MODELLING AN END-TO-END SUPPLY CHAIN SYSTEM USING SIMULATION

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Copyright Statement

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Abstract

Supply chains (SCs) are an important part of today's world. Many businesses operate in the global marketplace where individual companies are no longer treated as separate entities, but as a vital part of an end-to-end supply chain (E2E-SC) system. Key challenges and issues in managing E2E-SCs are duly attributed to their extended, complex and systemic nature. In the era of uncertainty, risks and market volatility, decision makers are searching for modelling techniques to be able to understand, to control, design or evaluate their E2E-SC. This research aims to support academics and decision makers by defining a generic simulation modelling approach that can be used for any E2E-SC.

This study considers the challenges and issues associated with modelling complex E2E-SC systems using simulation and underlines the key requirements for modelling an E2E-SC. The systematic literature review approach is applied to provide a twofold theoretical contribution [a] an insightful review of various contributions to knowledge surrounding simulation methods within the literature on end-to-end supply chains and [b] to propose a conceptual framework that suggests generic elements required for modelling such systems using simulation.

The research adopts a simulation methodology and develops a generic guide to an E2E-SC simulation model creation process. It is a mindful inquiry into the implications relative to a simulation model development process in presence of generic elements from the proposed conceptual framework. The conceptual framework is validated with industry experts and insightful remarks are drawn.

In conclusion, it is acknowledged that modelling an E2E-SC system using simulation is a challenge, and this area is not fully exploited by the business. A guide to an E2E-SC simulation model development is a theoretical and practical contribution of this research, immensely sought by businesses, which are continuously tackling day to day issues and challenges, hence often lacking resources and time to focus on modelling. The conceptual framework captures generic elements of the E2E-SC system; however, it also highlights multiple challenges around simulation model development process such as technical constraints and almost impracticability of a true reflection of an E2E-SC system simulation model.

The significant contribution of this thesis is the evaluation of the proposed generic guide to E2E-SC simulate model development, which provides the architecture for better strategic supply and demand balancing as new products, price fluctuations, and options for physical network changes can be dynamically incorporated into the model. The research provides an insightful journey through key challenges and issues when modelling E2E-SC systems and contributes with key recommendations for mindful inquiries into E2E-SC simulation models.

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Dedications

I would like to dedicate this thesis to my beloved Parents who taught me how to become hardworking and persistent.

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List of Acronyms

ABS	Agent-based simulation
AI	Artificial Intelligence
AIS	Artificial Immune System
AM/SS	Analytical Model/ Simulation Study
ANOVA	Analysis of Variance
AOR	Annals of Operations Research
APIOBPCS	Automatic Pipeline, Inventory and Order Based Production Control System
BOM	Bill of Materials
C	Computational complexity
CAS	Complex Adaptive System
CIE	Computers and Industrial Engineering
CIM	Centre for International Manufacturing
COR	Computers and Operations Research
COTS	Commercial-Off-The-Shelf
CS	Computer Science
CU	Capacity utilisation
CVI	Capacity utilisation, variability and inventory
DAP-US	Dynamic Allocation Problem with uncertain
DC	Distribution centres
DES	Discrete Event Simulation
DoE	Design of Experiment
DS	Decision Sciences
EA	Evolutionary algorithm
EBSCO	Business Source Complete
E2E-SC	End to end supply chain
EDI	Evolutionary algorithm
eGA	Extended Genetic Algorithm
EJOR	European Journal of Operational Research
ENG	Engineering
ES	Exponential Smoothing
FCLRP	Fuzzy capacitated location-routing problem
FG	Finished Goods
FMCG	Fast-moving consumer goods
GA	Genetic Algorithm
GM	General management
H	Heuristics
HBR	Harvard Business review
Hbrd	Hybrid simulation
HLA	High level architecture
HLA-RTI	High level architecture – Run Time Infrastructure
HSAA	Hybrid simulated annealing algorithm
HSAM	Hybrid simulated annealing-mutation
IDEF	Integrated Definition
IDEF0	Integration Definition for Process Modelling
IE	Industrial Engineering

IEEE-TEM	Institute of Electrical and Electronics Engineers - Transactions on Engineering Management
IIE	IIE Transactions
IJMS	International Journal of Modelling and Simulation
IJOPM	International Journal of Operations and Productions Management
IJPDLM	International Journal of Physical Distribution and Logistics Management
IJPE	International Journal of Production Economics
IJPR	International Journal of Production Research
IJSIMM	International Journal of Simulation Modelling
IJSPM	International Journal of Simulation and Process Modelling
INFCS	Interfaces
IP	Integer programming
JOM	Journal of Operations Management
JORS	Journal of Operational Research Society
JOS	Journal of Simulation
JSCM	Journal of Supply Chain Management
KPI	Key Performance Indicators
LHS	Latin Hypercube Sampling
LSSP	Lot sizing and scheduling problem
LT	Lead time
M	Manufacturing site
Mths	Mathematics
MA	Moving average
MAS	Multi-agent simulation
MCQS	Monte Carlo/Queuing simulation
MD	Master Data
MFV	Minimum Flow Time Variation
MILP	Mixed Integer Linear Programming
MIS	Management information systems
MLR	Multinomial logistics regression
MTO	Make-to-order
MTS	Make-to-stock
MS	Management science
M&S	Modelling and simulation
NN	Neural Nets
NPDev	New Product Development
NPDiff	New Product Diffusion
NRL	Naval Research Logistics
OME	Omega
OOS	Object-oriented simulation
OR	Operational research
P	Product
PERT	Program evaluation and review technique
PIM	Production and Inventory Management Journal
POM	Productions and Operations Management
PN	Petri nets
PTS	Product Technical Set
QN	Queuing Network

R	Retailers
RL	Reinforced Learning
RM	Raw materials
RQ	Research question
RSM	Response Surface Methodology
S	Supplier
SKU	Stock keeping unit
StrC	Structural complexity
SA	Simulated Annealing
SC	Supply chain
SCM	Supply chain management
SCM:IJ	Supply Chain Management: An International
SCOR	Supply Chain Operations Reference
SCN	Supply chain network
SD	System Dynamics
SLR	Systematic literature review
SM	Scientific management
SMPT	Simulation Modelling Practice and Theory
SO	Systemic organizational
SP	Stock out probability
SPM	Simulation Process Modelling
SS	Safety stock
ssGA	Steady State Genetic Algorithm
SSM	System Simulation and Modelling
UK	United Kingdom
VA	Value added
VBA	Visual Basic for Applications
VIS	Visual Interactive Simulation
VMI	Vendor managed inventory
VRP	Vehicle Routing Problem

Chapter 1

An inquiry into modelling complex end-to-end supply chains using simulation

1.1. Introduction

The chapter aims to briefly introduce the purpose of this research by firstly outlining the motivational reasons that led to this inquiry and defining the research context and scope. The key definitions and concepts related to this research are also explained, subsequently linking up the structure of the remaining parts of the thesis.

1.2. Research background

Supply chain (SC) systems and networks are an integral part of today's world. Supply chain is often defined as management of materials and information across an end-to-end supply network, from suppliers' supplier through component producers and other parties involved in assembly or other activities required to prepare finished goods for distributions to the ultimate customers' customer (Lee, Cho, Kim, & Kim, 2002). As businesses operate in the global marketplace, individual companies are no longer treated as separate entities, but as an integral part of a supply chain network or system. These companies are required to collaborate with their supply chain partners and invest in their supply chain systems so more effective and efficient solutions can be developed that are capable to deliver better and cheaper products with shorter and shorter life cycle (Skjoțt-Larsen and Schary, 2007; Min and Zhou, 2002). More often, businesses consider competing as part of a SC against other SCs, instead of a single firm against other firms (Christopher, 2011).

Increasing customers' expectations have shifted the competition between supply chain systems to another level, where supply chain leaders are faced with more challenges and issues in managing these complex structures to ensure that their products stay competitive, but do not jeopardise business profits and gross margin. One way to help business leaders is by using operational research and management science models and modelling techniques. Models and modelling, particularly simulation modelling has been recognized as a decision supporting approach that can be used in attempt to control supply chain systems (van der Zee & van der Vorst, 2005).

Pidd (2004) defined a model as "an external and explicit representation of part of reality as seen by the people who wish to use that model to understand, to change, to manage and to control that part of reality" (Pidd, 2004, p.12). Such models aim to represent a part of reality and serve as vehicles to inquiry into subjects that help in better understanding of that reality. This research attempted to develop a generic simulation model to be used by decision makers and researchers to further the knowledge around simulation modelling in extended supply chain systems.

The word "generic" has been defined by the Oxford English Dictionary as: "characteristic of or relating to a class or type of objects, phenomena, etc.; applicable to a large group or class, or any member of it; not specific, general. Also: characteristic of or relating to the use of language, as generic name, term, word, etc. Freq. opposed to specific" (Simpson & Weiner, 1991). In line with the above definition, this research attempted to define a generic modelling approach that can be used for any end to end supply chain (E2E-SC) or any of it members. It is an inquiry into challenges and issues associated with modelling complex E2E-SC systems using simulation, attempting to unveil and discuss each of the steps in modelling and how they can be impacted by system complexity, computational considerations and/or modelling assumptions and approximations (Venkateswaran & Son, 2004).

This research argues that simulation methodology is a suitable approach to study complex E2E-SC systems, nevertheless benefits of combining with other modelling techniques are presented. This is not an attempt to define the optimal modelling solution or the best class of modules, but rather a way to better understanding and appreciation of the complexity observed in E2E-SC systems structure and organisation as well as an opportunity to learn more about these systems and their systemic attributes. Therefore, in order to broaden this understanding, the research attempted to engage into discussion on the conceptualisation and use of the E2E-SC model (Pidd & Carvalho, 2006).

In the following sections of this chapter the research motivation and context of this study is discussed, which concludes with research questions, aims and objectives as well as formulation of the thesis structure.

1.2.1. Research context

In the recent years, one can observe a drastic change in the way that supply chain (SC) operate mainly as a consequence of technological advancements, high dynamics and market volatility as well as sophisticated relationships between various end-to-end supply chain parties (Ekinci & Baykasoglu, 2016). Therefore, according to Ekinci and Baykasoglu (2016) managing complexity will gain popularity for many businesses with global scope of operations pressing on participating organizations to rethink on how to manage their E2E-SC efficiently. The Gartner's research into the top 25 SCs highlighted some insights on best strategies to overcome increasing complexity through sharing best practices, and development of customers' centric approaches (Gartner, 2014). The research recommended that better expertise and partnership in delivering superior and sustainable SC solutions may be a good approach to lead in this turbulent era.

The Gartner's research analysed many supply chains and highlighted the key drivers affecting their performance. Similarly, the work of Ekinci and Baykasoglu

(2016) as well as Serdarasan (2013) discussed supply chain complexity drivers and provided some practical solutions as a guideline to support the development of supply chain management strategies. Despite the existence of many theoretical recommendations and proposal, many companies seem to be focusing on ensuring that fundamental elements of their end-to-end supply chain (E2E-SC) system are clearly understood. One way to achieve this is via using modelling techniques that can help to build the knowledge and communication, vertically and horizontally, across many functional areas and businesses (Gartner, 2014). The benefits of modelling involve work on improving core SC business functions and processes, providing environmentally friendly yet optimal solutions that allow for a healthy growth of the entire SC (Shapiro, 2007a).

This can be seen in the current research stream in the Centre for International Manufacturing (CIM) at the University of Cambridge, which emphasised on the impact that international manufacturing has on the global value networks (Institute for Manufacturing, 2016). The attention was brought to a strategic aspiration of businesses and ways to gain a competitive advantage in the context of enhanced or rather E2E-SC. CIM research efforts led to the development of a new methods for aligning E2E-SC network configuration and capabilities across internal business functions and external collaborators/partners. This resulted in a new concept of meta-capabilities linking distinctive group of capabilities with specific E2E-SC configuration.

Sharing the best practises and considering all elements of the E2E-SC system has been regarded as a necessity, where commonality, simplification and demand-driven practises are put on the forefront of business strategic objectives. E2E-SC term has been often used within logistics and supply chains operations with the focus on providing enhanced solutions. With the global scope of operations, the scale of challenges associated with managing such systems are shifted towards multidimensional perspective. This calls for innovative methodologies to capture E2E-SC system structure as well as the organisation of its business processes. Whether the efforts are geared towards SC configuration or management, this research highlights opportunities relative to simulation modelling and models that are capable to reflect the E2E-SC system.

Within E2E-SCs there are various aspects that require the immediate attention of practitioners and/or researchers particularly in response to the rapid and continuous market changes. Consequently, E2E-SCs are characterised by an intense level of complexity and competition. One way of gaining the knowledge on these systems is through an examination of the four elements: SC length, SC geographical dispersion, review of processes within the SC and activities performed across all processes (Tompkins, 2012). This requires a new approach to capture E2E-SC system configuration and capabilities, but also a new way to plan, control and evaluate the impact of innovative solutions on the performance of the system. Therefore, this research attempted to further the knowledge around E2E-SC systems structure and organisation as well as simulation modelling and use of models to understand these structures better. Likewise, it considers computational challenges relative to modelling complex systems and develops a generic framework for simulation model development process in context of E2E-SC system or network.

1.2.2. Research motivation

This insightful research journey was inspired by a supervised work experience at one of the market leading Fast Moving Consumer Goods (FMCG) companies, where the lack of end-to-end supply chain system models was brought to the attention of the researcher. The researcher observed that various aspects within SCs require immediate attention from practitioners and academics particularly in response to the rapid market changes. Businesses alike supply chains are characterised by high dynamics and everchanging environments and there is still room to gain further insights into various scenarios when modelling logistical business processes for entire SC systems (Cannella, González-Ramírez, Dominguez, López-Campos, & Miranda, 2017; van der Zee & van der Vorst, 2005).

SC experts are keen to have not only a model that can replicate the entire SC system, but also a modelling flexibility and ease to adapt the developed model to the needs of the business. The knowledge on the potential impacts of a decision maker choices on the supply chain system performance can be gained through developing various experiments and testing multiple scenarios. This research undertook an interdisciplinary approach, where system thinking and complexity theories, where used as fundamentals for developing a generic E2E-SC system model.

Supply chain (SC) networks have fundamentally changed over the past years especially because of high dynamics, implanted by globalisation, market segmentation and more of this due to the sophisticated relationships between various parties all focused towards customer satisfaction. Merkuryeva, Merkuryev, and Vanmaele (2011) affirm that the attention is increasingly placed on the analysis, performance and design of the entire SC embedding the holistic viewpoint with the common aim to improve or optimise global SC performance.

Dynamics has been identified as an important phenomenon affecting behaviour of many systems within complex global supply chains, despite its discovery more than half a century ago (Potter, 2005). As appointed by Forrester (1961) a delayed information feedback within an industry may cause a severe impact and amplification in various policies, which may be attributed to the structure of a system, however not solely (Angerhofer and Angelides, 2000).

Consequently, it is evident that SCs are characterised by an intense level of complexity and competition. Figure 1.2.2-1 presents a typical supply chain that consists of suppliers, manufacturers, warehouses, distribution centres and retailers working together to serve end-customers.

A competitive environment in which SC operate forces businesses to recognize opportunities for the market growth and react quickly by presenting the right product and market strategy thus always offering customers the added value (Wu, Huang, Blackhurst, Zhang, & Wang, 2013; Godsell, 2012). Figure 1.2.2-1 could be viewed as an 'End to End Supply Chain' (E2E SC); however as defining the scope of SC remains a significant challenge, many organisations tend to focus on the key business players within their SCs.

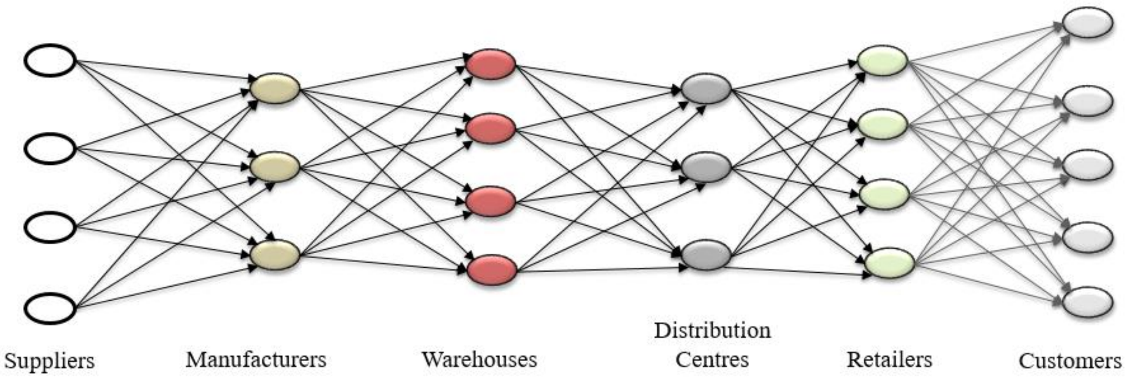


Figure 1.2.2-1 An example of supply chain structure

These complex and continuously changing structures have evolved over time and developed through advances in technology, computer science and humans' ability to successfully manage them. One way to study these complex systems is by applying modelling techniques, which can help in knowledge development relative to behaviours and complexity within these networks. One of the most frequently used tools capable to replicate complex systems is simulation, which became a necessity for modelling end-to-end SC systems (Rabelo, Sarmiento, Helal, & Jones, 2015). The efforts of this research are geared towards knowledge development around simulation in modelling end-to-end supply chain (E2E-SC) systems. E2E supply chain concerns various elements and this research is set to investigate their impact on modelling comlex E2E-SC systems.

Min and Zhou (2002) defined SC as an integrated system of various inter-related business processes that compete with other systems on the global marketplace arena. Authors emphasised on the importance of synchronisation between operational processes such as: physical distribution, materials management and coordination among SC entities.

Chopra and Meindl (2010) described supply chain as a network of suppliers, manufacturers, distributors and retailers, which are collectively involved in fulfilling customer orders. Authors further pointed out that the challenge exists in deciding on the number and location of production facilities; the capacity allocation within each of them; the choice of the market or markets that should be served by one or more of those facilities as well as selection of suppliers. One way of tackling these issues is to align strategic, tactical and operational aspects with the business overall goals and strategy.

Furthermore, Tarokh and Golkar (2006) augmented that decision makers should develop the best practices to facilitate an effective and efficient flow of materials and information within a SC network predominantly between its immediate suppliers and customers. Therefore, a robust SC network is expected to deliver the right product to the right customer at the right time and at lowest possible cost. Carvalho, Barroso, MacHado, Azevedo, and Cruz-Machado (2012) affirmed that despite of a big technological advancement, the immense change in people’s expectations as well as a perception of products value increased competition between companies. Consequently, businesses experienced global expansions and adoption of new philosophies such as lean, Quick Response or efficient customer response that resulted in added complexity and more challenges in managing SC systems/networks. These issues in line with shortening of products life cycle brought a need for more advanced and responsive SC thus a full comprehension of cross-functional business processes integration of purchasing, manufacturing, transportation, warehousing and inventory management within an organisation and across the entire network (Lambert, 2008).

Shapiro (2007a) further complemented that an integrated SC planning, where functional integration is supported by spatial integration of supply chain functions across geographically found vendors, facilities and markets enhances competitiveness of the SC network. These seem to be crucial to the fulfilment of the overall aim of an organisation to make the right long-term strategic decisions supported by inter-temporal integration of all activities performed within the SC. Execution of an organisation's business goals certainly requires adequate allocation of resources to support medium term tactical decisions, both uplifted by short term operational decisions.

Nevertheless, as stressed by Carvalho et al. (2012) the knowledge of collaborative business processes management needs to be further enhanced by clear understanding of counter measures to the potential problems resulting from implementation of those policies. Therefore, an organisation needs to be resilient and incorporate mitigation and contingency policies into the design of their SC network.

1.2.3. Supply chain management

Chan and Chan (2005) regarded Supply chain management (SCM) as one of the most appreciated strategies providing competitive advantage for those organizations that put an effort to align their strategic, tactical and operational activities to become more responsive to customer demand. However, as Wu et al. (2013) affirmed, many SCs are susceptible to risks and managing those seems somehow challenging. The importance of managing SCs efficiently has been a subject of numerous studies. The most frequently analyzed aspects of SCs are their design, planning and operations in line with decisions impact of strategies used (Chopra and Meindl 2010; Lambert 2008). Strategic, tactical and operational decisions around capacity and resource allocation to manage demand variability, has been considered as critical in ensuring SC resilience to turbulences (Wu et al., 2013).

The concept of SCM is often underpinned by a desire for integrating and interacting. This may be simplistically treated in theory and practice given the emergent properties which arise from integrating, feedbacks, nonlinearities, changes and strategies (Surana, Kumara, Greaves, & Raghavan, 2005). Often the extent and context dependencies of interactions can be neglected or improperly handled. It is also simplistic to assume that all stakeholders from far upstream suppliers to far downstream customers can be accurately identified, objectively prioritized and truly integrated with error free flows of information, products and services as the boundaries of control are limited to one organization and not the end to end chain/network (Li, Yang, Sun, Ji, & Feng, 2010). There is also a lack of research-based understanding of when or how SC dis-integration or re-integration occurs.

The E2E-SC system performance can be also affected by instability and dynamics (Bagdasaryan, 2011; Tipi, 2009). SC Dynamics refers to the demand amplification and the literature discusses this phenomenon widely, as one of the causes of the bullwhip effect (Taylor 1999; Kahn 1987). The small variation in demand from the customers' increases upstream the supply chain as a result of an ill structured demand management strategy, where decision makers over-respond to variation in demand, placing higher orders, which causes a surge of stocks level (Metters, 1997).

Moreover, information and materials time lags cause a false perception of production capacity shortages. The visibility of finished goods orders in the system gets distorted causing an increase in the noise level as orders move upstream in the SC, particularly at the factory level. This is known as a Bullwhip Effect or Forrester effect, which was firstly studied by Forrester in 1958.

1.2.4. System complexity

Pidd (2004) defined system as a set of elements that are interlinked with each other and operate within certain boundaries. The author further explained the importance of system behaviour, which may be derived from the relation between system elements and/or emerge as a result of combination with other system states, therefore often regarded as an emergent behaviour.

Reitsma (2003) attributed complex characteristics to any system where the whole could not be entirely understood just through the analysis of its components. Allen and Strathern (2003) reiterated that a complex system can respond to its environment in more than one way. Cilliers (2005) stressed that complex systems work under certain conditions and the state of the system is determined by the values of its inputs and outputs. The interactions between system elements are often nonlinear and instigated by historical information about its elements/components and their current context (Hogue & Lord, 2007).

A system can be complicated due to large number of components but if a complete and objective description of individual elements may be possible this complication of the system is treated as a quantitative escalation, which is theoretically reducible; i.e.

deterministic as in a chaotic system. In such a system, proximate initial condition could make a large difference to the end state or outcome, hence leading to unpredictability as in causal determinism (FHI360, 2014).

Therefore, a distinction could be made between a system that is complex or just complicated. This can be observed in the business research studies such as management, operations and supply chain, resulting in perhaps positivistic techniques to manage them (Nilsson et al., 2012). Golicic and Davis (2012) further reiterated that in result supply chain and logistics studies are influenced by order, objective reality, reductionism, deliberate design, rationality, stability, determinism, value-freeness, error-freeness, context independency, linearity, centralization, hierarchy, uniformity, unbiased, controllability, symmetric and noise-free information flows to name few. This dominant positivistic approach may be inclined towards research where objective and observable phenomena is considered hence posing a question around the appropriate assumption when approaching complex versus complicated supply chain systems.

This research views E2E-SCs as complex systems that operate in dynamic and continuously changing environment aiming to improve strategic approaches to become more responsive to customer requirement (Wu et al., 2013). Serdarasan (2013) acknowledged that there are three types of complexity observed in the supply chain:

- Static, which is about the structure and connections in the subsystems,
- Dynamic, which is about operational behaviours of the supply chain and its environment,
- And complexity affected by decision maker and shows both static and dynamic elements.

Globalisation is another important aspect, which contributes to the complexity in managing a supply chain (Skjoțt-Larsen & Schary, 2007). It is especially visible in the environmental and structural complexity (Guisinger, 2001). The environmental complexity refers to political, social and cultural issues. The special integration of the SC is particularly affected by the state of information technology developments around the world. Major challenges due to globalisations of SCs are around cross regional supplying of unique value proposition to spatially dispersed customers in the face of competition from around the world, which requires adverse management skills and understanding of the complexity to respond to dynamic changes (Skjott-Larsen et al., 2007).

Surana et al. (2005) argues that useful models require empirical evidence. Considering many complex systems within different fields (i.e. biology), this seems a reasonable statement, however, within SC the existing (tested) models may have been used for a long time yet not addressing all aspects of operational or organisational complexity. Therefore, to develop a useful model consideration should be given to conceptual models as well as to those empirically tested. The challenge is to understand all core processes within the business and inter-relationship between them. Moreover, the dynamics of the environment strives for simplistic/generic model that can be replicated within short period of time and give a reliable source of information for the decision maker. Thus, understanding of the core processes within each node of the SC seems to be a crucial element of the model design. A model that allows copying and creating as many entities as needed would support strategic level of analysis offering a powerful tool to support decisions at a higher level for example: facility location, increased market share, supplier choice, etc.

