary attempt was presented by Ponomarov and Holcomb [52], whose definition states the adaptive capability of the SC to prepare for unexpected events, respond to disruptions and recover form them by maintaining continuity of operations at the desired level of connectedness and control over structure and function. This approach was extended to include a proactive and reactive dimension proposed by Wieland and Wallenburg [53], who classified them as agility and robustness. Agility incorporates the idea of flexibility and responsiveness with it being principally the capability of the OSM SC to quickly and efficiently respond to change [50]. Robustness in contrast is the proactive aspect of resilience [54] and is defined as the ability of a SC to resist change without adapting it initial stable configuration [55]. The robustness of an OSM SC therefore could be considered its ability to both 1) resist external disruptions and 2) control a variety of situations without exhibiting adverse effects.

Significantly there exists a widely accepted research gap in understanding the most important elements of SC resilience and the relationships between them [53]. The literature has been identified by others, to lack theoretical justification for the established frameworks of resilient supply chains [52]. The determination of a conceptual framework through which to consider resilience in this research was through the incorporation of the principals presented being – agility and robustness of factors. Utilising the determination of the factors presented in

Figure 9 and ranked in Figure 11 above from the outcomes of the structural analysis matrix, the following conceptual approach was developed and incorporated to enable the consideration of resilience across the OSM SC (Figure 23).

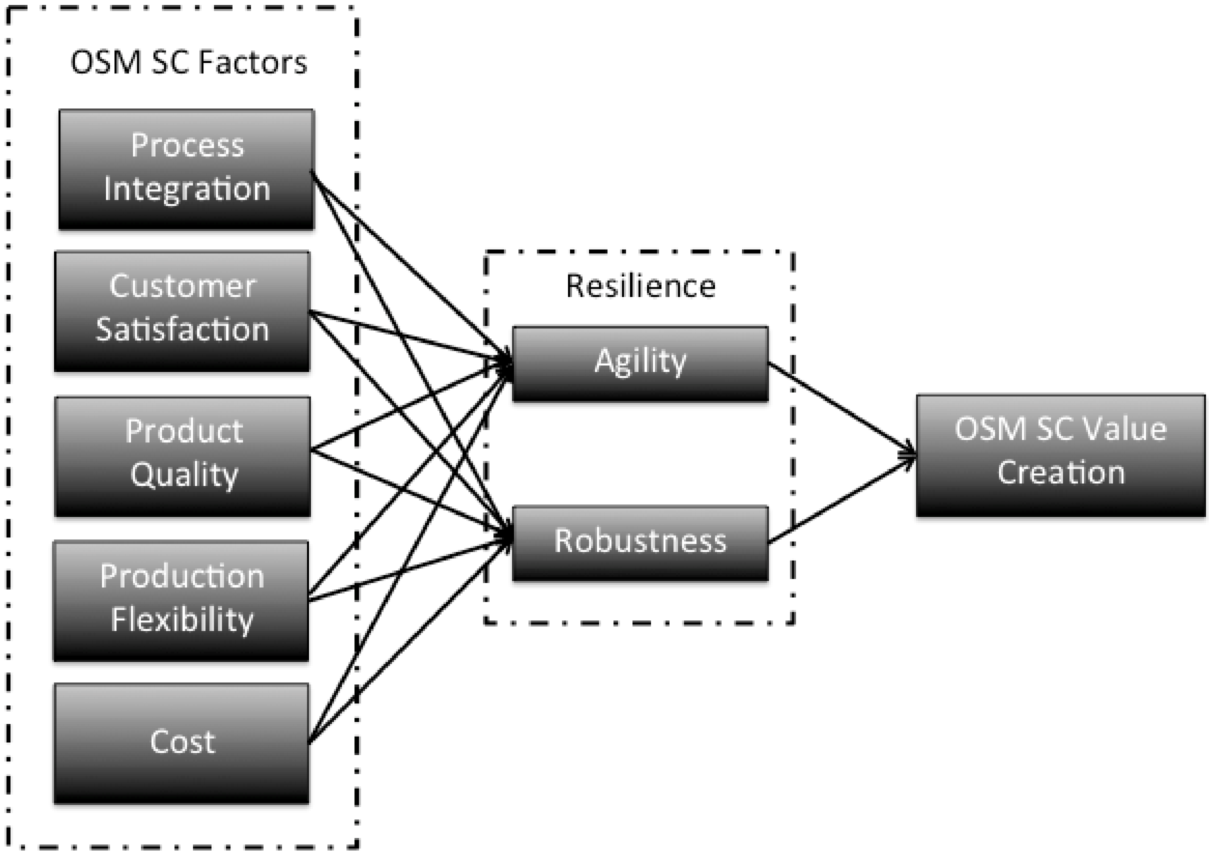

Figure 23: Conceptual approach adopted for the determination of OSM SC resilience