1.2.5. Supply chain designing, planning and controlling

Merkuryeva, Merkuryev, and Vanmaele (2011) confirm that multi-echelon SC consists of various processes like purchasing, production, picking and transportation as well as multiple stock-points (buffer or storage). Authors further discuss that the planning activities are based on the continuous or periodic inventory review which can be further classified as cyclic or non-cyclic. In cyclic planning production intervals are fixed and applied to all processes (order, production or delivery) while in the non-cyclic planning the intervals length varies. Similarly, cyclic planning seems to be more applicable to the multi-product and multi-stock policies mainly due to a better control through simplified planning procedure and possibly reduced administrative costs hence lower inventory cost. However, the authors reiterate that the non-cyclic planning procedure proves more applicable in a situation with the high demand variability that often occurs during product introduction and an end of the product life-cycle.

Introduction of a procedure and processes variability of demand, lot size or lead time that are characterised by non-linearity or combinatorial relationships within multi-echelon cyclic planning can only be achieved with the help of simulation modelling. A methodology was developed to help with simulation-based analysis of the optimality gap between planning policies of the product life cycle over the entire SC (switch from product introduction phase to product maturity thus to cyclical planning that mainly occurs within mature products when the efficiency of cyclic planning has been proved) and simulation-based optimisation of cyclic planning solutions at the product maturity stage. Algorithms for testing the end of product introduction stage are developed by Sukov while switching from a non-cyclic to a cyclic planning as well as a cyclic planning optimisation are the aim of the Merkuryeva et al. (2011) research.

Complexity within the SC operations can be significantly reduced if the assumption is made of a constant demand, fixed set-up costs, and fixed lead time (LT), which could be supported by Mixed Integer Linear Problem (MILP) analytical models. By incorporating the analytical model into the simulation-based planning optimisation techniques, a great angle of flexibility can be achieved, and various scenario analysis undertaken. Consequently, a multi-echelon cyclic production planning model can be defined where the demand is uncertain and the capacity limited. Thus, simulation – optimisation is often viewed as a powerful technique that allows to define, which of the variables within the SC contribute to the highest performance of the entire system. However, considering system view of the SC, it is also very important to clearly understand the SC system under investigation boundaries as the optimal or near-optimal solution may only be viable while considering critical nodes in the SC.

SC coordination can be defined as a decision-making approach that is supported by an exchange of information between various actors with the common purpose to satisfy set goals (Chen, Chen, Chiu, Choi, & Sethi, 2010). Chen et al. (2010) conducted a research that analysed and classified analytical and simulation studies related to a SC coordination. They summarised that simulation is a preferred method for the analysis of dynamic SC behaviours; however, the analytical approach seemed equally important. Consequently, they highlighted the need for flexible models that can incorporate various levels of uncertainty providing a tool that is adaptable to many scenarios/options.

Economic benefits resulting from information sharing and coordination however differs between parties depending on the strategy employed whereby more benefits are obtained from coordinated decision between parties (Sahin & Robinson Jr, 2005). Authors further point out that information sharing benefits are observable in the case of higher set up costs at vendors. Comparison between different strategies was conducted with the help of simulation modelling through testing various operational scenarios.

Moreover, coordination varies depending on the type of the SC hence within centralised SC the information sharing is higher offering easier task for the central decision maker who tries to optimise SC operations (Pezeshki, Baboli, Cheikhrouhou, Modarres, & Akbari Jokar, 2013). The authors further explain that decisions within decentralized SCs are focused on the benefits of a single entity often conflicting with those made by the others. Therefore, a well-designed contract between the parties can address all inconsistencies and provide the optimum benefits to the entire chain as well as clear and divided responsibilities and risks. Pezeshki et al. (2013) studied trust as a main factor alongside economic benefits that constitutes coordination mechanism and provide a deep analysis of the benefits that can be achieved.

1.2.6. Performance measures

The most frequently used SC performance measures are mostly linked with economic measures such as cost or profit. However, Beamon (1999) highlighted that there are common pitfalls in using cost as a performance measure within the SCM. The author emphasised on the importance in aligning the cost performance with the strategic aim of the company. Similarly, due to the high level of uncertainty and dynamism within the SC, a robust performance framework is required to improve the entire SC visibility.

Undoubtedly measuring a flexibility has the highest level of difficulty especially within production planning and scheduling but not solely. This is further affected by the inter-organisational relationships, type of the SC network, degree of information sharing, etc. Consideration should be given to all aspects that allow the SC modeller to understand the performance of the designed model as well as to address the performance measures trade-offs. Consequently, the challenge is in selection of the right measures that will enable monitoring of the complex SC inclusively of various operational policies, business models (strategy and tactics) and aspects of collaboration between entities. Nonetheless, a universal set of performance measures provides a platform to benchmark the performance of any given company against their competitors.

Fleisch and Tellkampf (2005) studied the impact of inventory inaccuracy on the performance of the SC. Authors emphasised on the importance of aligning the data sets that can be obtained through developments in the information sharing technology with physical levels of inventory held as well as the flow of those goods through the network. Furthermore, despite the existence of bullwhip effect, the other factors affecting an inventory inaccuracy are: theft, unsaleable, incorrect deliveries or stock counts. Accordingly, many efforts to address the issue had been undertaken and one of the advocated ways is to use Radio Frequency Identification Technology tags in retailing.

1.2.7. Modelling and simulation

The E2E-SC system exhibits complex and dynamic characteristics attributed to many entities and multiple processes performed in a continuously changing environment (Simchi-Levi, Kaminsky, & Simchi-Levi, 2008; Skjott-Larsen et al. 2007). Frequently businesses tend to introduce new products, which often lead to increased number of members in the E2E-SC. This requires a continuous review of the strategies used, often leading to a simplification of business processes and procedures used (Umeda and Zhang, 2006).

Skjoțt-Larsen and Schary (2007) stressed that it is difficult to define a structure and boundaries of an E2E-SC system as well as to understand all processes and inter-firm relationships. The authors further emphasized that to some extent, supply chain complexities can be handled by analytical tools. However, these may struggle with modelling an uncertain and a dynamic environment and/or large databases, which seem to prevail in the current globally dispersed SCs that exhibit differences related to technological, cultural and social aspects.

Notwithstanding technological advancements and growing knowledge engine, the existing modelling techniques, although widely used by SCs managers'/decision makers and researchers, are not fully embedded to model E2E-SC systems. Despite variety of models and modelling approaches there is still limited research on E2E-SC. One of the frequently used modelling techniques is a computer simulation. Various researchers dedicated their efforts to review simulation and supply chain related literature in search for trends, new developments and future prospects (Barbati, Bruno, & Genovese, 2012; Bellamy & Basole, 2013; Jahangirian, Eldabi, Naseer, Stergioulas, & Young, 2010; Manuj, Mentzer, & Bowers, 2009; Mustafee, Taylor, Katsaliaki, & Brailsford, 2009; Oliveira, Lima, & Montevechi, 2016; Santa-Eulalia, G. Halladjian, S. D'Amours, & J.-M. Frayret, 2011).

Oliveira et al. (2016) conducted a systematic literature review (SLR) and used a meta-analysis to represent relationships as well as perspectives in modelling and simulation and supply chain. The study reported that simulation models could be better integrated into supply chain systems operations and to focus more on the behaviour of these systems as well as its inherent dynamics. Likewise, the authors concluded that in the vanguard of the research in the field are allegedly combined simulation-optimisation and agent-based simulation models. Moreover, Oliveira et al. (2016) emphasised that hybrid simulations of normative and empirical model can be used to represent, evaluate supply chain performance and perform various scenarios.

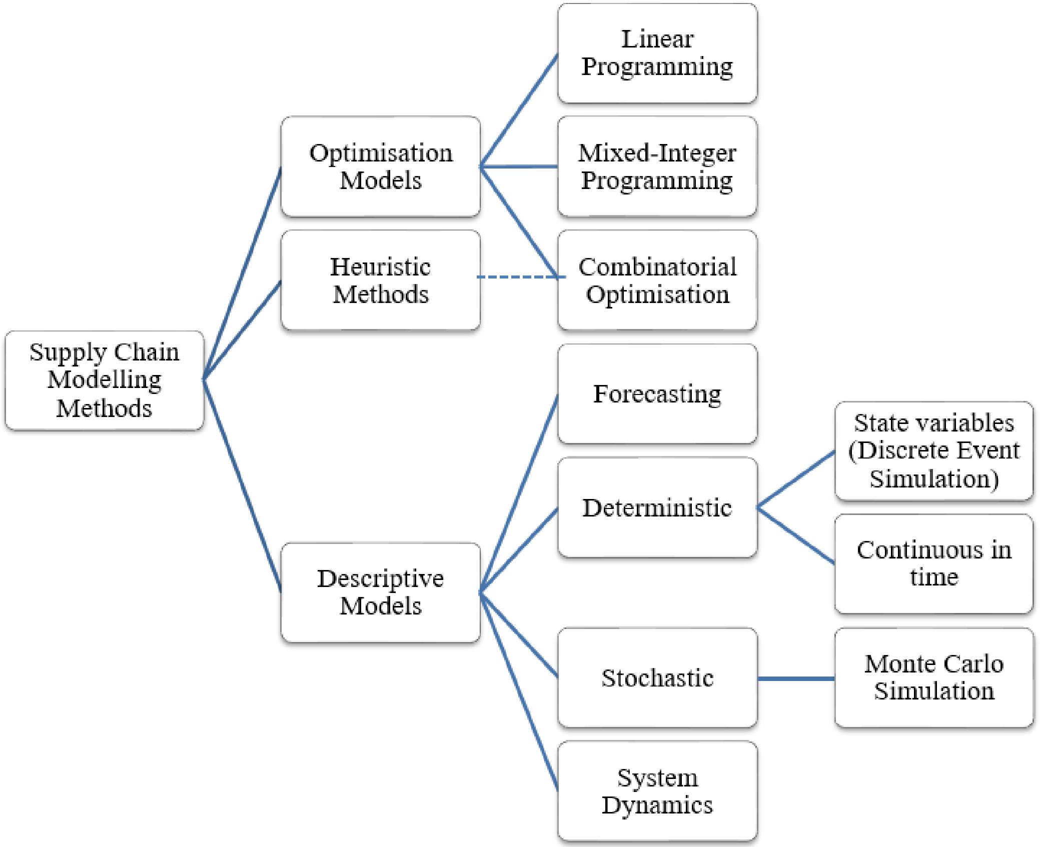
The existing research focused on advancements relative to methodological frameworks; as in case of Santa-Eulalia et al. (2011) who analysed modelling and agent-based simulation (ABS) frameworks, nevertheless, excluding the broader aspects of Supply Chain Management (SCM). Similar line of research can be observed in Barbati et al. (2012) which engrossed the application of modelling ABS in optimization problems. Another review focused on modelling and simulation in SC (Mustafee et al., 2012), simulation modelling process in logistics and SC (Manuj et al., 2009) or state of the art in supply chain simulation literature (Oliveira et al., 2016).

The existing literature underlined that increasing complexity of SC systems was somehow affected by uncertainty in supply and demand, conflicting objectives, ambiguity of information and many variables and constraints at different operating levels, which required robust tools to help decision makers. Simulation has been identified as the most powerful technique used in the research in the field of supply chain simulation modelling (Stefanovic, Stefanovic, & Radenkovic, 2009). This modelling technique provides an opportunity to test a designed model without the need to spend money on implementation and chose the best or the most applicable solution for the model under study (Campuzano & Mula, 2011; Kelton, Sadowski, & Swets, 2010; Rossetti, 2010).

Simulation modelling is widely used to map a real system; however, it does not provide the optimal solution applicable at each node. This can be achieved by combined use of optimisation and simulation; however, a question may be asked in relation to existence of trade-offs while optimising a set of processes. Simulation is often used to validate results of an analytical model or to support complex computations, therefore it appears that combined simulation based analytical model was needed that provides robust analysis of a dynamic system and offers flexible and quick solutions (Lee, Cho and Kim, 2002). Simulation can be used as a part of a hybrid approach to allow gaining benefits that each of separate methods delivers (Onggo, 2015).

Shapiro (2007a) provided an overview of supply chain modelling methods, which included analytical tools and methods and were classified into three groups: optimisation, heuristics and descriptive models (Figure 1.2.7-1). The author identified within descriptive models four methods: forecasting, stochastic, deterministic and system dynamics. Stochastic, deterministic and system dynamics belong to simulation models and the difference between them can be attributed to randomness as deterministic simulation models describe a system's dynamic behaviour with no random effects and stochastic simulation models which describe system behaviour with random effects. These methods were deemed to be used while solving supply chain planning problems.

Figure 1.2.7-1 SC Models and Modelling Systems Overview



Source: Further developed from Shapiro (2010)

Numerous studies such as Pundoor and Herrmann (2007); Fayez, Rabelo, and Mollaghasemi (2005) and Zee and Van der Vorst (2005) examined the use of simulation models and provided some examples of how this methodological approach could be used to address operational problems. However, same studies acknowledged that use of simulation required skilled analysts and powerful tools to capture many complex system elements, therefore industry members appeared skeptic of its applicability in a day to day operational decision. Cope, Fayez, Mollaghasemi, and Kaylani (2007) stressed that a simulation methodology should be used with a defined purpose and in order to obtain meaningful results based on some defined scenarios, an industrial support could be given during project creation, validation and execution.

Kelton, Sadowski, and Swets (2010) sustained that a focal point of simulation and modelling is to understand the reason behind the research study and provided directions on how to develop a model to tackle operational research (OR) and management science (MS) issues. The authors provided a comprehensive introduction to simulation modelling and Arena simulation software as well as its applicability across various fields. Some attention was given to generic models within OR/MS field, which were believed to be used across different organisations.

Some other work was presented by Robinson (2014) and Pidd (2004) who touched the base on how generic models could be created in OR/MS and how they could be validated. There seems to be limited work on how to develop a generic E2E-SC system model using simulation and this research aims to address this gap.

1.3. Aim, objectives and research questions

The research is guided by the research questions as specified below:

RQ1. When modelling an E2E-SC using simulation, which are the main elements, processes and characteristics that should be considered?

RQ2. How simulation methodology can be used to support modelling an E2E-SC?

RQ3. Considering the multidimensional nature of research stream, to what extent segmented models can be integrated with simulation?

The aim of this research project is to develop a generic end-to-end supply chain (E2E-SC) system model using simulation and to define requirements for modelling an E2E-SC system when using simulation methodology. To achieve this, the following set of objectives has been proposed:

- To develop a conceptual modelling framework for an E2E-SC system that cogitates on system thinking and complexity theory.
- To develop a computerized model using simulation that provides the architecture for combining various modelling techniques.
- To evaluate the implications to modelling when different elements from the proposed conceptual framework are included in the computerised/scientific model.
- To validate conceptual research framework and computerised/scientific model with industry experts.

1.4. Thesis structure

To provide a focus for this thesis, the aim and a set of supporting objectives have been developed and are outlined in Figure 1.4-1, along with a summary of each of the research chapters in this thesis. This is to present an overview of the research logic and to highlight how each chapter links to the objectives and the overall aim of the research.

In the introductory chapter, the research scope and context were defined and motivational reasons that led to this inquiry were highlighted. The chapter defined main concepts and frameworks relative to E2E-SC system (Hines, Holweg, and Rich, 2004; Lambert 2008; Chopra and Meindl 2010) as well as simulation modelling (Stefanovic et al., 2009, Pundoor and Herrmann, 2007; Rabelo et al., 2015). The review of extant work in the field of supply chain and simulation highlighted the need to develop a generic simulation model and to define key modelling requirements for modelling complex E2E-SC systems.

The central aim of the research was supported by chapter two where systematic review of the literature was conducted, which provided theoretical underpinnings for this thesis. There were two main foci of the chapter two, one of which was to provide an insightful review of various contributions to knowledge in the field of simulation modelling highlighting the gap and justifying the need for this research. The second focal point of the chapter two was to propose a conceptual framework that recommends generic elements required when modelling E2ESC systems using simulation.

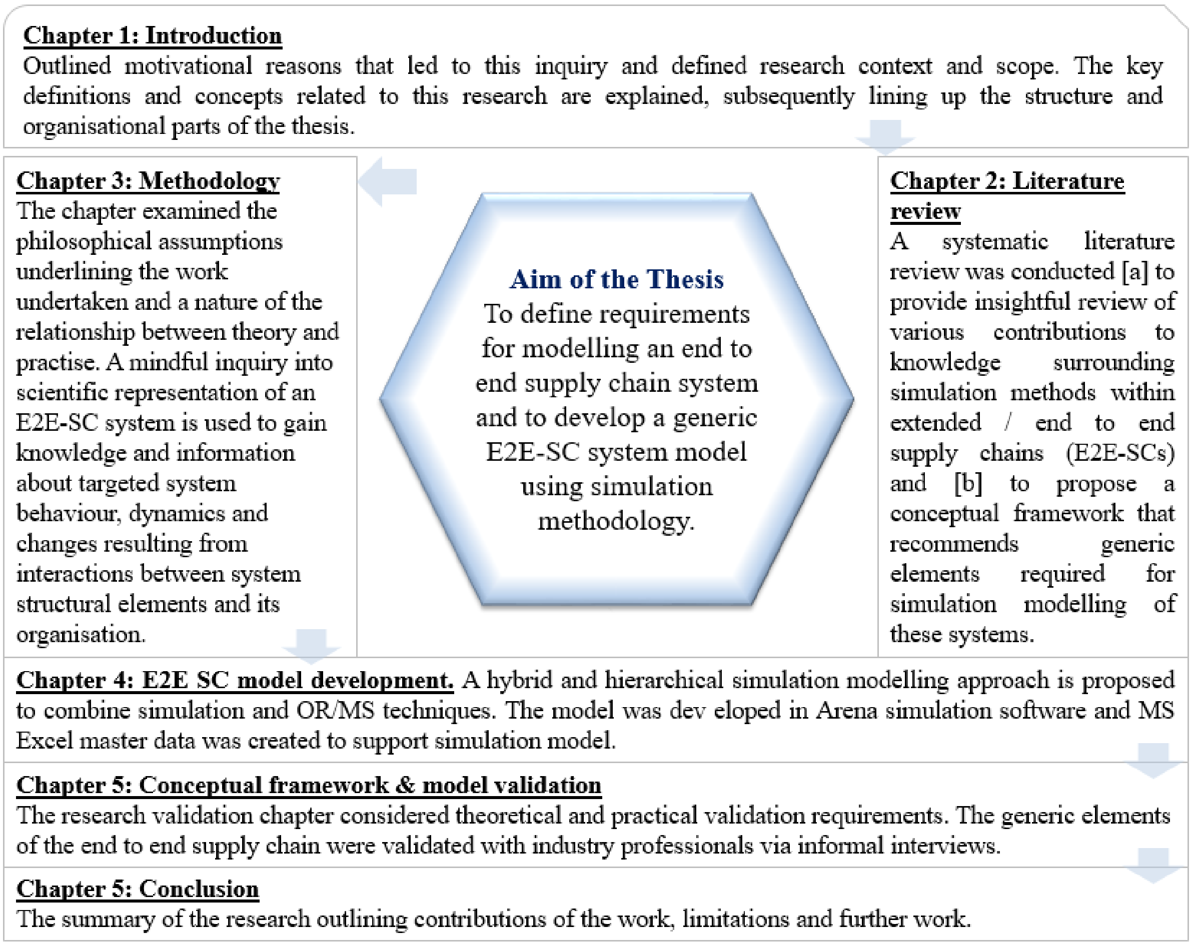


Figure 1.4-1 Aim and structure of the thesis

Next, chapter three outlined methodology and examined philosophical assumptions underpinning the research work undertaken. In line with Bentz and Shapiro (1998), a mindful inquiry into the scientific simulation model is used to gain knowledge into complex system behaviour and challenges and issues relative to modelling E2E-SC systems. A methodological approach undertaken in this research was derived from Mittroff’s scientific inquiry model, which was found closely linked to simulation methodology and once combined with conceptual framework elements led to formation of a generic E2E-SC system modelling architecture. The generic modelling architecture and Arena simulation model were outlined in chapter four.

Onggo (2015) pointed out the benefits of using hybrid approach, whereby strengths of combining multiple research methodologies can be gained. This idea was supported in this research and therefore simulation methodology was combined with MS/OR techniques and demonstrated how both approaches could be used. The E2E-SC system model development process was presented in chapter four and the generic simulation model validation and verification elements as well as a validation of the conceptual framework elements were highlighted in chapter five.

Chapter five focused on discussing results of the generic simulation model in Arena and discussing these results and well as theoretical validation of the research conceptual framework and an E2E-SC model architecture. A concluding chapter of the research focused on bringing findings form each chapter together to provide key requirements for modelling complex E2E-SC systems. Some practical implications and research limitation were also highlighted with recommendations for the future research.

1.5. Chapter summary

This chapter was designed to highlight the context and scope of the research. The structure of the thesis was outlined, and the research aim and objectives were discussed. These were complimented by four research questions, which were further deliberated in the thesis. The thesis structure was built around the aims and objectives of the research and each of the consecutive chapters has been linked to each other to provide a holistic view of the requirements for modelling E2E-SC system using simulation.

Chapter 2

Supply Chain Modelling using Simulation: A Systematic Literature Review and Formulation of a Conceptual Framework

2.1. Introduction

The purpose of this chapter is twofold; [a] to provide insightful review of various contributions to knowledge surrounding simulation methods within extended; end-to-end supply chains (E2E-SCs) literature and [b] to propose a conceptual framework that suggests generic elements required for simulation modelling of such systems. This is achieved by adopting a systematic literature review (SLR) approach, which attempts to examine the field of E2E-SC and simulation modelling; descriptively analyses, organises and integrates the research literature into themes.

The literature survey of the relevant, peer reviewed publications was undertaken, which considered the period between 2000 and 2016 and followed steps proposed by Denyer and Tranfield (2009), Kitchenham et al. (2009) and Centre for Review & Dissemination (2001) to systematic literature review (SLR), as well as recommendations offered by Tranfield, Denyer, & Smart (2003) to rigorous research synthesis. The research undertakes a SLR strategy as a means for dissemination of all carefully selected studies and was underpinned by the research background.

One of the aspects that has been continuously analysed is the research aim and how it fits within the focal area. Easterby-Smith, Thorpe, and Jackson (2012a) emphasised on the need to achieve the balance between a narrow focus around the subject of inquiry and broader view of potentially contributing literature from the outside of the focal area. This seemed particularly relevant to this research with the existence of numerous studies in the field of supply chain and simulation, requiring rigorous approach to ensure high quality of the research and applicability of search strings. Therefore, an exploratory scoping study was completed to access if SLRs were previously conducted within the field as well as to clarify the focus of a literature search (Saunders, Lewis, & Thornhill, 2015). Consequently, a SLR strategy followed a structured step by step approach (Denyer & Tranfield, 2009), which resulted in the selection of the relevant sample size for further investigation.

Following recommendations to SLR the research gathered all relevant literature, which was then carefully analysed to provide a theoretical foundation for the conceptual model building. To this extend the research adopted a deductive approach (Saunders et al., 2015) and through rigorous dissemination and synthesis of the existing studies an attempt has been made to contribute to the existing body of knowledge within the field. By implementing the SLR strategy, the research intends to advance the theoretical understanding of the methods used and applicability of simulation methodology in modelling an E2E-SC.

The current research highlights the need for more sophisticated frameworks to model complex E2E-SC systems. The use of systematic literature review approach has been chosen to provide an overview and evaluation of the simulation methods currently used in modelling E2E-SC systems. This thorough method was used to identify generic modelling elements for supporting modellers/decision makers in replicating, analysing and evaluating E2E-SC systems, and may ultimately result in the improved system performance. Likewise, the review attempted to answer the question regarding the capabilities of simulation to act as a standalone method to model E2E-SC, considering the multidimensional nature of research stream.

Because of the exploratory scoping study, the importance and contribution of system thinking paradigm and complexity theory to the development of a generic simulation framework for modelling holistic/end-to-end SC (E2E-SC) system were considered. These theoretical underpinnings were further examined during the literature review mainly from the following research domains: Operations Management (OM), Operations Research/Management Science (OR/MS) and Engineering (ENG) and modelling and simulation (M&S).

These research domains were purposefully discerned to clarify the context and boundaries of the subject of inquiry to fulfil the research aim and objectives and to provide a more focused view on generic E2E-SC system elements. This led to a different understanding of the requirements for modelling E2E-SC systems. The current research observed that the key challenges and issues were attributed to the complexities that exist in E2E-SC systems, which were grouped in three pillars: Structural, Computational and Systemic Organisational. This chapter further elaborated the three identified groups and its elements that formed the conceptual framework for modelling an E2E-SC system using simulation.