This conceptual approach was utilised to establish the resilience across the OSM SC using the perceptions of agility and robustness. For example, using the outcomes presented in Figure 23, Customer Satisfaction was integrated into the generation of resilience considerations. Using the outcomes detailed from the influence and dependence mapping, customer satisfaction was identified as an intermediate variable being both influential and dependant (Figure 9). By linking these factors with the barriers and enablers identified (Section 3.2.1), the ability of these factors to provide a degree of agility and robustness contributing to resilience was assessed. By overcoming several of the identified barriers (Figure 3) including: skills and knowledge shortage, initial cost, regulatory issues and market culture – the resilience of the OSM SC industry through increased customer satisfaction would increase. Similarly, by further improving the enablers (Figure 3) – resilience across the OSM SC through increased customer satisfaction would also occur. For example, by further improving quality, cost, customer preferences and time constraints – the resilience of the OSM SC would increase.

This approach was conducted for the factors presented across this research which were considered important to value creation in the OSM SC with the outcomes detailing improved resilience is available through its consideration in the OSM Factors presented (Figure 23).

6. RECOMMENDATIONS

Following the completion of this research, the following key recommendations were identified, in order for members of the OSM building industry to create value and resilience across the SC. These recommendations were identified as a result of both the participation of industry and academic representatives as well as the detailed modelling conducted.

The recommendations provided are as follows:

- Provide resources and incentives for the industry to overcome the barriers that exist to increase the market uptake of OSM buildings;
- Provide resources enabling the industry to highlight the benefits that exist to increase the market uptake of OSM buildings;
- A collaborative industry wide effort to progress the industry. Ad-hoc adoption of results in costly and repetitive R&D conducted internally in companies unnecessarily depletes available resources;
- Currently, innovation problems plague the building sector – OSM is a potential solution to this with appropriate investment;
- OSM potential improves the significant problems associated with delivering affordable housing. If the *value* is appropriately understood and quantifiable, then the ultimate reward would be the delivery of more affordable housing;
- Market stability is missing across the OSM industry – OSM should become more mainstream. The outcomes would be a resultant demand continuation through time. This research may help with catalysing market stability due highlighting value creation.

7. CONCLUSION

This report detailed an approach to understand, model and improve the creation of value in the OSM SC building industry. The identification of key factors contributing to this value creation was undertaken through a detailed background assessment of the OSM SC. This assessment included the outcomes of earlier SBEnrc research to incorporate SWOT analysis outcomes into model development as well as the barriers and enablers of the OSM SC conducted during this research. Various modelling stages facilitated continued feedback and review by relevant industry and academic representatives to ensure relevant outcomes. CLD diagrams for both the industry wide modelling approach, as well as stakeholder specific modelling was developed to present the influence different factors have on the creation of value across the OSM SC. These CLD provide a roadmap for reference and verification of the logic applied to their generation. The quantification and verification of the developed models was performed through industry participation to assess the influence and dependence of key factors based on the creation of value across the OSM SC. This research approach resulted in the ultimate scenario analysis conducted to enable prediction of the outcomes of changes to key factors across the OSM SC.

This research identified the creation of value across the OSM SC to include four (4) key factors: 1) Time, 2) Cost, 3) Quality and 4) Flexibility. Significantly, this was in agreement with the previously published literature. Each of these four key factors was made up of sub-factors that could be categorised under their contributions to each respectively.

Interestingly, and in partial disagreement with the literature, the outcomes of the modelling conducted indicated a detailed focus of the relevant industry stakeholders on aspects not expected to be their principal focus. For example, the manufacturers considered product value to be far more important than process value for value creation across the OSM SC. The consideration of these aspects related to higher product value, while not theoretically expected, shows the motivation of the stakeholders being to principally consider the perspective of the other OSM SC members.

Through the adoption of strategies aimed at improving outcomes related to the key factors presented by OSM SC members, the outcomes would result in value creation and increased resilience across the OSM SC. Following the completion of this research it was clear that limited effort has been directed towards understanding value and resilience across the OSM SC. This research conducted a research approach that conceptualised, measured and finally produced a model enabling both 1) the quantification of value and 2) the conceptualisation of resilience across the OSM SC.

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