The literature review chapter is structured as follows. Following an introductory section of the chapter, the thesis proceeds to the overview of the subject of inquiry. Section 2.3 elaborates this further by providing an overview of the theoretical background of this research and explains the applicability of system thinking and complexity theory. Systematic literature review (SLR) strategy and details of the review protocol is presented in Section 2.4. Section 2.5 opens with the classification of the identified themes and the generic processes relative to E2E-SC, which form a part of the review findings. Devised from the SLR finding and described in Section 2.6 is a conceptual framework for this research. The last section presents the simulation modelling process steps along with the applicability of the proposed framework. A summary of the research findings and areas for further work concludes the chapter.

2.2. Supply chain modelling inquiry

Supply chain (SC) can be regarded as a network of organizations, which are interconnected and involved in managing various activities and processes to deliver goods and/or services to the customer. When consideration is given to the interdependence of activities, organizations and processes, then the SC attribute becomes systemic (Skjoțt-Larsen et al., 2007) and regarded as supply chain (SC) system. This research has an interest in modelling E2E-SC systems using simulation. An E2E-SC system and simulation modelling areas are consistent with the aim of this thesis. Both areas are distinct and interlinked in the way that one investigates the generic elements that ultimately form a conceptual framework for modelling E2E-SC systems and the second contributes to the body of knowledge by testing the framework. The investigation further elaborates on the contribution that simulation modelling brings to enhance the proposed concepts, underpinned by the theory of complexity and system thinking and in the context of E2E-SC.

2.2.1. E2E-SC perspective

Over the past years the efforts of many companies seem to be focused on ensuring that the fundamental elements of their extended, also referred to as an entire or end-to-end supply chain system had been clearly understood, and the knowledge built in this area had been well communicated, vertically and horizontally, across many functional areas and businesses. An E2E-SC can be defined as a network of business entities with different set of objectives and constraints yet working together to deliver goods and services to the end customer in the most efficient and effective way (Swaminathan, Smith and Sadeh, 1998).

E2E-SC involves an end-to-end process that starts from product and service design, through control and planning of various activities in the chain i.e. sourcing, producing, distributing or forecasting (Acar & Atadeniz, 2015; Swaminathan & Tayur, 2003). E2E-SC is complex and difficult to manage due to its systemic attributes often spanning several supply chain networks/systems reaching from supplier's supplier to customer's customer (Lin et al., 2000), where interests of multiple firms are considered. This is also considered by Christopher (2011) who defined supply chain management in the context of the end-to-end supply chain by indicating the importance of the upstream and downstream relationships with customers and suppliers to deliver value in effective and cost-efficient way.

Godsell (2012) pointed out that a good understanding of the competitive environment in which businesses operate provides great opportunities for the market growth as this enables firms to proactively match the right product and market strategy thereby offering customers the added value. However, this is only possible if the scope of operations and all elements within an E2E-SC system are defined. As such, this can be challenged by multidimensional complexities that exist within SC systems as well as mapping and determining the primary customers base for the E2E-SC organisation (Godsell, 2012).

The knowledge on properties and attributes of these complex E2E-SC structures can be gained through modelling and development of various models that can incorporate concepts from several disciplines without the need to change the actual system. Jahangirian et al. (2010) pointed out that one of the important factors is around selecting the most appropriate and suitable simulation technique for modelling SC systems. This is due to increasing complexity in multi-level decision making affecting the entire SC system. Ghadge, Dani, and Kalawsky (2011) acknowledged that dynamic changes in the global business environment compel more robust modelling techniques that are able to incorporate different concepts into complex systems model (Shapiro, 2001) and support academics and practitioners with many useful frameworks to handle cross-disciplinary issues within these complex systems.

A literature review conducted by Jahangirian et al. (2010) provided an overview of simulation application in manufacturing and business. The authors considered a wide coverage of the literature and simulation techniques in the context of OM and real-world applications of simulation techniques, which was then streamlined with the help of various filtering tools and techniques to a number of 281 papers for the final review. Their research highlighted a popularity of Discrete Event Simulation (DES) technique in addressing scheduling issues and applicability in wide scope of OM issues in various industries. Although DES had less stakeholder engagement than other simulation techniques such as System Dynamics (SD) or gaming, likely due to modelling lead time and context. Furthermore, the study concludes that hybrid simulation is increasingly used to model complex enterprise wise E2E-SC systems.

Olhager, Pashaei, and Sternberg (2015) conducted a systematic literature review on global supply chain networks and categorised research on production and distribution networks based on strategic and structural decisions such as opening, closing and location of facilities as well as capacity changes. The authors suggested that future research should consider multiple stages in the supply chain and focus not only on the focal manufacturing plant but also transportation links between facilities within an end-to-end supply chain network.

The current research in SC and modelling is inclined towards investigating complex, system wise phenomena, which affects performance of the E2E-SC system, its behaviour and dynamics whether related to the changes within the system or changes caused by interactions with external environment (Acar & Atadeniz, 2015; Narayanan & Moritz, 2015; Oliveira, Lima, & Montevechi, 2016).

2.2.2. The importance of modelling

There is a wide range of SC system models within existing literature. Numerous attempts by Beamon (1998), Shapiro (2001), Min and Zhou (2002), Chopra and Meindl (2007) and Lee and Kim (2008) have classified these models into either static, dynamic, analytical, deterministic, simulation or hybrid models. However, these classifications appear to have focused on the particulars of the system to be modelled and/or a specific SC research agenda. Studies that seem to have addressed matters such as SC coordination and system dynamics (Chan & Chan, 2010) often built upon the existing model classifications to further the knowledge on certain SC system aspects or areas. In addition, others focused on definite modelling techniques and considered the broader application of such modelling methods (Chatfield, Hayya, & Harrison, 2007; Hwarng, Chong, Xie, & Burgess, 2005).

It is noted that the current literature offers a wide range of SC system models, which provide a good understanding of different SC aspects and serve as useful decision support tools. Nevertheless, if one considers the growing complexity of SCs and the system evolution, the current research stream would benefit from studies presenting models that are capable to reflect integrated, complex and continuously evolving E2E-SC systems. Albeit the efforts in developing powerful modelling techniques are rather immense and accredited to many, still there seems to be an appetite for more sophisticated and efficient frameworks for modelling SC systems (Özbayrak, Papadopoulou, & Akgun, 2007).

This may be attributable to the systemic properties of an E2E-SC and the complexity observed in such systems, which would require powerful modelling technique/s to support decision maker. Simulation is one of the most suitable methods to model complex systems (Terzi and Cavalieri, 2004). Therefore, this section of the research attempted to undertake a systematic literature review, to broaden the knowledge on modelling E2E-SCs with focus on simulation methodology, although simulation interactions with other methods are also considered.

A wide spectrum of OR/MS and OM as well as simulation models are available in the extant literature for decision makers' perusal, however in the context of E2E-SC, a profound investigation and examination of key pillars required to model contemporary SC systems would benefit the realm of current research. The attempt of this research is to address this aspect and explore the field of modelling and simulation in E2E-SCs by developing a generic simulation modelling framework that would provide the underlying principles for modelling SC systems, considering impact of complexity, dynamics as well as structure and organisation of SC system under consideration.

2.2.3. Simulation in OR/OM/MS

SC systems are characterised by high complexity embedded and developed through constant changes and more sophisticated requirements of the final customer. As the evolution speed increases so as challenges in keeping up with the advancements in technology and expectations of the market. One example of this is the increasing importance and developments in computer simulation (Shafer and Smunt, 2004). Its wide applicability and popularity calls for a thorough investigation of the existing literature and requires a clear specification of the research area and methodology for example by narrowing it down to the field of operations management (OM) or/and operational research (OR) and management science (MS).

The OM research agenda has been studied previously by Pannirselvam, Ferguson, Ash, and Siferd (1999) and Creighead and Meredith (2008), where exhaustive examination of trends, gaps in the literature and areas for further research within operations management methodologies were highlighted. Subsequently, the results of their studies have shown that M&S are the top two methodologies discussed within many publications that they have analysed.

Petersen, Aase, and Heiser (2011) found that the OM field has evolved over time and included more supply chain journals. The analysis conducted by the authors highlighted an increase in the breadth of the research within OM field, which is spanning into various business fields and behavioural sciences. Moreover, the research further emphasised on the difference between journals that despite the high-quality fall short in relevance to the OM field. Notwithstanding the difference between OM and OR/MS there seems to be no explicit distinction of the two as separate fields of inquiry (Barman, Hanna, & LaForge, 2001). Barman et al. (2001) drew attention to the perception of quality and showed that relevance of various journals in OM varies between scholars all over the world as the emergent specialisation of papers usually focuses on one or another. For example, journals in the OR/MS field tend to be of a high quality but low relevance to the OM field (Craighead and Meredith, 2008). Craighead and Meredith (2008) pointed out that this is primarily attributed to the fact that various disciplines within OM like for example OR/MS or Industrial Engineering (IE) provide an insightful analysis of a topic or methodology used.

Shafer and Smunt (2004) evaluated the empirical simulation studies between 1970 and 2000, building further on the work of Petersen and Aase (2004) and identified trends and indicated future research areas. Since then various authors' attempts have focused on analysing simulation frameworks and proposed various methodologies (Stefanovic et al. 2009; Van der Zee and Van der Vorst 2005). Such authors as Li and Liu (2012) Stefanovic et al. (2009) focused on modelling complex SCs based on process approach and relation between different business processes. This method allowed them to develop a set of generic object-oriented models that allowed to model specific SC process. Grubic, Veza, and Bilic (2011) argued that focus on the object modelling approach may be constraining and preventing from devising sufficient attention on SC processes. This highlighted that the current research reflects multiple viewpoints on the aspects of simulation methodology use in theory and practise.

The focus of this study is mainly on the OM, which Chase, Jacobs, and Aquilano (2005) defined as the area of the research that is focused on the product and service design, operations and system improvements. Nevertheless, it is important to acknowledge that a definition of the research field can be difficult. Petersen et al. (2011) attributed this to the challenges and issues associated with classification of studies from numerous overlapping disciplines such as OM, general management (GM), industrial engineering (IE) or management information systems (MIS) and operations research and management science (OR/MS) to name a few. This undoubtedly applies to SC and simulation publications.

2.2.4. Simulation in supply chain

One of the requirement for the study that assumes simulation methodology is to understand whether the simulation is the most appropriate tool to be used (Kelton et al., 2010). Therefore, for the research to assume a simulation methodology the following aspects should be considered beforehand, as defined by Shannon (1975):

- There is no mathematical formulation that could solve the problem in hand.
- There is no analytical resolution method to a defined mathematical problem.
- Simulation is a suitable tool to use allowing to:
    - Perform Business Process Reengineering study before configuring the SC,
    - Test a solution before implementation in the real SC.
- Research requires to observe SC performance over time.

This research believes that modelling complex E2E-SCs adheres to all above-mentioned points. Therefore, simulation method is of an interest within this research aiming to comprehend how and why simulation is so often used in studies on complex SC systems as well as how such methodology would apply to modelling E2E-SCs. The current research requires more focus on evaluating E2E-SC simulation models and providing classification of such models, their specificities, capabilities and scope.

2.2.4.1. Supply chain management (SCM)

One important aspect to be considered is the past years' shift in modelling SC systems towards supply chain management (SCM) and towards more generic frameworks or classifications of SC studies based not solely on the quantitative aspects and modelling techniques themselves but derived from various epistemological dimensions (Soni & Kodali, 2013). Soni & Kodali (2013) reviewed the existing SCM frameworks and emphasised on the existing differences between the framework and model, although the latter often can be derived from the former.

The disjointed coexistence of mathematical models and principles of SCM proved to have an adverse impact on SC performance. This resulted in the shift of operations management (OM) philosophy towards more radical approaches and appreciation to a wider range of disciplines and their inclusive contribution to the field and knowledge development. While the focus of the research is on modelling E2E-SC using simulation, a considerable attention is given to OM, viewed as part of a value system (Porter, 2004, p. 34). OM as a core element of a value system is embedded in the organisations activities within the SC system, which when viewed from an E2E-SC perspective involves many participants that interact with other members in the same or other chains and such relationship results in superior input to the overall system (Skjoţt-Larsen et al., 2007). Once the value is created and transformed by multiple organizations within the network, where each is required to perform certain activities to create such value, then this is referred to as a value network concept (Daaboul, Castagna, Da Cunha, & Bernard, 2014).

2.2.4.2. The value network concept

The value network concept seems particularly relevant to E2E-SCs, where consideration is given not to one company but a system of companies that work together in common efforts of value creation. This can be noted in many E2E-SCs, which have changed drastically over the past years, mainly as a result of high dynamics and volatility within the market place and more so due to the sophisticated relationships between various parties, all focused towards customer satisfaction (Daaboul et al., 2014).

Key challenges and issues in managing SCs are duly attributed to the extended structure of such systems, which becomes complex to control, predominantly in the era of disturbances (Christopher, 2012). E2E-SCs have changed drastically over the past years, mainly because of high dynamics and volatility within market place and more so due to the sophisticated relationships between various parties all focused towards customer satisfaction. This is observed in many large E2E-SC like: Apple, Amazon or Unilever, whose global scope of operations has brought pressure on participating organizations and requiring a major rethink on how to manage their E2E-SC efficiently (Gartner, 2014). As a result, modelling of E2E-SCs becomes a major challenge and should be conducted with the support of the most suitable and powerful technique that allows to consider their complex nature and systemic properties.

This research extends the knowledge in this area by undertaking a systematic review of supply chain and simulation literature to provide an integrated and holistic assessment of an end-to-end SC system. The study applies a simulation methodology and considers market/demand scenarios, through production planning processes, and physical distribution. The aim is to progress the theoretical understanding of the methods used and applicability of simulation methodology in modelling an E2E-SC and further contribute to the body of knowledge within this subject of inquiry.

Through a rigorous literature review process, the research identifies potential elements that could form point of a generic framework for modelling an E2E-SC, where related policies and techniques could be captured and supported by the powerful capabilities of simulation. The existing research stream focused on various aspects and issues relative to SCs underlining the benefits of using various simulation techniques, which due to their inherent capabilities allow to:

- consider more elements or characteristics of a complex system within model/s (Chatfield et al., 2007);
- combine aspects relative to SC systems as well as SCM within model/s (Caridi, Cigolini, & De Marco, 2005);
- integrate multidisciplinary knowledge from various fields such as: computer science, engineering (Petersen, Aase, & Heiser, 2011), biology (Giannoccaro, 2011; Surana, Kumara, Greaves, & Raghavan, 2005) and behavioural sciences (Govindu & Chinnam, 2010).

A review of studies that have adopted simulation paradigm to supply chain (SC) modelling is also included to facilitate the framework development that would allow to replicate a real E2E-SC based on the devised scope, objectives, level of details and assumptions. The logic behind modelling SC using simulation is explained and justified with evidence obtained from the systematic literature review (SLR). The research aims to empower the knowledge and understanding of an E2E-SC along with identifying the key prerequisite characteristics for simulation modelling of this system.

2.3. System thinking and complexity

E2E-SCs should be regarded as complex systems and this part of the thesis is set to elaborate further on these theoretical underpinnings and highlight the contributory aspects that further enhance the knowledge on simulation modelling of such systems. By investigating the system theory in the context of the E2E-SC, the inherent system complexity properties are evaluated and discussed. A system can be defined as a set of elements that work together as a network or mechanism as well as an organized scheme/method (Oxford Dictionary, 2001). Banks, Carson and Nelson's (1996) definition emphasized on the regular interactions and interdependence of such elements, which ultimately form a distinguishable entity from its environment (Morin, 1977).

This implies that elements or parts of a system, for instance a set of suppliers, manufacturers, distributors and customers forming SC system, interact between each other not in absolute terms but in a relative sense. Normally, each element (i.e. suppliers) can be treated as a fundamental building block of a SC system or if viewed from another perspective, the same element can be decomposed into smaller parts (i.e. considering critical processes performed at suppliers' level). Interactions and relations between suppliers, manufacturers, distributors and customers instigate modifications in the SC system behaviour compared to when those elements are not a part of the system.

Viewing this more generally, Morin (1992) appreciated that the paradigmatic view of the system can be multidimensional. This is attributed to the existing varying levels of confluence between the two important ontological derivatives: (1) that a system is a physical construct based on the fundamentals of realism, where the perception of the observer depicts the system description, or (2) a system is a perception of the ideal, heuristic and pragmatic model in nature designed with the aim to evaluate, improve, control or just model a phenomenon. The author further deliberated on the difference between system structure and system organization, where the former is derived from simplicity and reductionism of the system to the structural whole (all elements/parts), also referred to as holism.

On the other hand, system organization or herein referred to systemic organizational (SO) considers the knowledge on elements/parts as well as a whole of the system beyond its structure, which takes an account of the recursive influence of the emergent phenomena created by such structure. This implies that system elements can evolve over time leading to the changes within the SO and interactions between parts and systems. Understanding the complexity of these interactions whether related to the system structure or SO is fundamental to research as well as for rationalization and knowledge development about systems themselves in addition to characteristics of its organizational interactions.

SC systems have been studied from various perspectives relative to the system theory for example to cogitate on:

- The holistic view of the SC system structure simplified for example in Ertem, Buyurgan, & Rossetti (2010) to procurement process of particular product within entire SC.
- The emerging nature of the system organization where SCs have been studied using complex adaptive system tools and techniques to better understand the complexity of SC system and how it occurs (Surana, Kumara, Greaves & Raghavan, 2005) or emergent architecture of system levels (Shang, Li, & Tadikamalla, 2004).
- The hierarchical nature of the system organization where system is regarded as a set of sub-systems that form complex interactions, where the system outperforms the sum of its parts (Pundoor and Herrmann, 2006) or hierarchical linkages of the SC system elements modelled using Petri nets to detect conflicts between entities/parts (Blackhurst, Wu, & Craighead, 2008).

- Entropy methodology that compares the different types/levels of information sharing approaches in the SC, where the organization produces entropy due to the uncertainty of information that lead to system degradation and on the other hand with the help of auto-corrective information sharing mechanisms regeneration of system (negentropy) occurs (Martinez-Olvera, 2008).

All these discuss various perspectives of system theory in line with the researchers' perception that SCs should be regarded as complex systems. These compel the current study to similarly ascertain the complexity factors. Consideration is given to the system theory principles from the paradigm level, observing a system as a simplified structure or as an emerging organization, through SC system phenomenal level, up to the level of principal explanations in order to understand the source of complexities (Morin, 1992) and considering the impact that complexity has on the simulation modelling efforts.

The challenge in modelling SCs as systems emanates not only from SC dynamics but also from the complexities that derive from structural and operational levels. These exist within the organizational aspects of such systems (Temponi, Bryant and Fernandez, 2009), therefore requiring a clear and comprehensive framework that could serve as a blueprint and provide focus while developing SC oriented simulation models. All in all, the intelligence of complexity, enhances research efforts by allowing to explore the field of possibilities. Hence in relation to modelling E2E-SC systems, the aim is to overcome these restricting conditions of what's probable and to continue to innovate and revolutionise with more sustainable solutions.

2.4. Literature survey

A literature survey of the specifically selected journals has been conducted as a method of disseminating the existing research. This approach that applies SLR strategy provides rigour and builds upon the existing work within the area. It does not, however lack criticism therefore the applicability and the importance of selected approach is presented henceforth.

2.4.1. SLR approach

SLR strategy initiated in medical sciences as a rigorous approach to evaluate medical treatments. Notwithstanding the growing popularity and the importance of this approach in the past decade in various disciplines including SC and management fields, to the best of the researcher’s knowledge there are none in the field of modelling an E2E-SC system using simulation. Simulation is a well-recognized methodology to study SCs and complex issues within these systems (Albino, Carbonara, & Giannoccaro, 2007; Barlas & Gunduz, 2011). The existing reviews in the field of SC tend to evaluate a particular simulation methodology as in Stiel (2014) focusing on the defined context and investigating Discrete Event Simulation in research on environmental sustainability, or in Santa-Eulalia, Halladjian, D'Amours, and Frayret (2011) reviewing extant methodological frameworks in Agent Based Simulation modelling. Previous literature reviews considered multiple aspects relative to simulation in supply chain. Some authors focused on wider domain of operation management and applications of simulation within the field (Shafer and Smunt, 2004; Smith, 2003; Baines and Harrison, 1999).

However, this research could not identify any previous reviews that systematically studied literature about modelling complex E2E-SC using simulation. The challenge with applying SLR methodology to studies on modelling E2E-SC systems using simulation is compelled by the wide-range of heterogeneous studies within the field. The existing research stream in the field of E2E-SC and simulation can return a wide range of literature, hence to select the relevant studies for further examination, the focus needs to be devised to access parallel research ideologies, values and quality in judgement to become more rigorous and contribute to an evidence-based body of knowledge (Rousseau, Manning, & Denyer, 2008). This is central to academia as well as industry practitioners as the model implementation process can have adverse financial consequences and implication for firms.

Exclusively, this becomes a significant element for any research that discusses matters within an E2E-SC system, which could be defined as a multi-dimensional structure that works together as a network or mechanism towards realising definite aims or tasks (Gershenson, 2013). Considering the complexity component, which is an exemplary attribute of such a system, the constituent elements within and interactions between them can only be controlled if operations management (OM) processes as well as operations research and management science (OR/MS) techniques are well understood. These are frequently supported by powerful capabilities of simulation in consequence enhancing the heterogeneity of studies in this field.

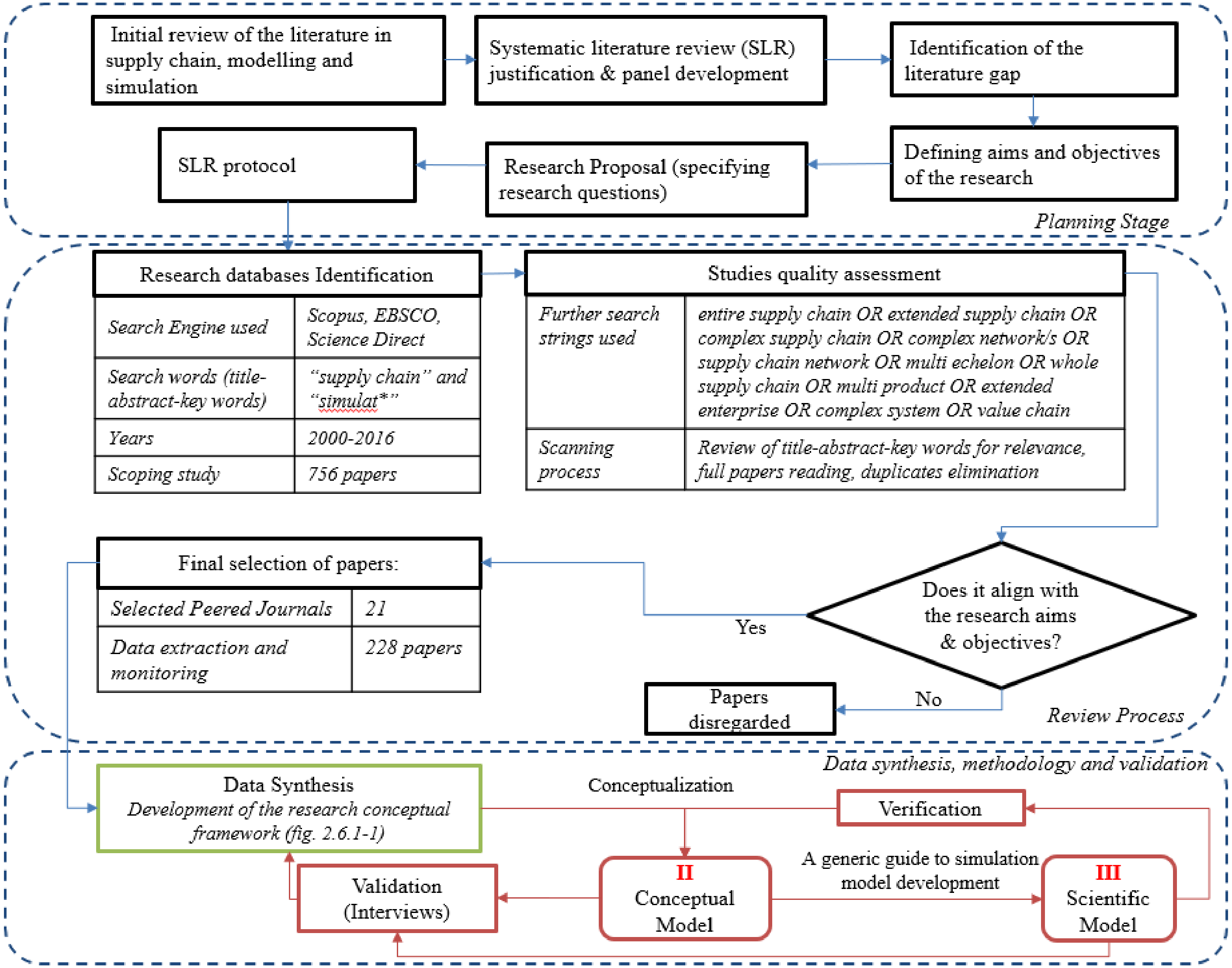
OM studies often span across various disciplines like general management (GM), industrial engineering (IE) or management information systems (MIS) hence the pertinence of SLR, which brings clarity to the subject of inquiry within a research and enhances the credibility of the literature review process. This facilitates the replication of the research and further extends the findings. Due to limited studies that are dedicated on identifying and analysing existing publications within the modelling of an E2E-SC from a product and/or process view, the approach chosen for this research was to conduct a systematic literature review. The SLR process elements are further discussed in the section 2.4.2.

2.4.2. Study selection protocol

A SLR methodology has been successfully applied in the simulation studies within life sciences, where the quality of the literature review process and the synthesis of the research require transparency and rigour (Tranfield, Denyer, & Smart, 2003). The systematic approach to literature review involves evaluating and interpreting existing work surrounding a research question, area of interest or phenomena under investigation within defined research boundaries (Ashby, Leat, & Hudson-Smith, 2012; Hohenstein, Feisel, Hartmann, & Giunipero, 2015; Olhager et al., 2015; Pashaei & Olhager, 2015; Rousseau et al., 2008). However, this seems to be of diminutive scientific value unless if concluded in accordance with a predefined strategy which requires systematic identification, analysis and evaluation of selected studies (Ashby et al., 2012; Kitchenham et al., 2009). This implies that the inquiry needs to explicitly specify the inclusion and exclusion criterion of studies that fall within the scope of the SLR (Centre for Review & Dissemination, 2001; Tranfield et al., 2003; Kitchenham et al., 2009).

SLR strategy infers transparent process where selection of studies is grounded not only on the predefined strategy, but also in line with quality assessments to allow analysis, evaluation and synthesis of results and achieving consensus about matters relative to subject of inquiry (Saunders et al., 2015). This provides an arena for further discussion on aspects that are known and unknown regarding the research, subsequently consenting to join the debate within the subject.

Figure 2.4.2-1 Systematic Literature Review Process



Source: Adapted from Khan, Dinnes, Kleijnen (2001) and Kitchenam (2004)

Figure 2.4.2-1 highlights the SLR process and how this approach is linked to the development of the conceptual framework, scientific/simulation model and research validation and verification. In line with SLR principles, the initial review of the literature highlighted the need for the SLR in the field of modelling E2E-SC systems using simulation due to the gap in literature relative to this subject of injury. The SLR planning stage included formation of aim, objectives and definition of the research questions to guide the researcher. These were discussed with the research supervisory panel to enable next stage (review process) in the SLR approach. Subsequently, the profound explanation of all assumptions relative to review process i.e. study selection, quality assessment is presented below to provide better understanding of the literature that best suits the research purpose.

An initial review of existing literature on SC management and SC modelling revealed that companies incessantly appraise their strategies with the objective of streamlining processes and procedures (Caridi, Perego & Tumino, 2013). Limited studies incorporate simulation modelling methodology within their inquiries on extended SCs and within these the generic principles to facilitate the development of such models is indistinct. In addressing this gap, a SLR strategy adopted a step-by step approach as highlighted in Figure 2.4.2-1 and following similar approach found in Hohenstein et al. (2015), Pashaei & Olhager (2015), Ashby et al. (2012), Colicchia & Strozzi (2012), Pilbeam et al. (2012), Tranfield et al. (2003) and Reviews and Dissemination (2001). Table 2.4.2-1 presents further details on the SLR approach steps relative to this research.

Table 2.4.2-1 SLR Framework

Phases	Steps	Actions
Planning	Justification for SLR	No SLR on this subject area
	Research Proposal	Research proposal discussed between the researchers Research questions defined
Conducting Review	Research Identification	Aims and objectives of the study discussed by researchers and search process defined Scoping study: 28 journals, 756 papers
	Studies quality assessment	Peer-reviewed publications Manual evaluation of the selected studies for relevance
	Final Selection of Studies	Time Span: 2000-2016 Search Engine used: Scopus, Business Source Complete (EBSCO), Science Direct Search in: title-abstract-key words Additional search strings (Figure 2.4.1-1) Selected studies: 21 journals, 228 papers
	Data extraction and monitoring	Using computer assisted tools for extracting to Excel (xlm file) and EndNote (ris file)
	Data Synthesis	Descriptive and thematic analysis
Reporting	Reporting	Review Findings

The overall perspective deliberated within this study vis-à-vis modelling of an E2E-SC using simulation mainly encompasses commonly used elements, processes and the incorporation of system characteristics. The SLR seeks to further expound on these aspects and is guided by the research questions presented in Section 1.3.

The initial steps of the second phase of the review highlighted in Figure 2.4.2-1 in the middle box called "Review Process", focused on searching for the relevant literature by applying a well-established key words/search strings: "supply chain" AND "Simulat*" (Shafer & Smunt, 2004). This resulted in a large number of studies when searched in the Scopus, EBSCO or Science Direct database with no time limit and no search restriction to any field (All Fields-considered). For example, Scopus returned 51967 publications based on search performed on the 30th of August 2017. Therefore, to provide more focus to the research, a rigorous approach to papers selection and a range of quality assessment activities were undertaken starting with scoping study (Pilbeam et al., 2012).

In the scoping study, the initial selection criterion was to consider two distinct aspects of an E2E-SC grounded upon the concept of supply chain and operations management and referring to:

- The cumulative efforts of multiple organisations directed towards product or service delivery to the end user/customer;
- The entire chain of processes/ activities undertaken to deliver the product/ service to the final user/customer (Handfield, 2011).

This was accomplished by focusing on a selected number of high rank journals within the field, and particularly work and journal selection in Shafer and Smunt (2004) was considered, that focused on simulation studies within the OM field. Shafer and Smunt (2004) investigated empirical simulation studies in OM, whereby the efforts of this research are focused on building the knowledge surrounding simulation methodologies within the context of E2E-SC.

With the aim to address the research questions and enhance this study, a further seven journals were added to Shafer and Smunt's list to integrate elements from the field of SC and simulation modelling resulting in total of 28 journals. Although the number of journals selected in the process of identification of relevant papers was 28, this number was reduced to 21 through the process of inclusion, exclusion and quality assessment. Similar approach was observed in Ashby et al. (2012) were the authors added further journals, which were not in the scope, but were considered relevant due to the interdisciplinary nature of the subject of inquiry. The list of initially selected journals is presented in the Table 2.4.2-2 (added journal are in red italicized text). The search was managed with the help of three databases, which were previously used for SLRs; Scopus, Science Direct, Business Source Complete also known as EBSCO (Durach et al., 2015; Hohenstein et al., 2015; Ntabe et al., 2015; Pashaei and Olhager, 2015).

The next step within the scoping study was to identify all peer reviewed articles published between the years 2000 to 2016 in the selected journals from the Table 2.4.2-2. This timeframe was selected to continue the work of Shafer and Smunt (2004) whose investigation considered literature until 2000.

A keyword search was employed using the search string “supply chain” and wildcard characters to search for variations of the word within simulation (search string: “simulat*”) to search for literature in the 28 selected journals. The choice of articles was based on the appearance of the search strings within the title, abstract, or key words of a paper. The use of inverted commas allowed to locate documents with both words adjacent to each other (Scopus, 2013). This resulted in an initial selection of 756 peer-reviewed journal papers covering a period of 16 years.

During a profound manual review of the selected literature, it was noted that some articles were not included in the Scopus results and were manually added to the study sample after careful checks within each of the journals publisher (Appendix 1 and 2 highlight details of a literature selection and journals classification). These were then crosschecked individually using the same keyword search strategy to ensure that the sample consisted of all relevant studies. Under the SLR strategy, the pre-selected set of journals and the use of multiple search engines as well as the individual journal publishers has been considered as a sufficiently reliable quality assessment for ensuring that the relevant literature has been selected.

Table 2.4.2-2 List of journals surveyed and number of papers fulfilling scoping criteria (Year covered 2000-2016)

No.	Journal Title	Abbr.	Research Domain	"supply chain" AND "simulat*"	Selected Studies
1	International Journal of Production Research	IJPR	OM	170	54
2	International Journal of Production Economics	IJPE	OM	148	44
3	European Journal of Operational Research	EJOR	OR/MS	77	25
4	Computers and Industrial Engineering	CIE	IE/ENG	61	25
5	*International Journal of Simulation and Process Modelling*	IJSPM	SPM	44	8
6	*International Journal of Physical Distribution and Logistics Management*	IJPDLM		23	6
7	Journal of Operational Research Society	JORS	OR/MS	22	8
8	*International Journal of Simulation Modelling*	IJSIMM	CS	22	6
9	Computers and Operations Research	COR	OR/MS	20	7
10	*Simulation Modelling Practice and Theory*	SMPT	SSM	20	12
11	Productions and Operations Management	POM	OM	16	5
12	Omega	OME	OR/MS	15	4
13	*Supply Chain Management: An International*	SCM:IJ	OR/MS	15	0
14	Decision Sciences	DS	OR/MS	12	1
15	IIE Transactions	IIE	IE/ENG	12	0
16	Interfaces	INFCS	OR/MS	12	5
17	*Annals of Operations Research*	AOR	OR	11	2
18	Journal of Operations Management	JOM	OM	10	5
19	*Journal of Simulation*	JOS	OR/MS	10	1
20	International Journal of Operations and Productions Management	IJOPM	OM	8	3
21	Operations Research	OR	OR/MS	8	2
22	IEEE Transactions on Engineering Management	IEEE-TEM	IE/ENG	7	2
23	*International Journal of Modelling and Simulation*	IJMS	CS/ENG/M	6	3
24	Management Science	MS	OR/MS	3	0
25	Naval Research Logistics	NRL	OR/MS	3	0
26	Journal of Supply Chain Management	JSCM		1	0
27	Harvard Business review	HBR	GM	0	0
28	Production and Inventory Management Journal	PIM		0	0
	**** Total number of papers selected via scoping study.***			756*	228

*****In red italics journals added by this research.***

A further search strings were applied to ensure that the relevant articles for further synthesis and analysis were selected. A review of the title, abstract and key words was then conducted selecting papers adhering to the following search criteria: *entire supply chain OR extended supply chain OR complex supply chain OR complex network/s OR supply chain network OR multi echelon OR whole supply chain OR multi product OR extended enterprise OR complex system OR value chain*.

A final number of 228 journal papers from 21 journals were selected for evaluation as a result of rigorous and systematic literature search process. Papers from 7 journals were excluded narrowing down the number of journals from 28 to 21. All selected articles were extracted to Microsoft Excel as well as Reuters Bibliographic Software- End Note and were hereafter classified into thematic and methodological categories. As a starting point, a thematic classification of Shafer and Smunt (2004) was considered, however the rapid change in the field brought upon new categories. Likewise, simulation methodologies were identified and further analysed considering model elements, scope and characteristics.

The selected articles were classified thematically into various groups and categories that took into consideration aspects such as: simulation model elements and scope, industry type, nature of data, as well as the type of simulation used for analysis. This process provided a detailed understanding of the trends and themes developed by academics and practitioners over the preceding seventeen years in relation to E2E-SC system modelling using simulation.

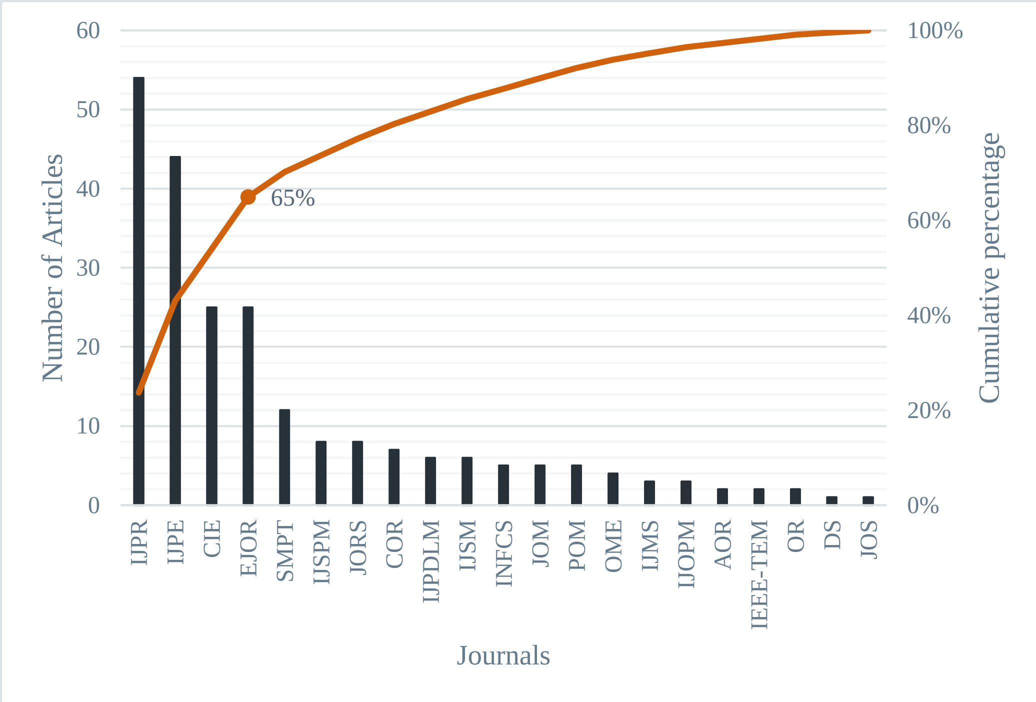
2.5. Review findings

This section provides an overview of the SLR findings and presents the classified themes and categories that embrace the system thinking and complexity theory, with the view of underlining the relevance and application of complexity elements into a generic modelling framework.

2.5.1. Journals

This section provides an informed overview of the distribution of the selected papers by journal, thematic categories identified and most often used simulation modelling techniques. The review outlined that more than majority of selected studies had been published in four journals: *International Journal of Production Research (IJPR), International Journal of Production Economics (IJPE), Computers and Industrial Engineering* (CIE) as well as *European Journal of Operational Research (EJOR)* (Figure 2.5.1-1). The amber line in Figure 2.5.1-1 highlights a cumulative percentage of the top papers in top journals, showing that 65% of papers were published in the four journals mentioned above.

Figure 2.5.1-1 Distribution of selected E2E-SC Studies



Source: Based on the selected papers for SLR

This can be indicative that the most often discussed aspects should consider production and manufacturing research, as per journals' aims and scope (Taylor and Francis 2013, Elsevier 2014). The review was not able to identify any publications that adhered to the main selection criteria from the following seven journals: HBR, IEE, MS, NRL, JSCM, PIM and SCM. The journal papers that were selected for the review covered the following research domains and span from OM, OR/MS through Industrial Engineering/Engineering (IE/E), Computer Science (CS), Mathematics (M) to Simulation Process Modelling (SPM) and System Simulation and Modelling (SSM).

2.5.2. Thematic categories

The interpretation provided by Shafer and Smunt (2004) presented that within the empirical simulation studies in OM, scheduling was the matter of inquiry that was the most recurrent. This was followed by the capacity planning and the cellular manufacturing categories. Although, this paper considered thematic categories highlighted by Shafer and Smunt (2004), the study identified a set of new categories, following the classification criteria and SLR protocol to capture relevant literature in the field of E2E-SC system simulation modelling. The categories presented in Table 2.5.2-1 (in bold) correspond to those named by Shafer and Smunt (2004) while the rest (in italics) be the evaluation of this research.

The examination of 228 studies revealed that supply chain management (SCM) and inventory management are the most frequent subjects of inquiry, also categories named by Shafer and Smunt (2004). The current paper also established 22 supplementary themes that have not been featured within the classification presented by Shafer and Smunt (2004). The highest number of studies focused on: SC dynamics (Bullwhip Effect), SC performance, Information sharing /uncertainty, SC collaboration (co-ordination), SC network and SC design as well as transport and logistics (Table 2.5.2-1). The rationale for extending the selection of these categories was based on the influence SCM doctrine has on modelling the SCs. Many of the themes have proved to have a noteworthy impact on the SC behaviour and were considered to enrich the knowledge on SC systems and its properties (i.e. the study of Cannella, Ciancimino and Marquez (2008) investigated the impact of SC dynamics on inventory management and on the entire system performance).

Table 2.5.2-1 Classification of selected papers based on common themes and simulation modelling techniques

Category	No. of papers	ABS	DES	SD	MC/QS	AM/SS	Hbrd
SCM	59	✓	✓	✓	✓	✓	✓
Inventory management	46	✓	✓		✓	✓	✓
Production Planning & Inventory Control	12		✓	✓		✓	✓
Strategy	13	✓	✓	✓		✓	✓
Production Planning & Scheduling	11		✓	✓	✓	✓	✓
Manufacturing	8	✓		✓		✓	✓
Capacity Planning/Management	6		✓	✓	✓	✓	
Forecasting	4		✓	✓			
Purchasing	4	✓					
Resource Allocation	1					✓	
SC Process Design	1					✓	
SC Dynamics (Bullwhip)	43	✓	✓	✓	✓	✓	✓
SC Performance	26	✓	✓	✓	✓	✓	✓
Information Sharing/ Uncertainty	19	✓	✓	✓	✓	✓	
SC Network/s	17		✓	✓	✓	✓	✓
Collaboration (Co-ordination)	15	✓	✓		✓	✓	✓
SC Design/ Redesign	12		✓	✓		✓	
Production-Distribution	11	✓		✓		✓	✓
Transport & Logistics	9		✓			✓	✓
Closed Loop SC	7			✓		✓	
Process Management	7	✓	✓			✓	✓
Reverse SC (Logistics)	7			✓	✓	✓	
Decision Support Framework (DSF)	6		✓	✓			✓
Order Fulfilment	5		✓			✓	
Outsourcing	4				✓	✓	
SC Configuration	4		✓			✓	
Mass Customisation	4	✓	✓			✓	
New Product Development (NPDev)	3					✓	✓
SC Integration/Synchronisation	3		✓			✓	
New Product Diffusion (NPDiff)	2	✓		✓			
SC Planning & Control	2	✓				✓	
System Re-engineering	2		✓				
Manpower Planning	1			✓			
Note: While 228 articles were reviewed most of the articles were placed in multiple categories							

All studies revised within SLR selection extend across multiple categories, therefore for clarity purposes the classification in Table 2.5.2-1 emphasizes upon the key aspects discussed within each individual paper to provide a generic understanding of trends in modelling an E2E-SC system.

Simulation has been expressly used within research on topics that consider the interface between various cross-disciplinary areas as parallel to complex SC systems. This directed the study to consider the complex dynamics that impact an E2E-SC system relative to simulation modelling and system theory.

2.5.3. Simulation modelling techniques

Pegden, Shannon, & Sadowski (1995) definition of simulation reflects on powerful tools used to study complex systems, hence, the most frequently used technique in modelling SCs (Carvalho, Barroso, MacHado, Azevedo, & Cruz-Machado, 2012; Bagdasaryn, 2011; Persson, 2011; Merkuryev, Merkuryeva, Bikovska, Hatem, & Desmet, 2009; Persson & Araldi, 2009; Chatfield et al., 2007; Venkateswaran & Son, 2004; Holweg & Bicheno, 2002; Petrovic, 2001;). Simulation provides a robust tool to help decision makers as well as the aptitude to address complex issues caused by uncertainty within supply and demand, conflicting objectives, ambiguity of information coupled with the numerous variables and constraints at different levels (Abo-Hamad and Arisha, 2011). Simulation can be defined as “a broad collection of methods and applications that mimic the behaviour of a real system” (Kelton, 2004, p.3) usually supported by computer-based tools; General Software, Specialist Packages or Simulation Languages.

Pegden, Shannon, and Sadowski (1995) cogitate on a model and a system as fundamental elements of simulation modelling, which according to Altiok and Melamed’s (2007) inference on the latter, as a well-known paradigm that offers a simplified representation of a complex system. The experimentation on such systems is typically guided by defined aims and objectives and ultimately presents descriptive results of the system behaviour and structure over time.

A classification of simulation modelling techniques is presented alongside the identified categories to highlight a wide range of simulation modelling opportunities related to modelling of a process or issue within an E2E-SC (Table 2.5.3-1). Depending on the technique specified these were grouped as follow:

- Agent based simulation (ABS) - an approach to modelling systems as autonomous and intelligent entities often incorporating existing decision modelling techniques (i.e., optimisation or heuristics) and knowledge from diverse disciplines (game theory, biology, computational intelligence) (Govindu and Chinnam, 2010); includes agent-based models;
- Discrete-event simulation (DES) - an approach that models the system as activities and queues that change at discrete points of time (Tako and Robinson, 2009);
- System dynamics (SD) - an approach that studies the dynamic behaviour of systems that incorporates a feedback concept into the system model and uses visual representation which is then translated into mathematical formulas by computer software (Poles, 2013);
- Monte Carlo/Queuing simulation (MCQS) - a modelling approach that simulates a system by varying its parameters according to pre-determined distributions to obtain statistical interferences (Pezeshki et al., 2013);
- Analytical Model/ Simulation Study (AM/SS) - a modelling approach that is based on developing complex analytical technique supported by simulation;

- Hybrid simulation (Hbrd) - a modelling approach based on developing a platform or architecture that combines two or more modelling techniques (Venkateswaran and Son, 2005, 2009).

These modelling techniques have been used to discuss an aspect/s within selected thematic categories as shown in Table 2.5.2-1 above. The review presents the most significant modelling approaches starting from purely simulation techniques such as ABS, DES and SD through MC/QS and closes the classification with mixed or combined modelling approaches, where simulation has been used alongside other modelling technique/s.

The classification presented above could be extended to consider object-oriented modelling or parallel and distributed simulation, however, it was observed that these modelling approaches were often derived from one of the categories presented above. Therefore, they were considered as a characteristic or feature of one of the already presented techniques.

The above identified simulation modelling techniques were further summarised in Table 2.5.3-1 below. The main research findings are described for each of the modelling techniques within selected studies as well as the potential challenges and issues in applying such a methodology to modelling E2E-SC systems.

Table 2.5.3-1 Summary of simulation modelling techniques

Modelling Method	Summary of research findings / challenges and issues	Authors
Agent Based Simulation (ABS)	Multi-agent simulation (MAS) approach allows modelling SC as a network or a system of intelligent business units with hierarchical and autonomous characteristics. ABS method used to model SCs behaviour capturing non-linear decisions making and impact of various operational and strategic policies. Agents' techniques allow incorporating knowledge from other disciplines i.e. social science aspects and incorporating them into the model. Multiple, complex and interacting components of an E2E-SC system studied as complex adaptive system; agent software engineering approach is capable to capture emergent behaviour of agents in the complex system. Considers interactions between decision maker and quantitative model equations by creating artificial intelligence developed as a computer program. Intelligent agent technology permits to model vertical and horizontal processes within SC structures, where multi-agents replicate SC partners, who exchange information, collaborate, negotiate or make operational or strategic decisions. Agents possess normative characteristics allowing for regulation of SC system behaviour during simulation run. Requires skilled programmer to develop agents and apply changes as models often developed to handle specific problem or context. Research work focused on focal company or on solving/addressing particular problem. Lack of studies/models representing E2E-SC. ABS or MAS models may be difficult to validate and analysis of results may be difficult to explain.	Albino et al. (2007); Allwood and Lee (2005); Amini et al. (2012); Caridi et al. (2005); Chong et al. (2014); Dai, Lin and Long (2014); Datta and Christopher (2011); Dominguez, Cannella and Framinan (2014);; Dominguez, Framinan and Cannella (2014); Ferreira and Borenstein (2011); Govindu and Chinnam (2010); Kaihara (2001); Labarthe et al. (2007); Lau et al. (2004); Li et al. (2010); Li and Sheng (2011); Li, Sheng, and Liu (2010); Long (2014); Mizgier et al. (2012); Zhang et al. (2006)
Discrete Event Simulation (DES)	DES used to examine different aspects relative to E2E-SC systems, for instance SC configurations considering given set of operational parameters, in terms of number of SC levels, echelons, policies and linkages Design of Experiment (DoE) is often used to evaluate various simulation scenarios SC boundaries are set depending on the criticality of the processes and flow of materials and information DES often used for modelling operational aspects of SCs; incorporating OM/MS and OR techniques within simulation model, for example integrating Excel spreadsheet with Arena simulation software through Visual Basic for Applications (VBA). Uses hierarchical approach to modelling, which provides a ground for varying level of simulation details i.e. relative to SC processes. Optimization is featured in Arena simulation software allowing for quick change of input parameters and search for the best combination of those parameters so as to achieve optimal output performance through set of simulation runs. This allows for greater level of experimentation.	Beamon and Chen (2001); Bottani and Montanari (2010); Byrne and Heavey (2006); Carvalho et al. (2012); Cigolini et al. (2014); Dev et al. (2014); Costantino, Gravio, Shaban, and Tronci (2015); Elia and Gnoni (2015); Fridgen, Stepanek, and Wolf (2015); Ganeshan et al. (2001); Giannoccaro and Pontrandolfo (2002); Gnoni, Iavagnilio, Mossa, Mummolo, and Di Leva (2003); Gumrukcu, Rossetti, and Buyurgan (2008); Gupta et al. (2002); Hung, Kucherenko, Samsatli, and Shah (2004); Hwarng et al. (2005); Jammernegg and Reiner (2007); Kleijnen and Smits (2003); Lin et al. (2000); Longo and Mirabelli (2008); Lyu et al. (2010); Manuj, Mentzer, and Bowers (2009);

	Existing Simulation Software Packages like eM-Plant, Anylogic, Arena etc. can be further advanced through programming efforts to incorporate analytical relations to simulation inputs and outputs. Simulation usually limited in scope; considering one or limited number of products and processes; focusing on deterministic assumptions, focusing on objectives of focal company. Further work required to allow integration of existing information technology developments (i.e. EDI) into simulation model.	Martínez-Olvera (2008); Pan, Nigrelli, Ballot, Sarraj, and Yang (2015); Persson (2011); Persson and Araldi (2009); Fredrik Persson, Olhager, Tekniska, Linköpings, and Institutionen för (2002); Pundoor and Herrmann (2007); Rao, Scheller-Wolf, and Tayur (2000); Xiang and Rossetti, (2014); Sari (2007); Schmitt and Singh (2012); Schwede et al. (2009); Stefanovic et al. (2009); Tannock, Cao, Farr, and Byrne (2007); Thron, Nagy, and Wassan (2006); Vamanan, Wang, Batta, and Szczerba (2004); Van Der Vorst et al. (2000); Van Der Vorst et al. (2009); Venkateswaran and Son (2004); Verma (2006); Wadhwa, Saxena, and Chan (2008); Wikner, Naim, and Rudberg (2007); Xudong, Kumar, and Tan (2008);; Zhang and Zhang (2007)
System Dynamics (SD)	SD method used to simulate dynamic movements in SCs. This modelling technique is derived from control theory and causal loop diagrams, which allow defining SC structure and its flows as well as feedback loops. The method is based on mathematical formulation consisting of system of differential equations, which is solved via simulation. Focused on system thinking and is not data driven. This modelling method is primarily used to study aspects relative to Bullwhip Effects in the SCs considering the impacts of various SCM techniques such as products returns, remanufacturing or recycling within forward or closed loop SCs on the entire SC performance. Used to study hybrid business models i.e. considering combination of two different strategies make-to-order (MTO) and make-to-stock (MTS). Control parameters used within the model which affect the forward and feedback loops particularly when stochastic parameters are considered. Often used to model dynamics in automobile SCs. Powerful simulation packages such as Vensim, iThink, Powersim or Stella are used to enhance model functionality, capacity and performance. Although, the advancement in these tools capabilities allow for optimisation and are geared more towards business managers, there is still lack of E2E-SC system models and guidance on how to develop such models.	Anderson et al. (2000); Barlas and Gunduz (2011); Croson and Donohue (2003); Das and Dutta (2013); Georgiadis and Athanasiou (2013); Helo (2000); Higuchi and Troutt (2004); Holweg and Bicheno (2002); Holweg et al. (2005); Hussain and Drake (2011); Kleijnen and Smits (2003); Marquez, Bianchi, and Gupta (2004); Martínez-Olvera (2009); Mendoza, Mula and Campuzano_Bolarin (2014); Moreno, Mula, and Campuzano-Bolarin (2015); Özbayrak et al. (2007); Pierreval, Bruniaux, and Caux (2007); Poles (2013); Rabelo, Helal, Lertpattarapong, Moraga, and Sarmiento (2008); Spengler and Schröter (2003); Springer and Kim (2010); Vlachos, Georgiadis, and Iakovou (2007); Wangphanich, Kara, and Kayis (2010)
Analytical Model/ Simulation Study (AM/SS)	Simulation often used to facilitate development of analytical models that combine multiple mathematical techniques and various SCM strategies to better understand the effects of interactions amongst factors in complex E2E-SC systems, allowing to:	Acar and Atadeniz (2015); Abdel-Malek, Kullpattaranirun, and Nanthavanij (2005); Ali and Boylan (2011); Banerjee, Banerjee, Burton, and Bistline (2001); Bayraktar, Lenny Koh, Gunasekaran, Sari, and Tatoglu (2008); Ben-

	• Perform multiple scenarios analysis so as to capture different SC strategies, policies, configurations, designs or uncertain parameters. • Search for optimal or near optimal solutions in combinatorial optimisation of large-scale problems with stochastic parameters. • Gain further insides into SC designs by incorporating complex OR techniques into the model scope so more echelons, layers, products, processes etc. can be considered. Results of analytic models can be incorporated into a simulation model to study SC related problems over a period of time (also to consider statistical distribution in the place of various stochastic parameters). Simulation aids experimentation on complex analytical models so the knowledge from various cross-disciplinary fields such as natural sciences, physics or biology can be incorporated and the further impact on E2E-SC system performance can be analysed and evaluated. Models are usually derived from well-established and known mathematical formulation relative to modelling SC systems such as inventory management methods (particularly surrounding SC dynamics and bullwhip effect), production planning and control, SCM strategic decisions, production and distribution. Simulation offers an arena for manipulating parameters within complex analytical models to aid decision maker with the most suitable operational, tactical or strategic solutions or trade-offs. Analytical models and analytics can add value to holistic SCM by considering information and data, which are cross-functional, spanning multiple system levels and focusing on historic and future time dimensions. However, analytic models are limited in scope as the computational calculation tractability is too difficult when consideration is given to complex E2E-SC systems; hence simulation is often used as a facilitator. Research is required to progress the knowledge on various ways to mix or combine analytics with simulation to address more complex issues within E2E-SC systems.	Tal, Golany, and Shtern (2009); Biehl, Prater, and Realff (2007); Bottani, Montanari, Rinaldi, and Vignali (2015); Boulaksil and Fransoo (2009); Cannella, Bruccoleri, and Framinan (2016); Caggiano, Jackson, Muckstadt, and Rappold (2009); Chaharsooghi and Heydari (2010); Chebolu-Subramanian and Gaukler (2015); Chen and Huang (2006); Chiu and Huang (2003); Chern, Chen, and Huang (2014); Ciancimino, Cannella, Bruccoleri, and Framinan (2012); De Sensi, Longo, and Mirabelli (2008); Daultani, Kumar, Vaidya, and Tiwari (2015); Diabat (2014); Disney and Towill (2002a, 2002b, 2003); Dixit, Seshadrinath, and Tiwari (2016); Fleischhacker, Ninh, and Zhao (2015); Fleischmann, Van Nunen, Gräve, and Gapp (2005); Fröhling, Schwaderer, Bartusch, and Rentz (2010); Fu, Ionescu, Aghezzaf, and De Keyser (2015); Garvey, Carnovale, and Yeniyurt (2014); Gill (2009); Gong, Liu, and Lu (2015); Gomez Padilla and Mishina (2009); Govindan and Fattahi (2017); Güller, Uygun, and Noche (2015); Ho (2007); Hsu and Liu (2009); Karaman and Altiok (2009); Kull and Closs (2008); Lai, Wu, Shi, Wang, and Kong (2015); Lau, Xie, and Zhao (2008); M. Li, Wu, Zhang, and You (2015); C. Li and Liu (2012); Lin and Chen (2003); Liu and Nagurney (2011, 2013); Mahnam, Yadollahpour, Famil-Dardashti, and Hejazi (2009); Manuel, Al-Hamadi, and Qureshi (2015); Mateen, Chatterjee, and Mitra (2015); Martinez-Olvera (2010); Meijboom and Obel (2007); Meixell and Wu (2005); Merkuryev, Merkuryeva, Bikovska, Hatem, and Desmet (2009); Mohebbi and Choobineh (2005); Mousavi, Alikar, Niaki, and Bahreininejad (2015); Munoz and Dunbar (2015); Nativi and Lee (2012); Ovalle and Marquez (2003); Özdemir, Yücesan, and Herer (2006); Petrovic (2001); Poojari, Lucas, and Mitra (2008); Riddalls and Bennett (2002);

		Sagawa and Nagano (2015); Sahin and Robinson Jr (2005); Sarrafha, Rahmati, Niaki, and Zaretalab (2014); Shu and Barton (2012); Shu and Karimi (2009); Shukla, Shukla, Tiwari, and Chan (2009); Solis, Longo, Nicoletti, Caruso, and Fazzari (2014); Son and Sheu (2008); Tiacci and Saetta (2011); Tiwari, Raghavendra, Agrawal, and Goyal (2010); Truong and Azadivar (2005); Tsadikovich, Levner, Tell, and Werner (2016); Van Landeghem and Vanmaele (2002); Viswanathan, Widiarta, and Piplani (2007); Wang, Wang, and Ouyang (2015); Yadav, Mishra and Chan (2012); Yan, Robb, and Silver (2009); Yu, Kaihara, Fujii, Sun, and Yang (2015); Zeng and Xiao (2014); X. Zhang and Huang (2010); J. Zhang, Liu, Zhang, and Bai (2015); L. Zhang (2015).
Monte Carlo/ Queuing Simulation (MC/Q)	The method allows for continuous review of SCs performance. Samplings from statistical distribution are used in place of uncertain parameters. Based on analytical model or mathematical assumptions. --- Although this method allows for evaluating different control structures and/or varying level of approximation for E2E-SC systems in continuous manner, some technological advancement within this method are required. This method could be developed further to incorporate intelligent features such as learning during simulation runs, whereby through alteration of simulation parameters or simulated policies an intelligent control of inventory, production or distribution could be performed and evaluated.	Adenso-Díaz et al. (2012); Ayanso et al. (2006); Cannella et al. (2008); Cattani et al. (2011); Celik and Son (2012); Dai and Zheng (2015); Hovelaque et al. (2009); Mizgier, Wagner, and Jüttner (2015); Pezeshki et al. (2013); Sari (2008); Wu and Olson (2008)
Hybrid Simulation (Hbrd)	This category considers models that combine simulation with analytical models, other simulation methods, other research methodologies (i.e. case study) or with artificial intelligence. There is varying level of interactions between the techniques, whereby some models present sequential or combined use of two or more modelling techniques and others more sophisticated architectures, where model runs and connects between methods automatically. Attempts made to use local versus global optimisation in hybrid mixed integer linear programming model combined with simulation. --- Further work is needed to develop/enhance iterative procedures for combining simulation with various modelling techniques. Hybrid models offer scope for developing and building upon all the above presented techniques, yet need clear framework to ensure validity, tractability and replicability.	Acar et al. (2010); Ahire, Gorman, Dwiggins, and Mudry (2007); Arns, Fischer, Kemper, and Tepper (2002); Chatfield et al. (2007); Iannone, Miranda, and Riemma (2007); Lee et al. (2002); Lee and Kim (2002); Min (2009); Pathak, Dilts, and Biswas (2007; Rabelo, Eskandari, Shaalan, and Helal (2007); Reiner (2005); Shang et al. (2004); Rossetti and Thomas (2006); Roy and Arunachalam (2004); Shi, Liu, Shang, and Cui (2013); Y. J. Son and Venkateswaran (2005, 2007); Vahdani, Zandieh, and Roshanaei (2011); Venkateswaran and Son (2009); Venkateswaran and Son (2004)

The review found that within selected papers on E2E-SC system simulation modelling there were many papers, where analytical models were considered as a primary research approach and a simulation study conducted to tackle computational difficulties or to enlarge the scope of the model. Moreover, simulation has been often used within E2E-SC systems analytical models as a facilitator helping to solve otherwise difficult mathematical problems, i.e. solution to intractable mathematical calculations or as a search engine for the optimal or near optimal input/output parameters that are to be considered in the mathematical formulation (Chiu and Huang, 2003).

It has been noted that more often research combined different methodologies with simulation such as in (Rabelo et al., 2008)), where neural networks were used to build on the knowledge gained from developed SD simulation model to learn and identify the impacts as well as consequences of changes in key parameters on SC system behaviour. In that case a sequential use of simulation and artificial intelligence methods has been observed.

Parallel and distributed simulation models is another approach found in the literature that simulates system as multiple models developed on various computers but run in a co-ordinated manner often interconnected via a local or wide network (Fujimoto, 1999; Iannone et al., 2007). Such simulation models can be based on existing simulation technique as observed in Roy and Arunachalam (2004), where DES was utilised, and large-scale simulation models developed on multiple processors. This method has been considered as a part or characteristics of one of the above identified simulation modelling technique.

Research in modelling SC systems provides a wide range of detailed and often dedicated simulation models, which are difficult to replicate to other business types or SCs. There is a lack of a generic modelling framework that brings holistic yet simple to follow and understand view of an E2E-SC system to allow decision makers to adopt, change, manipulate and perform desired scenario analysis. Such framework could be used to explain exceptional facets behind the design, planning and controlling of E2E-SC systems, addressing issues relative to dynamics, volatility, risk or sustainable developments in pursuit to improve the functioning of any industry.

The research in modelling E2E-SC systems requires more simplistic yet flexible and clever models that are easy to implement and reuse. This may require a combination of knowledge from trans-disciplinary fields and cross-sections. Cattani, Jacobs, and Schoenfelder (2011) pointed out that one way to do so is by developing an approach that could use intelligent heuristics that are embedded into simulation methodology and are able to learn in time and utilize the acquired knowledge during simulation run.

To address this need, the next section looks upon the conceptual framework that has been developed to appreciate the theoretical perspective, concepts and aspects or issues relative to the research topic.

2.6. Conceptual framework

Simulation modelling of an E2E-SC system can be multi-disciplinary and cross-sectional surrounded by various ontological, epistemological and methodological assumptions. One way to enhance the clarity of the simulation modelling process is through developing a conceptual framework, inclusive of associated theoretical underpinnings, relative concepts, variables or issues (Miles and Huberman, 1994; Leshem and Trafford, 2007). The consideration, however, should be also given to the broader research design implication as the abstraction of concepts, forming a conceptual framework should inform the empirical investigation around the subject of inquiry (Rudestam and Newton, 1992).

With varying school of thoughts on what is a conceptual framework and how to conceptualise a research, the approach taken in this thesis is to follow definition provided by Miles and Huberman (1994) and Rudestam and Newton (1992). Based on the work of the above authors, the current research views a conceptual framework as an activity mapping the scope of the research and the boundaries of the area under investigation. This requires a deep examination of theoretical underpinnings, linking concepts and ideas with empirical data. The purpose of the conceptual framework is to describe an abstract phenomenon that occurs under similar condition (Rudestam & Newton, 1992).

The literature in the field of simulation modelling defines this as conceptual modelling, where the real system is abstracted to aid the modeller with the right level of assumption and information required to proceed to a computerised model (Robinson, 2014). The conceptual framework developed within this research is based on system thinking and complexity theories, which prevails in research on extended supply chain systems and their management. Furthermore, it links these two theories with computer simulation and relative scientific knowledge on OR/MS. Through examination of the current literature this research defines a set of concepts and groups them into structural, computational and systemic organisational pillars.

The relation between the conceptual framework and the research methodology is further discussed in chapters 3 and 4, where the key steps for developing a generic simulation model for an E2E-SC system is presented. The conceptual framework described an E2E-SC system phenomenon and its structural, computational and systemic organisational pillars as well as specific elements within each of them, which are incorporated in the conceptual and scientific models. The conceptual framework for this research is presented in Figure 2.6.1-1 below. A practical applicability of the conceptual framework is presented in Chapter 4 and validation of the framework in Chapter 5.

2.6.1. Key pillars of the conceptual framework

Within this research, a modelling activity is viewed from more paradigmatic perspective and the conceptual framework is a derivative of the system thinking, complexity theory and simulation methodology. Referring to the SLR strategy, it has been observed that although complexity has not been explicitly a part of the paper selection criteria, yet 26 studies exclusively incorporated complexity within the title, abstract or key words (Table 2.6.1-1).

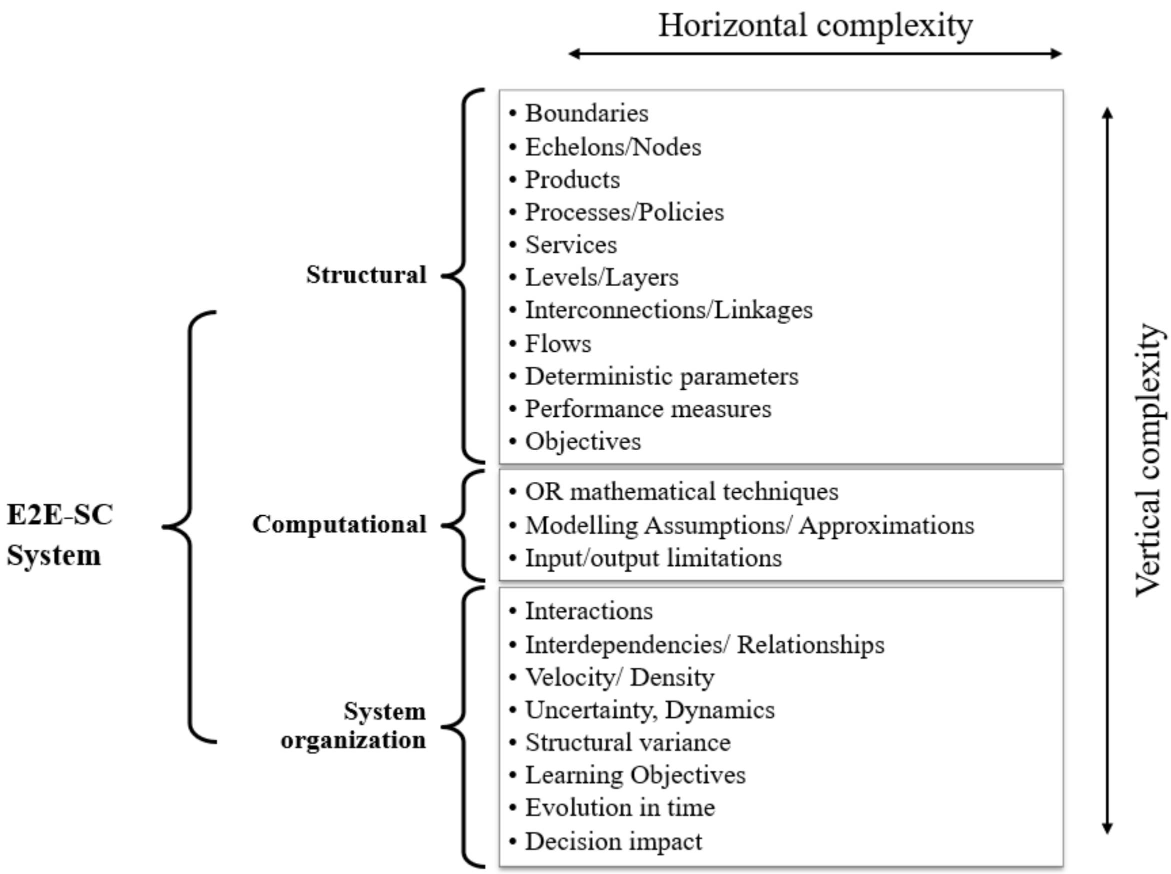


Figure 2.6.1-1 Generic framework for modelling E2E-SC system using simulation

These studies were selected for examination to elucidate potential concepts or elements that should not be abrogated while developing a conceptual framework for simulation modelling of the E2E-SC. These were viewed through paradigmatic lenses (Morin, 1991) and were classified under structural, computational and SO artefacts (Figure 2.6.1-1). Table 2.6.1-1 captures all elements from the framework in more details relative to the above-mentioned selection of 26 studies.

The structural group of concepts focused on the holistic elements of an E2E-SC, where parts and the whole of a simplified system could be recognized and represented in one model. These referred to varied structural complexity factors such as; number of echelons, players or parties within each echelon, SC layers, number of products or processes as well as system boundaries. Various aspects such as number of echelons/nodes often spanning multiple levels, with parts belonging to the same echelon, but having different characteristics, can have a considerable impact on the complexity and modelling of E2E-SCs (Hwarng et al., 2005). The number of products and flows could further amplify this together with the type and number of processes and their structure while also considering the structure of services offered (Adenso-Diaz et al., 2006; Byrne and Heavey, 2006; Liston, Byrne, Byrne, & Heavey, 2007; Min, 2009; Carvalho et al., 2012; Lehr, Thun, & Milling, 2013).

Complexity in an E2E-SC system is viewed in this research as the structural, computational and systemic organizational differentiation or variety that may exist in any E2E-SC system under consideration (Choi & Hong, 2002). This is also relevant for modelling E2E-SCs. The complexity of the model can arise from the number of sub-models used to depict the E2E-SC system structure and organization as well as the number of mathematical techniques applied to reflect operational management techniques used. In modelling an E2E-SC system, the horizontal complexity refers to the number of elements/components at the same level as presented in the conceptual framework, for instance the number of products or the number of modelling objectives.

Various elements within the framework such as number of products, policies or echelons/nodes are often spanning across multiple levels with parts belonging to the same echelon, but having different characteristics (Hwarng et al., 2005), hence requiring different mathematical (OR) techniques to depict interactions/relationships within an E2E-SC system. This can be referred to as a vertical complexity (Choi & Hong, 2002).

Likewise, modelling process would require setting clear objectives and performance measures as those would determine boundaries of the considered system, number of elements as well as links between them. These were also included under structural part of the framework.

Table 2.6.1-1 Complexity factors relative to E2E-SC and simulation modelling

No	Author	Journal	Key elements	Complexity drivers	S	C	SO
1	Abdel-Malek et al. (2005)	IJPE	Purchasing, Outsourcing, DSF	• parent company and 4 supply layers with different order arrival rates and service rates (Levels) • queuing model- Markovian assumption of sojourn times of orders in process at various levels in SC (considering SS, LT)	✓	✓	
2	Adenso-Diaz et al. (2012)	SCM	Reverse SC (Logistics), SC dynamics	• Supply network reliability evaluated by Monte Carlo simulation subject to identified design factors and their viabilities tested at two levels by multi-factorial design of experiment	✓	✓	
3	Arora and Kumar (2000)	INFCS	SC (enterprise) re-engineering	• dynamics of SC system environment that creates challenges is setting SC system model boundaries, capturing and selecting all relevant interactions between system and the environment (system, subsystem components) • challenge in categorization of system and environment variables	✓		✓
4	Ayanso et al. (2006)	EJOR	Inventory system, SCM	• LT, and demand uncertainty; cost and distribution variability in the multi-channel distribution SC	✓		
5	Byrne and Heavey (2006)	IJPE	SC Visibility (information sharing, forecasting)	• multiple product flow through multi-echelon SC, capacity constraints (network structure)	✓		
6	Carvalho et al. (2012)	CIE	SC design	• SC interconnecting links, relations (e.g. number of nodes, facilities within each node, policies, processes) • SC performance measure	✓		✓
7	Dai et al. (2014)	IJPR	SCM	• Fractal concept used to model SC at various levels and scales	✓	✓	
8	Dominguez et al. (2014)	CIE	Bullwhip Effect, SC network	• divergent SC network structure impact on the computational results versus those achieved in serial SC	✓	✓	
9	Dominguez et al. (2014)	JPR	Bullwhip Effect, SC network	• computational technique (Smoothing replenishment rule) used to improve SC performance		✓	
10	Hwarng et al. (2005)	IJPR	SC integration, SCM	• multiple levels (echelons) • oversimplified assumptions (assumed distributions rather than distributional parameters based on real data)	✓	✓	
11	Iannone et al. (2007)	SMPT	SCM, performance evaluation	• technological obstacles to integration of distributed SC simulation models across geographical locations (complex interdependencies between SC participants)		✓	✓
12	Khilwani et al. (2011)	IJPR	SC network design	• discrete event timings interactions in the model (customer arrival, manufacturing of products) • generalizability and simplifications but including all production processes (hierarchical simplification)	✓	✓	✓

No	Author	Journal	Key elements	Complexity drivers	S	C	SO
13	Li and Liu (2012)	SMPT	Order Management	• dynamic behavior because of interactions (order amplification in multi-stage SC system) • orders specification at the SC system level	✓		✓
14	Li et al. (2010)	IJPE	SCM, SC network	• evolving organizational SC structures and functions • diversity of interconnections and relations (collaboration that changes/evolves subject to various factors, changes in environment) • dynamics of the model entities	✓		✓
15	Long (2014)	IJPR	SCN	• hierarchical framework based on SCOR- structure modeling and ABS – function modeling		✓	
16	Mishra and Chan (2012)	IJPR	Manufacturing	• computational difficulty in process planning of distributed manufacturing SC		✓	
17	Mizgier et al. (2012)	IJPE	SCM, production	• SC network structure affected by interconnection channels • logistical system interconnection density • production dynamics due to number of stages, products, periods and economic environment	✓	✓	✓
18	Özbayrak et al. (2007)	SMPT	Manufacturing	• SC structure with many variables and linkages	✓		
19	Surana et al. (2005)	IJPR	SC coordination	• interactions and interdependencies between entities, processes and resources • SC structure spanning several levels, which evolves and self-organizes over time • highly structured hierarchical robust SC system prone to disturbances	✓		✓
20	Tannock et al. (2007)	IJPE	Manufacturing (SC design, performance measures)	• SC interconnections and variability in performance affected by those connections • product, process complex structure attributable to the SC type (aerospace)	✓		✓
21	Temponi et al. (2009)	EJOR	Strategy	• aggregated enterprise model that considers multiple business functions with interacting elements • various business functions modelled as sub-models and described with differential equations		✓	✓
22	Venkateswaran and Son (2004)	IJPR	SC modelling	• level of model details and approximations used to model the SC	✓	✓	
23	Vlachos et al. (2007)	COR	Capacity Planning, Reverse SC	• variability in return flows impact on the capacity planning for remanufacturing process	✓		
24	Wikner et al. (2007)	IEEE-TEM	Mass customization, manufacturing,	• dynamics (uncertainty) of the environment (customer demand)			✓
25	Wu et al. (2007)	IJPE	SCM	• SC structure defined by the expected amount of information (entropy) to describe the state of planned system and operational complexity determined by amount of information required to describe system deviation from the plan	✓	✓	✓
26	Zeng and Xiao (2014)	IJPR	SCN	• modeling used to address cascading failure spread in cluster SCN (layers)	✓		
	S-structural complexity, C- computational complexity, SO- Systemic organizational complexity, LT-lead time, SS- safety stock, SP-stock out probability, MTO- make to order						

The second group emerged as concepts relative to simulation modelling and the inherent computational complexity. For instance, in Abdel-Malek et al. (2005), a structural dimension of the multi-level SC was modelled as a series of tandem queues to account stochastic parameters and provide relevant assumption.

Multiple computational factors need to be considered when modelling E2E-SC system. These are often used to allow for greater representation of any E2E-SC system, particularly because modelling more often involves multi-disciplinary aspects relative to any of the elements identified under SLR themes. The study isolates the complexity factors as embedded within multi-dimensional aspects that derive from three categories: Structural, Computational and a further complexity element being linked with the SO aspects. These factors are often interrelated hence present a distinctive approach towards modelling issues relative to complex SCs. This is corroborated in various studies: for instance, Arns et al. (2002) provided a hybrid model that adopted a hierarchical modelling approach to reduce the computational complexity, allowing the aggregation of various sub-models through different approaches (i.e., Queuing Network and Petri Nets).

Supply Chain Operations Reference (SCOR) model has also been incorporated within many studies to define and/or map SC processes given its standard functionality (Long, 2014; Carvalho et al., 2012; Persson, 2011; Persson & Araldi, 2009; Pundoor & Herrmann, 2007; Rabelo et al., 2007). Herrmann et al. (2003) proposed a SC simulation model based on Discrete Event Simulation (DES) and SCOR model to study the dynamic nature of the SC incorporating a multiple level detail element that permits the addition of extra features.

Dynamic behaviour of the SC system instigated by supply, demand or lead time uncertainties has similarly been modelled by Pirard, Iassinovski, and Riane

(2011), where the work presented by the authors evaluated various SC design scenarios under different control policies that were applied to inventory management, scheduling and production activities. Within this study, the decision maker was involved in optimising the selected elements (rules) in the model to improve the SC system performance.

Simulation capabilities have also been employed in detailed process modelling to support decision-making procedures as in Fröhling et al. (2010), where consideration was given to the integration of complex SC planning processes. The authors presented an innovative application of OR techniques to closed-loop SC and designed a recycling process model that allocated residues from different sources to recycling sites.

2.6.2. Computational complexity factors

Review of the selected literature on complexity revealed that challenges in modelling complex SC systems using simulation can arise from generic factors that differentiate SCs for example: SC type, level of details, purpose of the model, the interactions with the environment and system change. Perishable multi-seasonal SCs for instance, can differ significantly depending on the product and demand characteristics, which ultimately changes management objectives (purpose) requiring increased SC responsiveness or flexibility to deliver innovative or functional products to the market (Adamides et al., 2012; Fisher, 1997).

Those challenges further comprehend structural, computational and organizational complexity in modelling SC systems thus such models often remain limited and not replicable across different industries (Carvalho et al., 2012). Moreover, representation of such complex SC system may require multiple models' due to the scale of changes and interactions between elements within such system.

Table 2.6.2-1 Computational complexity factors specification

OR/MS mathematical techniques	
Category	***Specification***
Optimisation, mathematical programming	Multi-echelon, multi-objective optimisation
	multi-echelon inventory allocation problem (4 allocation schemes: lexicographic with priority to intermediate demand, lexicographic with priority to downstream demand, predetermined proportional allocation, and proportional allocation) to search for the best base-stock level (Niranjan and Ciarallo, 2011)
	Integer programming (IP) model with Taguchi technique and Artificial Immune System (AIS) to search for near optimal solution to distribution problem (Shang et al., 2004)
	Taguchi technique and Response Surface Methodology (RSM) (Tiwari et al., 2010)
	Stochastic optimisation problem solved using Infinitesimal Perturbation Analysis procedure (Total Cost minimisation) (Ozdemir et al., 2006)
	2-stage stochastic IP (Liu and Nagurney, 2013; Poojari et al., 2008)
	Chance Constrained Programming for SC risk evaluation (Wu and Olson, 2008)
	Mixed-integer Quadratic model to SC co-ordination (Pezeshki et al., 2013)
	Mixed-integer linear programming (MILP) model with decomposition technique (Profit maximisation) (Meijboom and Obel, 2007)
	Dynamic Allocation Problem with uncertain supply (DAP-US) addressed by developing a two-stage extended Genetic Algorithm (eGA) (Lin and Chen, 2003)
	Automatic Pipeline, Inventory and Order Based Production Control System (APIOBPCS) algorithm (transfer function model of the system developed using causal diagrams, block diagrams, difference equations and z-transform) (Disney and Towill, 2002)
	Robust optimisation to control serial multi-echelon, multi-period SC (Aharon et al., 2009)
	Minimum Flow Time Variation (MFV) rule for customer order scheduling (Hsu and Liu, 2009)
Heuristics	Heuristics for inventory balancing and transhipment policy to minimise the overall cost (Tiacci and Saetta, 2011)
	Metaheuristics optimisation; Inventory model that incorporates fuzzy sets and multi-objective Particle Swarm Optimisation (Cost minimisation) (Mahnam et al., 2009)
	Heuristics of Capacity utilisation, variability and inventory (CVI) in complex SC operations (Klassen and Menor, 2007)
	Heuristic algorithms for strategic safety stock placement problem that use simulation to compare results for iterative LP and MIP approximation of (Shu and Karimi, 2009)
	Evolutionary algorithm (EA) –AIS used for batch sequencing in multi-stage SC,
Forecasting	Moving average (MA), Exponential Smoothing ES (DES, SES, TES), regression (multiple-regression) (Anderson et al., 2000; Bayraktar et al., 2008)
Project management	Fuzzy Set Numbers combined with Program Evaluation and Review Technique to analyse Supply chain network (SCN) (Vadhani et al., 2011)
Intelligence	Petri nets (PN)- hybrid, generalised, stochastic, deterministic and stochastic (Arns et al., 2002)
	Steady State Genetic Algorithm (ssGA) for SCN design (Altiparmak et al., 2009)
	Queuing Network (QN) (Arns et al., 2002)
	Markov decision process supported by Reinforced Learning (RL) to control inventory policies between multiple actors in SC (Giannoccaro and Pentadelphy, 2002)
	Neural Nets (NN); Eigenvalue Analysis to evaluate SD model outputs (Rabelo et al., 2008)
	Complex Adaptive System (CAS) (Surana et al., 2005)
	SCN modelled as CAS and Fitness Landscape Theory to highlight evolutionary complexities of such SC systems (Li et al., 2010)

This can be observed in most of the selected papers, where a singular model was not capable to capture or reflect all aspects of the modelled system (Pidd, 2012) or to fully fit with the purpose of such system model. This often determines the use of multidisciplinary modelling techniques where simulation methodology is combined with other OR/MS models/techniques. Computational factors considered in Figure 2.6.1-1 are regarded as those modelling techniques that were used in the selected studies to model an E2E-SC system and their particulars are presented in Table 2.6.2-1. Modelling techniques that were identified during SLR address multiple OR/MS problems across three levels in the SC: strategic, tactical and operational (Table 2.6.2-1).

It has been observed that the computational complexity is relative to OR/MS mathematical techniques used to model an E2E-SC system. Those techniques consider such fields of modelling as optimisation, mathematical programming, heuristics, forecasting, project management and intelligent state-of-art methods. Some of the specificities of such techniques are presented in Table 2.6.2-1 alongside the reason for use. In modelling complex E2E-SC systems the challenge is driven not only by its structural and systemic organisational elements, but also by the computational complexity that OR/MS methods bring (Manzini, Ferrari, Gamberi, & Regattieri, 2005).

It has been noted that the computational complexity is derived from developments as well as technological shift in modelling where a new era of combining modelling approaches prevails, particularly observed in hybrid and dedicated models. A hierarchical approach to simulation modelling allows to incorporate different levels of details where each sub-model can be supported by different simulation modelling techniques. Interestingly, such models often feature

AI algorithms (i.e., GA, NN, AIS, and RL etc.) and researchers continuously seek to test capabilities of such algorithms as well as their applicability to model complex E2E-SC systems.

2.6.3. Contribution of SLR findings

Business environment in which SCs operate has undergone tremendous changes and significantly evolved over time. Big advancements in technology and immense changes in peoples' expectations as well as a perception of products value triggered increased competition between companies, enhancing complexity in all dimensions within and outside the system (Serdarasan, 2013). SC system performance is influenced by the changes in the environment, clearly observed in the example of recent risks striking many supply chains.

The disturbance in the environment can take many forms such as economic crisis, environmental catastrophe, government regulations or demand/supply risks. SC system can also be faced with unexpected malfunction of any of the parts of the system or linkages (Carvalho et al., 2012). Both types of disturbances often generate new information that causes system evolution over time, particularly due to the changes taking place in system environment (Gershenson, 2013). In the light of this, modelling SC systems can be difficult even when powered by simulation methodologies.

Holistic view, although criticized by Morin (1992) due to its reductive and simplificatory facets, seems to be a suitable starting point during SC system simulation model development. Recursive and system thinking approach enhanced by development in technology and knowledge itself allows to incorporate evolved simulation taxonomies (i.e. hierarchical, distributed, stochastic, artificial intelligence or hybrid) so more features of a real system and its environment can be included in the model.

Morin (1992) reflected on the concept of the system and concluded that complexity creates a challenge during system abstraction, which is often embraced in studies on modelling SC systems. Examination of complexity factors within selected peer reviewed studies on supply chain (extended) and simulation provided epistemological importance of conceptual systems thinking and its relevance to modelling SC systems.

Main elements echoed within studies on complexity are relative to the SC structure (i.e. SC type, boundaries and interactions between them) and system organization (i.e. dynamics and uncertainties in product/ process interaction; performance management relative to strategic, tactical and operational levels) as well as computational challenges that come with modelling of such systems.

Based on the findings from SLR, derived from system thinking philosophy and imposed by factors affecting complexity in modelling SC systems, a simplified framework of relations between various elements in a generic E2E-SC system model has been drawn.

Typical SC system is built based on generic elements such as supply, operations and product distribution to the market, which becomes much more complicated if enhanced by complexity factors specified in Figure 2.6.1-1. In result confluence of relevant elements of the system and its characteristics is differentiated by industry and crucial to the SC system model development. Therefore, identification and analysis of the most frequently studied SC processes could enable identification of the critical elements of the SC system model and their attributes.

Simulation methodology allows the incorporation of different levels of SC system abstraction, which can be regarded as a step (activity) that leads towards the design of a conceptual model (Labarthe, Espinasse, Ferrarini, & Montreuil, 2007; Lendermann et al., 2003; Stefanovic et al., 2009). This may require considerable level of assumptions included in the model design thus providing lower level of details, which according to Venkateswaran and Son (2004) impacts on the analysis and results of the simulation runs. One way to tackle this issue is by adopting hierarchical modelling approach. Venkateswaran and Son (2005) used this technique to production planning to reduce complexity and increase control of the system by focusing on the aspects of decision elements at more aggregated level, which absorbed random events and need for details, offered better visibility and improved forecasting. Studies that consider simulation methodology appreciate computational constraints that analytical methods provide thus often combine / mix modelling methods. This is particularly important in modelling complex SC systems and has been reflected in various studies combining optimisation with heuristics and simulation or analytical models with simulation.

2.7. Chapter summary

A complexity is the important attribute of many systems and can be observed in E2E-SC systems. This chapter systematically reviewed literature in the field of the supply chain and simulation providing a holistic assessment of an E2E-SC, from market-demand scenarios through order management and planning processes, and on to manufacturing and physical distribution. This rigorous approach allowed to develop the body of knowledge within this subject of inquiry by advancing the understanding of theories, methods used and applicability of modelling the E2E-SC systems using simulation.

Section 2.6.1 provided a review of 26 papers that included complexity in the title, abstract or key words, which were further analysed with the aim to extract the generic elements required for modelling E2E-SC systems. This approach was further corroborated by Morin’s (1992) work on systems and complex aspects that constitute them. The methodological approaches were thoughtfully evaluated within the selected studies and conclusion was drawn that each element from the conceptual framework brought some challenges to modelling an E2E-SC system using simulation.

This was noted by evaluating simulation techniques used and implications that adding more elements from the E2E-SC system had on the modelling activities. It was observed that the complexity can vary depending on the scope, organizational structure and the nature of phenomena under investigation.

In conclusion, the development of a generic framework requires three crucial components that need to be considered during the model design stage: structural, computational and systemic organizational that are vital elements of complex systems like SCs. Modelling an E2E-SC system using simulation demands a good understanding of the principles of SCM, modelling and simulation.

The SLR exhibited that various issues and practical decisions relative to E2E-SC simulation modelling are influenced by the complex computational techniques and methods that often span across various disciplines such as mathematics, computer engineering, software design, biology, education amongst others (Surana et al., 2005). Conclusively, the SLR underlined the following points about modelling E2E-SC systems using simulation:

- The most frequently researched themes relative to simulation modelling of the E2E-SC system are SCM, Inventory management, SC dynamics, Production Planning and Inventory control, which seem to be particularly important to achieve high level SC system performance. Although, these themes are usually subjects within multi-disciplinary and cross-sectional studies, where multiple aspects, issues and processes are considered.
- The complexity in E2E-SC system models are derived from structural, computational and systemic organizational factors, which are also crucial elements of such systems and need to be considered during the modelling process.
- An advanced and extended version of existing modelling techniques are often used to facilitate E2E-SC simulation model developments.
- There is an observed shift in simulation modelling towards combined (hybrid) models that are characterised by the amalgamation of multiple modelling techniques and research methodologies.
- Simulation model outputs are often reinforced by artificial intelligence algorithms to aid the decision maker and provide a better understanding of the system behaviour and system evolution.
- E2E-SC system models are often hierarchical, where multiple decisions are made at various levels that have ultimate impact on the entire SC system performance.

This chapter contributed to knowledge and understanding of the characteristics of E2E-SC systems as well as the requirements for simulation modelling. The next step would be to implement and test the proposed generic E2E-SC simulation framework and develop an E2E-SC system model using simulation to underline its applicability and practicality.

Chapter 3

Research Methodological Foundation

3.1. Introduction

The previous chapters established the purpose and context of the thesis and raised a set of concerns for further consideration, relative to modelling an E2E-SC using simulation. A SLR strategy discussed the importance of complexity and system thinking theory in studies on modelling SC systems using simulation and led to the development of a conceptual framework (Figure 2.6.1-1).

This chapter maintains the research rigor and aims to explain the research design and identify the value of the chapter's structure to the overall context of the thesis, as well as to highlight the importance of each research question. The research philosophical stance i.e. paradigm will take an important part of this chapter. As pointed out by Näslund (2002) the research paradigm is a reflection of researcher's perspective on the world surrounding them and is closely linked to the choice of research methodology. Research paradigm comprises of three elements ontology, epistemology and methodology, therefore, by examining the research philosophy, the researcher defines methodological approach, which impacts on the way that knowledge is developed and provides clarity to the research (Näslund, 2002).

The chapter will begin with an examination of the philosophical assumptions underlining the work undertaken, which is a crucial step to establish the nature of the relationship that exists between theory and practice. It will refer to the researcher's paradigmatic position, which was defined by Guba (1990) as a "basic set of beliefs that guides action" (Guba 1990 p.17). This section of the thesis will also attempt to create a unique and systematic link between theoretical frameworks/concepts and the key components (methodology, methods), which is a central constituent of any study.

The chapter devises considerable attention to discuss methodological approach undertaken in this research hence elaborating on each aspect presented in the Figure 3.1-1. Following up from discussion on research design elements, the role of modelling and clarification of the subject of inquiry, this chapter links all elements of the methodological approach in the context of modelling E2E-SC systems using simulation.

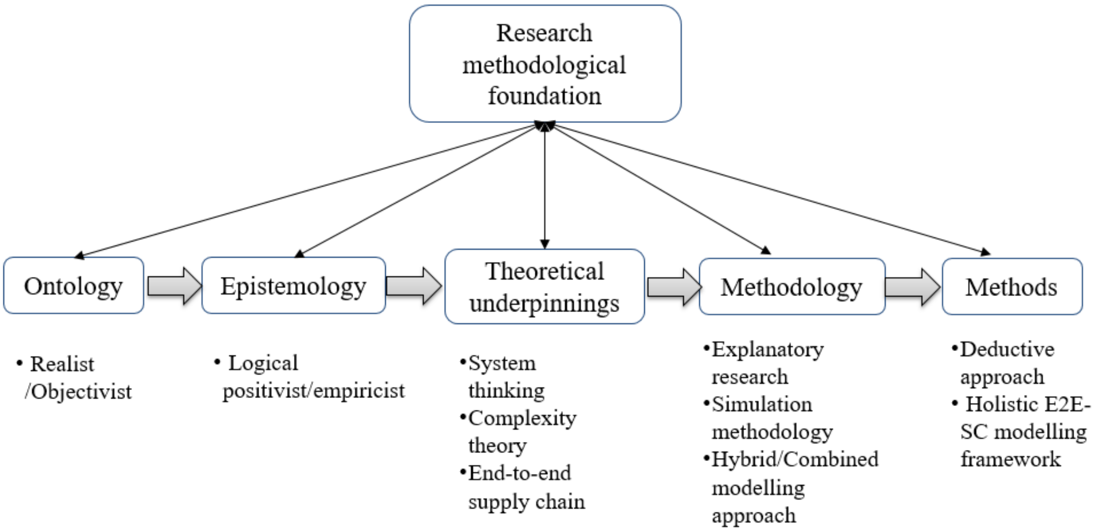


Figure 3.1-1 Research methodological approach

Applications of OR techniques and combined/hybrid modelling approach will be discussed as well, culminating in explaining the need for generic approach to model E2E-SC systems using simulation that can consider all three pillars defined in the conceptual framework. It further advocates the scientific rigor of the research, hence implies the necessity to provide a clear contribution of the conceptual framework to practitioners and academia. This is achieved in this section of the thesis by deliberating on the philosophical underpinnings and methodological approach that create valued points within the research design. A brief description, explanation and justification of the end-to-end modelling architecture design process will be presented here and in Chapter 4 a generic end-to-end supply chain system model development will be described.

3.2. Research design elements

A philosophical debate that surrounds matters of knowledge creation is an important constituent of any research, also within social science and management. Many research textbooks highlight the advantages of explicitly stating the philosophical underpinnings, which also proved to form a strong connection linking all parts of the research design (Easterby-Smith, Thorpe, & Jackson, 2012b).

Creswell (2009) complemented, that the choice of the research design reflects the researcher's viewpoint originating from the philosophical assumption through the selection of appropriate strategy, which is ultimately executed by adopting suitable research methods. The author further reiterates that understanding and appreciating each of the research design elements plays a fundamental role throughout the research process. The research design is often regarded as a strategy adopted by a study that enhances research originality and clarity by incorporating the following objectives:

- To explain what aspects led to the study,
- To identify the gaps in the literature relative to such aspects,
- To select and understand the audience that could be interested in the underlying purpose of the study (Creswell, 2009).

The current research attempted to address the above objectives in chapters one and two, where the research motivational reasons were described as well as the research background and context. Chapter 1 defined research aim, objectives as well as research questions. This was further complemented by the systematic literature review, which culminated in development of the conceptual framework that captured generic E2E-SC system elements and justified the need for a generic E2E-SC model. Identification of the research objectives provided clarity to the research purpose (i.e. explanatory, descriptive or exploratory) and this chapter will attempt to achieve ontological and epistemological consensus for this thesis (Saunders, Lewis, & Thornhill, 2015).

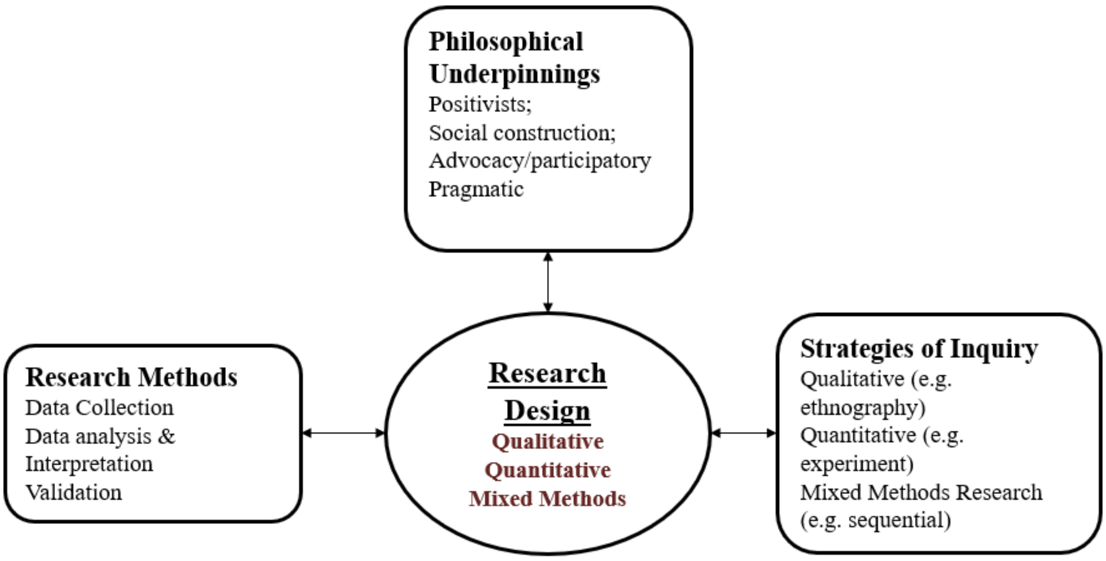


Figure 3.2-1 Research Design Elements
Source: Adapted from Creswell (2009)

Figure 3.2-1 depicts the interrelation between three major facets of the research design: philosophical underpinnings, strategy of inquiry and methods adopted, which are further deliberated in the context of this research. In the core of each research lies clarification of the ontological and epistemological assumptions, which are likely to reimburse the efforts of the research project if fully understood and their strengths and weaknesses are acknowledged. These further explain how the researcher views the world/reality (ontology) and how the knowledge is generated (epistemology).

Saunders et al. (2015) stressed the enduring importance of aligning research philosophical stance with appropriate methodological approach. This can considerably enhance the rigor of research design, particularly when combined with carefully selected tactics such as appropriate data collection methods (Quinlan, 2011).

The research design for this thesis is summarised in Table 3.2-1 below, where a brief description of the problem specification, the research strategy and methodology as well as literature synthesis methods is provided. The research initial aim was to adopt a quantitative approach in line with the study intended purpose, which was to develop a generic E2E-SC system model using simulation. This was supported by simulation methodology, which refers in this research to a step by step approach to an E2E-SC simulation model development process in line with Manuj, Mentzer, and Bowers (2009); Stefanovic et al. (2009); Van Der Vorst, Tromp, and Van Der Zee (2009). However, it became apparent that there were no defined guidelines to support a development of an E2E-SC generic model using simulation. The research identified a need for qualitative methods such as interviews to enable model validation and verification. Each of the points from Table 3.2-1 will be further discussed in this chapter, and then Chapter 4 will be dedicated to present a step by step model development process, with Chapter 5 presenting insights gained through model validation and verification.

In quantitative research methods for social science, simulation is also used to generate data in large and complex analytical models by running the model over a given period of time (Waters, 2008). Although, this is a frequently used approach, the purpose of this research is to develop a generic E2E-SC system model using simulation. Therefore, the aim is to define a set of generic requirements for modelling an E2E-SC system and to develop a simulation model that incorporates these elements. The E2E-SCs are complex and difficult to manage as acknowledged by Serdarasan (2013), who characterised supply chain complexities, its drivers and approaches to manage these. The author provided some solution strategies based on industry practises, however one other way to increase the understanding of complex SC systems is through modelling.

The current research identified modelling as an approach to gain the knowledge on complexities in E2E-SC systems. The research aims to investigate the challenges and issues when modelling an E2E-SC system using simulation and to discuss the implications associated with adding elements from the conceptual framework to the simulation model.

Table 3.2-1 Specification of research design elements

Research design	Research design characteristics
Problem specification	Lack of generic modelling framework for E2E-SC systems
Study purpose	E2E-SC system description Simulation model design to explain different levels of confluence
Research strategy	SLR to facilitate a design of the conceptual framework Simulation model development incorporating elements from the conceptual framework Simulation model validation via semi-structured interviews
Methodological formulation	Quantitative method approach: Simulation model development Verification through structured walkthrough and model debugging Validation with industry specialists
Data synthesis technique	Literature survey Qualitative data collected via interviews

The research adopted a quantitative approach as a leading research method for a development of an E2E-SC system model using simulation that was supported by qualitative methods in the validation stage. Research questions were guiding the researcher throughout the research process on modelling E2E-SC systems using simulation. Each research question had an impact on the methodological approach taken and a development of the modelling guide in chapter four (Figure 4.4.1-1). The first research question led to SLR and creation of the conceptual framework, which was presented in chapter two.

The implications of the second research question were discussed throughout chapters three and four, where the discussion on research design took place and guide to E2E-SC system model was developed. The answer to this question was underpinned by the philosophical foundations of the research and methodological choices made.

The third research question led to a discussion, brought by the End-to-end supply chain system model validation and verification section (chapter five), which considered implication of simulation model development and the impact of adding segmented models.

The role of a researcher spans far beyond research methods and techniques and involves entering the researcher communities, their conversations as well as engaging into 'the debate' surrounding its traditions and its social and historical context (Bentz & Shapiro, 1998). One could distinguish three phases of the history of culture as pointed by Bentz and Shapiro (1998): classical or traditional, surrounding the objective and external reality; modern, characterised by awakening consciousness and unconsciousness and accompanied by rationalisation and lastly postmodern, which all together denies objective reality and moves away from past traditions.

Postmodern concept has a significant impact on the research in social sciences and therefore any research should have a clear position regarding how this movement might have influenced the research. This is particularly important as many changes observed in the past few years such as move from mass to customised production, just-in-time production, lean and agile concept, influence and impact of media on everyday awareness or mass migration have been portrayed by many as a new era of postmodernity (Bentz & Shapiro, 1998).

Postmodern school of thought questions not only the aspect of what we know about the reality but also the fundamentals of knowledge, which is viewed as a set of constructs rather than representation of reality. Thus, many questions and doubts are on the forefront of any current research, presenting challenge and confusion or at least the need to stop by and reflect on how this might have impacted the research and somewhat to 'defend' the research philosophical position.

The fundamental of the philosophical debate is duly attributed to the positivism, which is associated with scientifically driven progression of the humanity and the world's development. Although merely based on science, there are different perceptions surrounding this philosophical and cultural doctrine, hence commonly researchers can hold only some positivists concepts or views (Bentz & Shapiro, 1998). Interestingly there are thinkers who hold strong positivist position and believe in the power behind scientific model yet personally can be very critical regarding positivism. This could be one of the influences of postmodern changes.

Bentz and Shapiro (1998) pointed out that often positivism is misinterpreted and used as a way to conduct a research. The authors rightfully emphasised on the importance to understand ontological and epistemological underpinnings surrounding this philosophy in relation to any research. On the opposite side to positivism lies social constructivism.

Fundamental philosophical assumptions surrounding worldview elements underlying SC research are those associated with positivism and social constructivism (Easterby-Smith et al., 2012b). However, there are other schools of thought used in supply chains research, with pragmatism regarded as particularly valuable one. This is because pragmatism seems to focus more on the research processes and methods than on the philosophical debate, advocating for practical approaches that can address research questions in the best way.

Table 3.2-2 provides summary of the philosophical assumption that underpin the two-key dimension of worldview; positivism, which views reality as objective and independent of social actors (based upon realism) and social constructivism, which focuses on presenting multiple perspective of the reality (based upon relativism). The Table 3.2-2 considers also pragmatism, which provides a platform for a research, where neither one of the traditional paradigmatic stances and associated with them methods, quantitative or qualitative, can fully investigate the subject of inquiry. The aim of using this approach is to overcome obstacles and limitations that emanate from use of qualitative or quantitative approaches in silos (Gelo, Braakmann, & Benetka, 2008).

However, the debate surrounding the epistemological and ontological assumptions surrounding mixed methods research focuses on noticeable differences between quantitative and qualitative research relative to paradigmatic underpinnings of the inquiry. Foci of the philosophical underpinnings relative to quantitative and qualitative research is rather substantial and the main differences between both types of the research lie noticeably at the paradigmatic level. Thus, a common argument between philosophers is that quantitative and qualitative methods cannot be mixed within a single study due to their incommensurability (Golicic & Davis, 2012).

Table 3.2-2 Philosophical assumptions underpinning various elements of worldviews

Worldview elements	**Positivism**	**Social Constructivism**	**Pragmatism**
Ontology (What is the nature of reality?)	Singular reality; external; objective and independent of social actors	Multiple realities presented by the researcher in the form of quotes to illustrate different perspectives	Singular and multiple view chosen as an enabler to best answer of research question; external
Epistemology (What constitutes acceptable knowledge from the researcher viewpoint?)	Credible data facts can be only obtained from observable phenomena; Focus on causality (generalisation)	Close interaction between researcher and participants; focus on interpretation and meaning of humans' experiences	Practical approach as the researcher collects data based on "what works" doctrine to address research question best
Axiology (What is the role of values?)	Value free, researcher treats the data objectively; unbiased (checks used to eliminate bias)	Biased (researcher considers various-biased interpretations to understand a phenomenon better)	Multiple stances where both biased and unbiased perspectives are included
Methodology (How can we go about acquiring that knowledge?)	Deductive (testing a priori theory)	Inductive (theory follows the data; based on participants' views researchers build up patterns, theories and generalizations)	Mixing (both qualitative and quantitative data collected and combined)

Source: Adapted from Grix (2002), Creswell and Plano Clark (2007), Tashakkori and Teddlie (2010) and Saunders et al. (2015)

Mertens (2010) stressed on the importance of specifying the philosophical assumptions underlining the research and continued that any research that abrogates such aspects remains an examined position. The author criticized the approach that appreciates the practical applicability of the research techniques adopted rather than philosophically derived worldview perspectives held by the researcher. Those views are reflected in practise and the methodological approach that researcher chooses.

Any research needs to devise a considerable attention to the assumptions being made about the reality, knowledge and values (Saunders et al., 2015). Therefore, the consensus between the traditional approaches is incremental and discusses the main issues within the philosophical debate. These are relative to:

- The ontological considerations that include multiple viewpoints, perceptions, experiences, theories influencing the observation of the reality which cannot be fully known.
- Theoretical aspects, were multiple theories can be applied to one empirical case; hypothesis testing cannot occur in isolation and is affected by "holistic network of beliefs" (Johnson & Onwuegbuzie, 2004, p.16) thus multiple explanations.
- Epistemological considerations: the knowledge the researchers generate is affected by values and beliefs derived from the social environment surrounding the research (Johnson & Onwuegbuzie, 2004).

Research in E2E-SCs saw various attempts to classifying the research paradigms. This research considers framework that was initially developed by Mitroff and Mason (1982) and further enhanced by Meredith, Raturi, Amoako-Gyampah, and Kaplan (1989) to suit particularly research in operations. The framework is building further on the generic philosophical assumptions surrounding the three distinct worldview elements presented in Table 3.2-2 and groups them into two primary key dimensions that shape the research; rational/existential and natural/artificial. The former covers philosophical aspects relative to researcher's ontological position such as; the understanding of reality and knowledge, and latter focuses on the type and source of data used to investigate the inquiry (Meredith et al., 1989).

NATURAL ⟷ **ARTIFICIAL**

RATIONAL

	DIRECT OBSERVATION OF OBJECT REALITY	PEOPLE'S PERCEPTIONS OF OBJECT REALITY	ARTIFICIAL RECONSTRUCTION OF OBJECT REALITY
AXIOMATIC (theorem proof research- strong positivism)			• Reason/ Logic/ Theorems • Normative Modelling • Descriptive Modelling
LOGICAL POSITIVIST/ EMPIRICIST	• Field Studies • Field Experiment	• Structured Interviewing • Survey Research	• Prototyping • Physical Modelling • Laboratory Experimentation • Simulation
INTERPRETIVE (constructivism)	• Action Research • Case Studies	• Historical Analysis • Delphi • Intensive Interviewing • Expert Panels • Futures/Scenarios	• Conceptual Modelling • Hermeneutics
CRITICAL THEORY		• Introspective Reflection	

EXISTENTIONAL

Figure 3.2-2 Research frameworks in operations

Source: Meredith et al. (1989)

The two dimensions are placed on diagonal axis to allow classification of methodological approaches and methods that are the most suitable for a given paradigmatic stance. As Meredith et al. (1989) pointed out, on the natural side of the continuum lies objective approach to the research process, which relies on direct contact with the phenomenon, aiming at delivering valid and real research outcome. On the other hand, the opposite side of the continuum is artificial dimension that is aiming at reconstruction of the reality. This approach is often adopted in operations research, where the essence of the research is to model systems and provide analytical analysis. Computer simulation falls into this category as one of the most appropriate tools to map operational issues within a business or SCs.

The efforts of this research are following Meredith et al. (1989) framework and in particular logical positivist/empiricist and artificial dimension, as shaded in grey in Figure 3.2-2. Although, the motivation is to study E2E-SCs, which endeavours span beyond operations and consider management science, engineering and business, the objective of the research is to develop a generic simulation modelling architecture. The research paradigmatic stance is further elaborated in the following sections of this chapter.

3.2.1. Research paradigmatic stance

The research paradigm is often considered as a fundamental constituent of the research process representing the researcher's perception on the proximate world (Näslund, 2002). As a result, the researcher's background is usually a vital pre-determinant of the central pillar(s) and podium for the research philosophy. Thus, clarifying ontological, epistemological and methodological position would not only provide guidance throughout the research process, but would also harness the reflection aspect of it by appreciating the impact that the research choices have on the world and the possible change that could occur as a result of such choices.

This research assumed an E2E-SC as inter-organisational forms, which exemplify ontological characteristics that appear to be unbiased of social entities, relations and the practices. Therefore, the activities that form an E2E-SC are perceived as dependent on the overall definition and scope of the system according to the desired principles of performance measures.

In line with Aastrup and Halldórsson (2008), this presents a natural perception and assumption that processes within an E2E-SC system are likely to remain predictable and businesses are likely to follow given designs without questioning them. Additionally, this would normally be in isolation from the context in which they operate. This ‘inter-connectivity’ element of an E2E-SC systems adheres to a positivist research paradigm, assumes a flat ontology based on regularities at the activity level and the fact that real events can be observed empirically with logical explanations of the analysis.

However, SC system performance is often evaluated by decision maker and the corrective measures are applied, although usually based on the quantifiable results, still can depend on the knowledge and expertise of the social actors. Likewise, current catastrophic events that impacted the SC around the world unveiled the vulnerability of the SCs and the associated risks, which require collaborative efforts of science and social, political and cultural appreciation (Daultani et al., 2015).

Understanding the relation between research philosophy, approach and strategy is essential for any research. This is mainly determined by the ontological and epistemological assumptions being made that consequently inform, determine and develop the methodological framework for the research study.

3.2.1.1. Ontology and epistemology in modelling E2E-SC

Challenges in modelling an E2E-SC system emanate from the definition and perception of an E2E-SC system/model scope. The existence of various ontological derivatives may result in different understanding of what is the scope, boundaries and objectives of modelling an E2E-SC. Alpaslan, Babb, Green, and Mitroff (2006) publication highlighted a combination of conflicting goals and varying perspective on the way that the reality is perceived by the professionals assuming similar philosophical stance. Their work concluded that even from positivist philosophical stance point of view, only an incomplete picture could be drawn of the objective reality.

This can be equally relevant to any research, as individuals are unique in the way they perceive the reality. This is particularly visible in the academic view against a practitioner perspective, which can vary significantly, hence generates the necessity to clarify and attain a consensual definition of the E2E-SC scope for this study to integrate these two perspectives. Thus, the critical reflection that will follow reflects on the ontological and epistemological positions around models and modelling an E2E-SC system and what is the position taken by this research.

Easterby-Smith et al. (2012a) defined a realist or objectivist ontology as an approach that views a phenomenon as existing outside of the social world and advocates for objective methods to study or measure its properties. The second approach originated from an interpretivist approach, where people’s experiences are appreciated, and the importance is given to explore the meaning of subjective actions taken by social actors to understand those actions (Saunders et al., 2015). In referral to the E2E-SC systems, these are often evaluated from the perspective of a decision maker, where more focus is given to company's core values, aims and objectives usually clearly communicated in a top-down approach with all employees.

The current research decisively seeks to study the E2E-SC as a system, that is a set of elements or as pointed out by Ashby (1956) a list of variables that can vary depending on the system scope and purpose. Likewise, the system state and behaviour can change over time due to interactions between system elements and the system environment.

In line with Morin's view, systems retain (a) structural attributes, which relative to SCs are echelons or SC participants and (b) system organisation, which is a way in which SC participants are linked together through various SC functions. System organisation is also viewed as a perception of the ideal, heuristic and pragmatic system model in nature designed with the aim to evaluate, improve, control or model a phenomenon. This research withstands that many systems including SCs can only be fully understood if consideration is given to both system structure and system organisation primarily due to the existing level of confluence between these two important ontological derivatives. The complexity arises from those interactions indicating that elements or parts of an E2E-SC are difficult to separate (Gershenson, 2013) or it can be observed within one element for instance, at supplier level, where operational complexity could involve planning, managing and controlling of business processes (Vrabic & Butala, 2012).

Additionally, this research advocates the importance of studying an E2E-SC system holistically by embedding a system point of view. The ontological position underpinning the research has its fundamentals in the system thinking and complexity theory. An E2E-SC can be viewed from a system thinking perspective by combining objective elements such as a simulation model, depicting real and measurable objects, which are SC participants; i.e. suppliers, manufactures, warehouses, retailers, customers and processes/functions with SC system organisation that is the relation between the structural elements and requires a mindful inquiry (Bentz & Shapiro, 1998).

The need for epistemological assumptions, which rest in the realm of the research process are relative to “the process of thinking” as well as “the relationship between what we know and what we see” and ultimately provide help with understanding “the truths we seek and believe as researchers” (Denzin and Lincoln, 2011; p.103). These relate to the choices that research makes, and epistemological assumptions derived from paradigmatic viewpoint surrounding subject of inquiry.

Although, there are certain frameworks or guiding principles, which drive the research or researcher choices, these demand great level of integration between personal and intellectual acumen (Bentz & Shapiro, 1998). Today’s research is striving for rigor regardless of the approach or paradigmatic position taken. This opens a window of opportunities as scholars tend to focus their research around cognitive frameworks or develop them into a new contribution. Nevertheless, such contribution is not only a matter of existential choices, but the influence or outcome of a thoughtful debate instigated by scientific and philosophical arguments (Bentz & Shapiro, 1998).

3.2.1.2. The role of modelling and models

The current research on modelling an E2E-SC system using simulation provides a platform, where scientific knowledge and developments play crucial role in progressing the knowledge on these systems. Modelling can be regarded and viewed in different ways, so as models and although they can define or represent a physical or fictional system, theoretical or conceptual structures, equations or descriptions, with varying level of confluence between some or all of these, there may not be an exact definition of models or it may be influenced by scholar's ontological standpoint (Frigg & Hartmann, 2012). Still, models are very useful means for knowledge development and learning. This is primarily due to the prevailing features of models, which depict a simplified representation of a system (Oakshott, 1997) and are used as surrogates for reasoning about the system that they represent (Bolinska, 2013; Swoyer, 1991). For example, SC system model can be developed using physical items such as 'LEGO' bricks or mathematical equations to represent transhipment process between SC players.

The importance here lies in defining and understanding a structural representation of a system, which requires clarity of assumptions as to its objects, elements, boundaries, etc. where strictness of such representation is often in question (Swoyer, 1991). It may be difficult or rather impossible to represent the entire SC system in a model due to the number of players, processes, products and other aspects that need to be considered although Swoyer (1991) emphasised on the importance of reductionism and surrogative reasoning while deciding on the structural representation of a system. Therefore, a clarity in assumptions is required not only during the system abstraction but also relative to system structural representation and the overall purpose of that representation, as well as a system and its model.

Such assumptions can be based on the existing knowledge, for instance; if a person working in a distribution centre as a picker or packer would be asked to go and pick a list of items in no particular order repeatedly, would probably learn with time the most efficient way to pick the items in order to save time and additional walking. This learning might have been achieved using a scientific model developed by means of mathematical equations to maximise the worker output. Moreover, to have a more efficient solution for picking the items, one could develop various operating scenarios using modelling techniques without the need to strain the worker.

Bolinska (2013) attempted to address this by proposing epistemic representation as a tool to obtain information about the system. The author argued that scientific models are representation of a targeted system through means of appropriate vehicle such as physical ‘LEGO’ blocks, or mathematical equations. Epistemic representation on the other hand refers to learnings achieved from these models. This seems to be particularly relevant to SC system models, mostly in relation to modelling techniques, which once applied to different context/problem may bring different learning about the SC system.

The contribution of the current research can be observed in the process of developing a generic model of an E2E-SC system, where the scientific representation of a system is used to gain knowledge and information about targeted system behaviour and changes resulting from interactions between system structural elements and its organisation. The challenge emanates from defining and understanding what should be regarded as generic model requiring clarity in assumptions and context of the subject of inquiry.

3.2.2. Subject of inquiry

Grix, (2002) reiterated that research encompasses a clear understanding of the ontological and epistemological position to grow the knowledge engine. This involves clear comprehension of the researcher's own and others' position regarding the social phenomena under investigation. For that reason, the subject of inquiry for this research is to understand the social reality/phenomenon thus the system boundaries that define the scope and design of an E2E-SC system.

This requires a coherent conceptualization of the entities that make up or define the term E2E-SC system, resulting in an abstract description of the content and rules governing the behaviour of the physical world/system that ultimately provides the linkage between the physical and conceptual world (Smyth, 1992). Such ontological perspective outlines the main entities and structural characteristics, its interactions and the rules that characterize system behaviour (Van Gigch, 1991).

The research endeavour is directed towards development of conceptual framework for modelling and creation of E2E-SC system simulation models. Such aspects as the E2E-SC/model scope (boundaries), objectives, level of details and assumptions are some of the key points that need to be defined during simulation model development process. OM is an area that is closely related to SCM and both are extensively covered within extant literature with large number of publications addressing issues within both disciplines by adopting cross functional principles often derived from OR/MS field. These are equally important for simulation modelling and are often used within simulation studies. System thinking approach is adopted to emphasise on the learning that can be achieved if the appropriate vehicle for studying subject of inquiry is used.

This directs the research study to consider the ontological issues under scrutiny with the initial concern aiming at achieving a consensus over the definition and/or perception of the term E2E-SC. From an academic perspective, adopting this term would imply that the research study needs to consider a generic structural design of the entire SC system that would include all upstream and downstream members within the supply chain as well as tiers 1,2,3, n suppliers as well as customers. Effectively, this would create a significant level of complexity within the model design stage.

3.2.3. Complex system

Oxford Dictionary of English (2005) provided a basic definition of a system, which is a set of elements working together as a mechanism or network as well as an organized scheme/ method. Banks et al. (1996) pointed out that the regular interactions and interdependence of such elements directed towards accomplishing a given task (aim).

A complexity observed in the E2E-SC systems can adversely affect the behaviour and performance of these systems. The E2E-SC consist of various nodes, interconnected and operating under boundary conditions, yet the reactions between them often generate new information, particularly if subjected to the changes occurring in the system environment (Gershenson, 2013). This could be seen through different ontological lenses, and herewith discussed an E2E-SC system regarded as a subjective and based on the experiences and perceptions of a researcher that are divergent for different persons and change over time and context, hence influenced by the way a researcher views the reality.

The system approach is appreciated in SCM and logistics research and practice as it provides a holistic view of an E2E-SC and implications of sub optimization (Nilsson and Gammelgaard, 2012). However, the SCM and logistics research is very much influenced by positivism and often assumes its underpinnings:

- Realism and rational people's behaviour,
- System efficiency and optimisation,
- Elimination of uncertainty and system simplification,
- Objectivism, normative models and sequential process frameworks,
- Reductionism,
- System boundaries and defined goals/objectives (Nilsson and Gammelgaard, 2012).

These assumptions are important and valuable, nevertheless in research on E2E-SC systems, where decisions can be influenced by people, a more reflective approach to paradigmatic view needs to be considered (Nilsson and Gammelgaard, 2012). This is to understand not only the scientific aspects on the models but also to reflect on its characteristics and how these became a part of the model.

3.2.3.1. Perceived attributes of complex system

A complex system can be associated with numerous parts (known or unknown) and the relation between them, which Van Gigch (1991) regarded as objective or subjective attributes of system complexity. Objective characteristics of a system complexity was assumed to be present when the number of participants, echelons or SC levels was explicitly known, while subjective elements were insofar pointing towards behavioural aspects of system features that were not always visible (presented within systemic organisational pillar of the E2E-SC system framework).

This somehow generates two orthogonal dimensions of complexity whereby, the ‘subjective complexity’ could be associated with incompleteness, uncertainty or paradox in understanding the interconnected workings of a system and ‘objective complexity’ representing a few jointly coupled, non-linear and recurrent interconnections of system components operating at some distance from equilibrium.

What can be observed in the literature and may at first seem counter-intuitive is that complexity is not a problem, but a path to solutions of many problems and especially issues that exhibit subjective or objective complexity. Referring to Ashby (1964) complexity could be viewed as numerous possible states of the system, which is affected by:

- number of elements,
- number of relationships between those elements,
- the dynamics of the system through time and perception of the observer.

Building further on the known aspects of structural representation of a SC system, Weaver (1947) classified complexity as:

- organised simplicity relative to the 19th Century research, which primarily focused on simple systems models with two variables;
- disorganized complexity of large models with numerous or erratic/unknown in behaviour variables observed in the 20th Century research and
- organised complexity that is a focus of research in 21st Century research (Figure 3.2.3.1-1).

Some changes relative to the developments in modelling, system analysis and a scientific research in the past can be broadly summarised as presented in Figure 3.2.3.1-1. Models developed in the era of organised simplicity were based on deterministic variables and aiming to explain and analyse relationship between such variables. This had changed into large scale mathematical models with stochastic variables, difficult to understand and capture hence statistical distribution was introduced to address this issue.

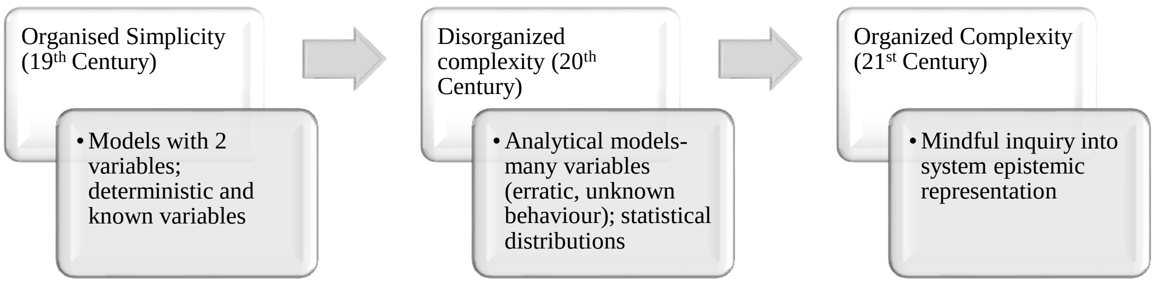


Figure 3.2.3.1-1 Changes in system complexity over time

Source: Adapted from Weaver (1947) and (Bentz & Shapiro, 1998)

The move from organised simplicity to disorganised complexity appeared to be in line with cultural developments relative to modernity and the modern belief that development and progression can be achieved through science (Bentz & Shapiro, 1998). However, disorganised complexity seemed to be lacking a clarity and furthering the knowledge and learning on how it occurred and why. This was addressed by the changes and advancements brought upon by the era of organised complexity and is almost certainly looked at until present time.

These changes had also been reflected in the research practise, particularly in different research approaches that were introduced and a vast amount of available information necessitating a mindful inquiry into a subject matter and a research approach itself. Bentz and Shapiro (1998) advocated that a researcher who is a mindful inquirer would have a better understanding on how different approaches to the research, that is the existence of multiple disciplines, theories, research methods and paradigms could impact the research. Moreover, this would allow to have an open-minded approach and a skill to navigate, comprehend and defend its own research.

3.2.3.2. Modelling the system

System models, such as proposed within this research E2E-SC system model, are developed based on assumptions relative to structural and systemic organisational elements, which consider rightfully selected, informative vehicles in the form of computational methods to represent such systems. This inclines that there are modelling techniques that are best suited to reflect certain elements of a system and its purpose; for instance, SC systems, which are characterised by set of attributes and its dynamic nature are best represented by simulation.

The new era of organised complexity appeared to be characterised by mindful inquiry into systems' epistemic representation (Bolinska, 2013) and the attempt to learn from changes observed in systems. For instance, early attempts to understand why complex systems are dynamic and interconnected (Ashby, 1956) and how manipulation of system element/s can trigger changes in other system elements, required a vehicle (for instance a SC model) that was informative about its target (SC system) hence consistently represented such target. This indicated that the vehicle or in the example of SC system, modelling techniques needed to be selected appropriately to ensure a true interpretation of the system.

This approach appeared to somehow reflect the changes and attributes of complex systems, which proven to be characterised by significant number of system elements and layers as well as interactions, nonlinearity, stochastic elements and non-holonomic constraints. The characteristics of organised system complexity suggested that a number of SC participants, products, processes and model entities was measurable and countable, where the level of system complexity was determined by the number of structural system elements and by interrelationships among different elements in the system. This was further complemented by the level of information that was required to address system uncertainty (Van Gigch, 1991).

Various authors attempted to look into characteristics and attributes of complex systems (Ashby, 1956; Flood, 1991; Yates, 1978), while others focused on analysing them (Li & Liu, 2012; Surana, Kumara, Greaves, & Raghavan, 2005; Zeng & Xiao, 2014). Amongst many others, there are following particulars typical to complex systems like SC systems that should not be abrogated and considered during modelling activities:

- Structural aspects relative to number of parts/elements, and interactions between them.
- The numbers and attributes of elements/parts are often stochastic.
- Elements/part interact in disorganised manner.
- Systems behaviour is dynamic and probabilistic.
- Systems evolve over time.
- System can be influenced by the environment (context in which it operates).

- Systems have a purpose although due to the fact that systems evolve over time, the new purpose of a system is what it actually does, which may differ from what it was initially designed for.
- Systems have hierarchical nature and are often consist of many subsystem, which have a purpose on its own.

The above-mentioned aspects are particularly relevant for E2E-SC systems, where large number of elements/parts is defined by their suppliers, manufacturers, distributors, retailers and customers. Likewise, a continuous change in number of these elements and their characteristics requires appropriate vehicles that are capable to reflect the targeted SC systems and allow to draw a meaningful inference about these systems. Although, the argument could be brought questioning if SC system elements are loosely organisation or perhaps characterised by probabilistic nature, there seems to be less available evidence to sustain this loose organisation. Yet, various research attempts considered the probabilistic behaviour of SC systems (Boulaksil & Fransoo, 2009; Nekooghadirli, Tavakkoli-Moghaddam, Ghezavati, & Javanmard, 2014).

Tipi (2009) pointed out that SC systems are not only characterised by loose organisation of elements but can form a structure of interlinked SC systems with unknown number of elements and organisation. Furthermore, these interlinked SC system structures have ability to evolve over time which can be observed in the form of new acquisitions, mergers; business expansion; NPDs; new suppliers or innovation relative to process or product and many other ways. Dynamic changes in product design triggers many other changes in processes or organisation of business functions as observed in (Kempf, Erhun, Hertzler, Rosenberg, & Peng, 2013), where the market pressure and speed of innovation pushed Intel

Corporation to look for solutions and develop a framework for capital investment optimisation.

In order to adapt to continuous changes and dynamic nature of SC systems, modelling techniques are used to capture and learn about these complex systems. The challenge appears to be in deciding and understanding which modelling techniques should be used to capture E2E-SC system so as to evaluate, manage, control and further improve the performance measures of such system. Based on the findings from SLR, this research contribution is reflected in the conceptual framework that provides simplified framework of relations between various elements in E2E-SC system has been drawn.

Different modelling techniques could be used to reflect changes within a particular echelon in the SC system, for instance in the number of distribution centres (DC) and retailers (R) or their location. These alongside other changes in SC systems triggered by customers' and consumers' behavioural movements are more often driven by internationalisation and diversification of marketplace (Labarthe et al., 2007) and result in continuous strive for SCs to adapt and ultimately increase structural and systemic organisational complexity.

This further impact on the computational pillar within E2E-SC system model requirements as identified through SLR in the previous chapter. Businesses are required to provide enhanced services often considering multi-perspective approach and cross functional collaboration. For example, a logistical service does not only revolve around physical distribution of products, but often requires product/service customisation according to clients' requirements so as to provide such options as online sales, home delivery and goods return option. This has adverse impact on planning, designing and controlling of SC system and its relative processes, ultimately increasing complexity and causing system changes/evolution.

The complexity of the SC system is further increased due to hierarchical nature of these systems. Each echelon can consist of many subsystems, which may be characterised by different set of objectives, constrains and goals. The implications of this are visible in Pezeshki et al. (2013), where the authors reported on the benefits of adopting rewarding-punishing mechanisms based on trust in order to share partial forecast information and ensure benefits to the entire SC system. In this example retailers aim to maximise their profits; hence the supplier proposes a mechanism to ensure that retailers provide accurate demand information. This is to ensure that the supplier's performance is not compromised as well as the performance of other companies that may relate to the supplier.

Gunasekaran, Hong, and Fujimoto (2014) emphasised on the need to build SC capabilities to tackle issues within more extended and complex SCs in the era of global turbulence. The authors stressed on the importance of constructing relevant strategies derived from sound theoretical frameworks and supported by practical evidence to efficient and effective E2E-SC systems. This was also acknowledged by Serdarasan (2013), who pointed out that managing complexity should be integrated in SCM to achieve superior SC performance. The author underlined that SC complexity drivers should be well understood and managed, which can ultimately lead to improved strategic and operational derivatives and the greater overall performance of the entire SC.

3.3. Modelling the end-to-end supply chain (E2E-SC)

There is a need for modelling E2E-SC systems/networks, whether to devise end-to-end risk management strategy (Daultani et al., 2015; Mizgier, 2017), evaluate entire SC system performance (Tsadikovich et al., 2016) or understand cognitive profile of the decision maker in the E2E-SC (Narayanan & Moritz, 2015). Simulation modelling is one of the most powerful tools available to a decision maker (Kelton, 2016) to address various complex aspects surrounding research in SC. This seems particularly important in the light of increased socio-economic and environmental threats that SC are prone to experience (Poojari et al., 2008). The survival of many if not all SCs depends on their abilities to respond to changing customer expectations promptly, hence often high level of flexibility and visibility over the entire i.e. E2E-SC system is needed. Simulation modelling allows to describe E2E-SC system behaviour and help experimentation and analysis of various strategic, tactical and operational decisions and the impact that these have on the overall system performance. Likewise, through applicability of scientific knowledge the impacts of external factors and the surrounding environment as well as various existing complexities can be factored during conceptualisation and model development. Simulation modelling is a process of developing a simplified representation of an E2E-SC system depending on the purpose of the research or study (Oakshott, 1997), no matter if the system already exists or needs to be brought into existence (Pegden et al., 1995).

The efforts of this research are directed towards development of a generic E2E-SC system model and explains the importance of simulation methodology in achieving this. The importance of system thinking, and complexity theory has been acknowledged throughout the research and culminated in the development of conceptual framework, which captured the key aspects behind these two theories. In principle, the framework focused on three pillars; structural, computational and systemic organisational. The research further argues that to model a complex E2E-SC system a modeller would need to consider the structural elements of the system and decide on the relevant computational technique/s and method/s to be used. Nevertheless, a systemic organisation of such system should not be abrogated and given equal attention as there are changes that can be seen in the system structure because of using different and continuously changing computational methods. E2E-SC systems and the functions that they perform can be very complex, hence often supported by OR/MS techniques.

The OR/MS techniques that can be used in modelling SC can be classified under analytical or mathematical methods and involve such techniques as linear programming (LP), forecasting or vehicle routing problem. This is further discussed in Chapter 4 with various examples on how simulation was combined with OR/MS techniques.

3.3.1. Application of OR research techniques

The OR/MS approach appreciates the scientific method within the decision-making aspect of management (Fabrycky, Ghare, & Torgersen, 1984), which further complements and enhances the SCM and results in an improved E2E-SC system structure and organisation thus more efficient and effective performance of the entire system. The use of OR/MS methods can be used in two ways to process an inquiry; one that calls for the systematic and logical development of the theoretical base for choosing operational technique and secondly empirical testing of the base (Fabrycky et al., 1984). Consequently, OR/MS models that are founded on scientific management (SM) consider discussing management problems through the common view of the philosophical applicability of methods to offer more complete and rigorous analysis of the phenomenon under investigation. Therefore, when focusing on offering a best solution to a problem which has a different set of constraints or perhaps a set of conflicting objectives, one needs to consider a trade-off between alternatives to find the best/optimal solution (Mabin, Davies, & Kim, 2008). However, Paucar-Caceres (2010) reiterates that the application of OR/MS in business has changed over the years and MS methodologies and methods are often used to many management problems primarily through application of OR techniques.

OR/MS methods can be defined as the application of scientific methods to operational problems (Fabrycky et al., 1984). One of such scientific method is a simulation, which is the most applicable method to study complex aspects in an E2E-SC such as a nature of connections between facilities and system components inter-relationship (Carvalho et al., 2012). Moreover, simulation adheres to the OR/MS method, whereby the researcher through comprehension of the existing reality creates a conceptual model based on the information obtained from various sources, justified and represented in a form that satisfies the purpose and value of the user (Fabrycky et al., 1984). OR techniques, which are purely derived from scientific knowledge, are applied to improve functionality of systems such as E2E-SC system. When referring to a system consideration is given to variables and links that define a structure called system, which is understood through the design of the input-throughput-output model. This goes beyond cause-effect and affirms that understanding of science and the effects of various modelling efforts within such a system/model can broaden researchers' knowledge and application of it. In many situations, systemic thinking has been used within SC management comparing SC with systems like ant colonies or climate (Silva, Sousa, Runkler, & Sá da Costa, 2009) and applying scientific knowledge about perturbation within such systems to SC systems. SCs are regarded as complex systems and researchers' often do not look for inputs that is somehow converted into materials/products, but rather they look at factors that perturb, or influence, the dynamics and structure of the system itself.

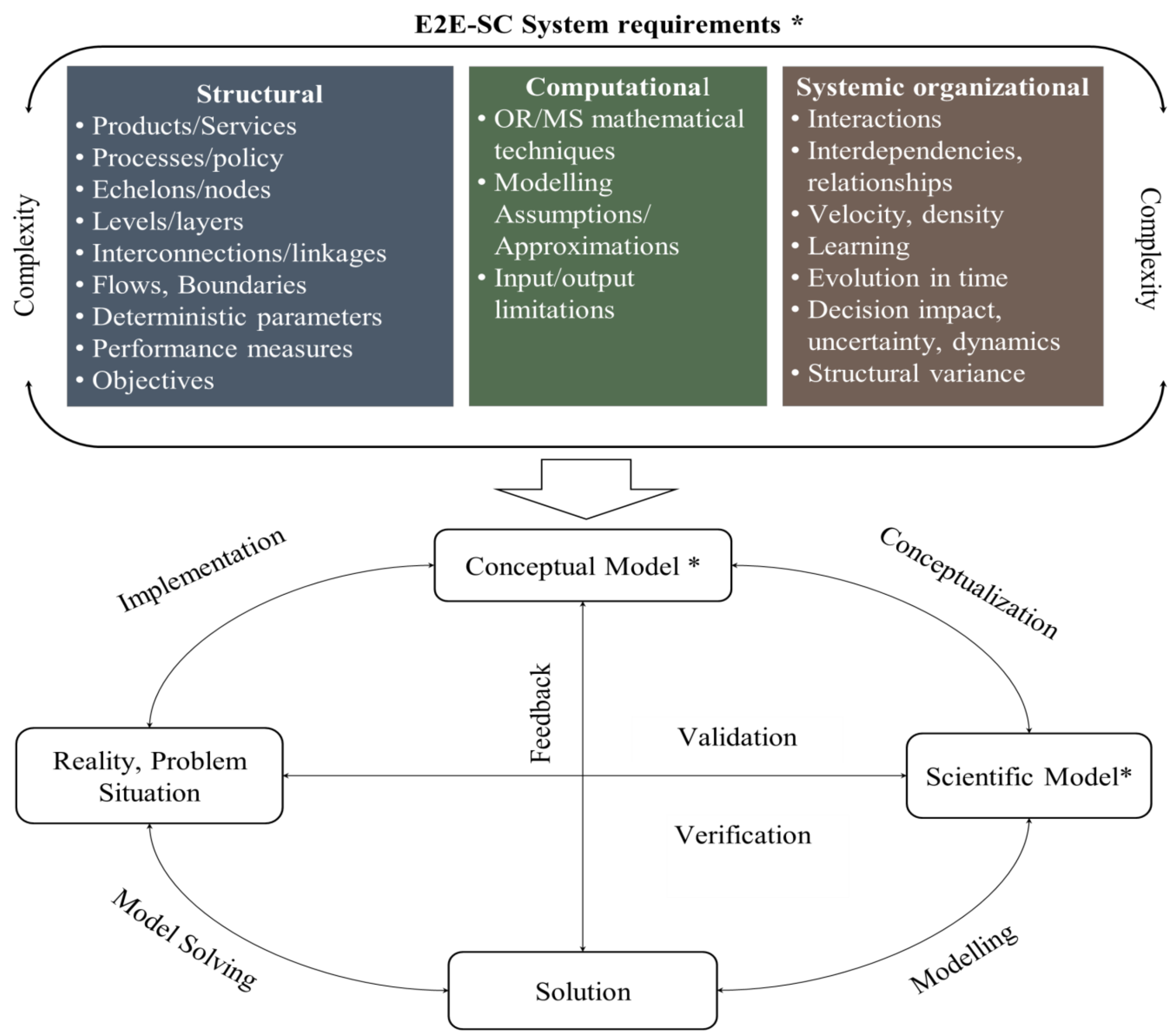
This research embraced Mitroff's 'scientific inquiry model', which offers a holistic view approach to a problem-solving inquiry while accepting the scientific management approach to operations. The inquiry into E2E-SC system key processes has been based on the SLR that reflected subjective as well as objective viewpoint of various social actors (authors). Notwithstanding the existence of diverse viewpoint presented within reviewed publications, the selection of the key processes is achieved through objective classification of all processes discussed within the literature and segregation of those that generic (appearing in all publications) and those that are industry specific.

3.3.2. Holistic E2E-SC modelling framework

One fundamental framework embraced within this research is Mitroff's 'scientific inquiry model' that provides a holistic view approach to a problem-solving inquiry. As highlighted in Figure 3.3.2-1 there are four major steps scientific inquiry process to address managerial and/or operational problems, whereby by undertaking sequential steps in the research one can correct misconceptions of science or advance its broad applications (concepts/ theories or empirical use) (Mitroff, Betz, Pondy, & Sagasti, 1974). When consideration is given to modelling SC systems and following philosophical underpinnings of system thinking and complexity theory, the development of scientific model needs to consider elements of an E2E-SC system.

Therefore, this research builds further on the fundamental principles behind the Mitroff's scientific inquiry framework, which is further enhanced to embrace a scientific management (SM) approach to operations, E2E-SC system elements and simulation methodology. SM relies on the application of systematic methods to managerial problems arising on the shop floor, which is a domain of OM.

Figure 3.3.2-1 Model Development Process
**contribution of this research*



Further developed from Sargent (2013), Morin (1992), Mitroff et al. (1974)

This research field applied analytical techniques focusing on the engineering aspects of empirically tested operational techniques, however lacking generic scientific knowledge about the business processes. This aspect will be addressed by applying OR techniques which emerged as a branch of OM focusing on the mathematical solutions to the problem and the quality of those solutions (Fransoo & Bertrand, 2002).

E2E-SC system elements formed a conceptual framework and were profoundly discussed within the literature review chapter. The framework contributed to the research and wider body of knowledge by bringing together all fundamental pillars needed for modelling complex E2E-SC system. Therefore, when developing E2E-SC system models, these three pillars need to be taken into consideration and reflected upon during development of a conceptual model, which then would be translated into computerised model. Modelling problems, reality or scenarios relative to E2E-SC systems can increase model and computational complexity significantly hence the applicability of simulation methodology.

The growing interest in SC systems is attributed to its structure or design, complexity inherently enhanced by the computational techniques and methods used not only to operate and manage SCs but also to study them as well as more sophisticated and diverse management policies often incorporated and combined with the structure and computational factors. Cigolini, Pero, and Rossi (2011) affirmed that performance measures come as a linking point between all those elements although the challenge is in determining the measurement system that will allow comparing different scenarios and changes in SC configurations. This is particularly difficult when the entire SC is considered and multiple organizations involved. Therefore, the model design specification that follows aspects considered and presented in the conceptual framework will be devised.

Development of an E2E-SC model is not a trivial exercise and can involve inductive and deductive approach. Within this research, a deductive approach was adopted to identify generic elements of the E2E-SC system through SLR approach. The literature was analysed and findings were gathered in the form of a conceptual framework highlighting generic E2E-SC elements/requirements. Research often connects such approach with qualitative research methods (Saunders et al., 2015). On the other hand, inductive approach involves developing theory from the data collected during the research process and often associated with quantitative research methods (Wilson, 2010). Simulation can produce large amount of data not only because of simulation run, but also including the values of system variables and outcomes for each iteration as well as the parameter settings and initial condition settings.

3.3.3. M&S methodological considerations

Modelling and simulation (M&S) involves various activities in simulation study, which can be grouped into four general stages, aligned with the scientific inquiry model steps proposed by Mitroff et al. (1974). Broadly speaking these activities require understanding and definition of the problem or reality that needs to be modelled, development of conceptual model, which is then used as a guide and help in creation of scientific model on the computer and finally running the model to obtain results. These steps are very generic and can certainly be extended depending on the research domain and needs of the modeller and/or decision maker, as observed in Manuj et al. (2009), where the authors provided a rigorous process for design and execution of DES studies in logistics and SC.

Increasingly studies offer more insightful tactics and research methodological approaches relative to each of the four simulation studies stages, which seems to be mainly driven by the complexity surrounding SC systems nature and behaviour. Attention has been devised to conceptual model development and defining methods and procedures for system abstraction (Robinson, 2008). Conceptual modelling stage of the simulation study is critical to ensure that the intended purpose of the model is achieved and the entire simulation study is successful. Development of conceptual model may require cross functional expertise and communication between multiple stakeholders to ensure clarity in data requirements and validation and verification aspects (Robinson & Brooks, 2010).

Table 3.3.3-1 Challenges and issues in SC simulation study

Simulation Study Stages	Challenges & Issues in SC modelling
Reality, Problem situation	• Understanding of E2E-SC structure and organisation (holistic and systemic approach) • Setting system wide business objectives at strategic, tactical and operational level
Conceptual Model	• Defining methods and procedures for system abstraction. • Setting modelling objectives • Multidisciplinary knowledge requirements • Alignment and communication between stakeholders • Defining data requirements • Reusability & Composition • Validation and verification
Scientific Model	• Defining the most appropriate type of M&S • Reusability & Composition • Validation and verification
Solution	• Results replicability

Source: Table developed based on Mitroff et al. (1974), Robinson (2008), Balci, Arthur, and Ormsby (2011).

Balci and Ormsby (2007) provided a comprehensive overview of the requirements for the conceptual modelling life cycle. The authors reiterated that multiple facets impact on the success of simulation study and the main step, which is the conceptual model development process. These are relative to applicability and reusability of the simulation model by community of interest such as supply chain stakeholders/decision makers. Each of the stages presented in Table 3.3.3-1 above requires attention and clarity in approach and methodology to ensure validity of the simulation model and ultimately results of the simulation run (Robinson, 2008).

Balci, Arthur, and Ormsby (2011) evaluated the quality aspect relative to model or model elements reusability and composability in M&S. Equally this is an important aspect of the M&S in E2E-SC systems as focusing on development of simulation models or sub-models that can be reused is beneficial to SC practitioners and academics as it allows for quick development of simulation models based on defined problem or purpose. To this extend it is important to acknowledge that reusability can relate to methods or strategy used to develop a conceptual model stages within simulation model development process, or to scientific model and a programming approach or routine, simulation software design patterns, simulation model or components (Balci et al., 2011). Therefore, a research needs to clearly define which elements can be reused and in what context. Following Mitroff et al. (1974), Banks et al. (1996), Kelton et al. (2010) and Sargent (2013) this research adopted a simulation methodology and focused on the SLR in order to establish the OM/OR/MS processes that are generic and should be considered during model development process. A conceptual model definition has been derived from SLR findings, where the main characteristics of the E2E-SC were established. Understanding of the main building blocks, processes and elements of the E2E-SC as well as other contributing factors and specification of the model design would lead to evaluation of the simulation method and selection of the simulation tool to assist with computerized model design. Model verification and validation will take place henceforth which is further described in the simulation methodology section. The research will adopt a hierarchical simulation modelling approach and integrate the Supply Chain Council's SCOR framework (F. Persson, 2011; F. Persson & Araldi, 2009; Fredrik Persson, Olhager, Tekniska, Linköpings, & Institutionen för, 2002; Pundoor & Herrmann, 2007). The description of individual elements that make up the SC processes will be defined using building blocks, which are also known as Process Categories based on the literature surveyed.

There are limited studies that provide the guidance on how to develop a simulation model relative to E2E-SC systems. This section aims at addressing this gap by devising flowchart of the simulation framework for modelling E2E-SC system. Figure 3.4-2 depicts a link between a generic E2E-SC simulation model and the conceptual framework.

The initial step in model design is to define model development purpose and type of the SC under consideration. Secondly, a structure of the aforementioned SC needs to be defined, if unknown, as well as its boundaries and clear reflection of system objectives presented. It is also important to understand the system organization and identify all existing uncertainties as this will require the definition of modelling assumption. Next steps are following generic simulation methodology, where a modeller needs to define specific KPI's, implement conceptual system model onto computer software and perform scenario analysis.

This research will focus on the simulation model design process as proposed by Sargent (2013) and Kelton et al. (2010) and addressing following elements:

- Identification of the generic processes within plan, source, make, deliver and return
- Description of the best practices associated with each of the process elements
- Identification of the software functionality that enables the best practices

In addition, the research project will also build further on the generic supply network modelling approach that will equally consist of a certain number of suppliers, manufacturers, distribution centres and customers who will be represented as nodes within the supply chain. The processes performed at each node will be interconnected within a single node as well as between nodes.

The simulation model development process will be supported by academic and industry experts during the validation stages (qualitatively). Inferences related to the problem entity obtained from the analysis and implementation phase during creation of the Conceptual Model will be applied to the computer software. This will be possible by undertaking computer tests on the Computerized Model during the experimentation phase throughout the model development process. The model will be further replicated across various companies to confirm its overall applicability and limitations to modelling of complex SCs (Stefanovic et al., 2009).

The external validity of the simulation model may be affected by the use of hypothesised parameter values and evaluated in the model rather than being derived from the real-world data (Meredith et al., 1989). This has been identified as a potential limitation during data collection process whereby some data that are required to perform simulation may not be readily available due to their sensitivity, insufficient sample or not collected by the company under investigation. Hence the use of approximated values within the model reduces its fit to the actual phenomena and increases the risk of irrelevance. Consequently, all such input values will be recorded and closely examined by the industry experts.

3.4. Explanatory design of the E2E-SC simulation model

Simulation methodology also referred in literature to computer simulation, is often used to study complex systems such as E2E-SC. Each of the individual elements presented in Figure 2.6.1-1 may seem simple and straightforward when studied separately and may be theoretically supported by previous research. However, when viewed from the E2E-SC system perspective, the outcomes of interactions between its elements may not be apparent. Simulation allows to examine system behaviours when subjected to simultaneous operations and it can be used for a variety of research purposes as defined by Harrison (1999):

- To predict system behaviour. This can be achieved by analysing simulation run output or by testing a hypothesis in an empirical study. This allows to observe how model variables behave when subjected to data changes or model structural changes (Seila, Ceric, & Tadikamalla, 2003).
- To proof model feasibility and demonstrate that the modelled processes/policies can show certain system behaviours in a given conditions (in the current research these would be structural and organisational setting when considering given computational elements).
- To discover/unveil unexpected system behaviours due to interaction between its elements. Simulation can be used in exploratory research to evaluate these behaviours by running multiple scenarios.

- To explain what processes/policies produce given system behaviour or as in case of this research to explain what elements should form the E2E-SC system model and how these affect modelling complexities.
- To examine and critique the current theoretical explanations for phenomena, to explore other existing explanations for these phenomena. Similarly, as in explanatory use of simulation, this approach pursues to explain phenomena, but this is achieved by analysing previous work and seeking for perhaps simpler explanations.

This research adopts the explanatory approach whereby all elements that constitute E2E-SC system where gathered via SLR and the consequence of modelling these were examined using simulation. As noted by Harrison (1999), the explanatory use of simulation can be also used to demonstrate model feasibility, hence in the current research shows how modelling can be affected by adding elements from the conceptual framework (Figure 2.6.1-1) to E2E-SC simulation model. Figure 3.4-1 depicts the research process starting from research aim and objectives formation through systematic literature review and E2E-SC model development to research validation and verification. In the introductory chapter, the background of this research was provided. It highlighted the need for the generic E2E-SC system model, which came about through desktop investigation of literature, attendance to seminars and conferences and multiple discussions with industry experts and academics.

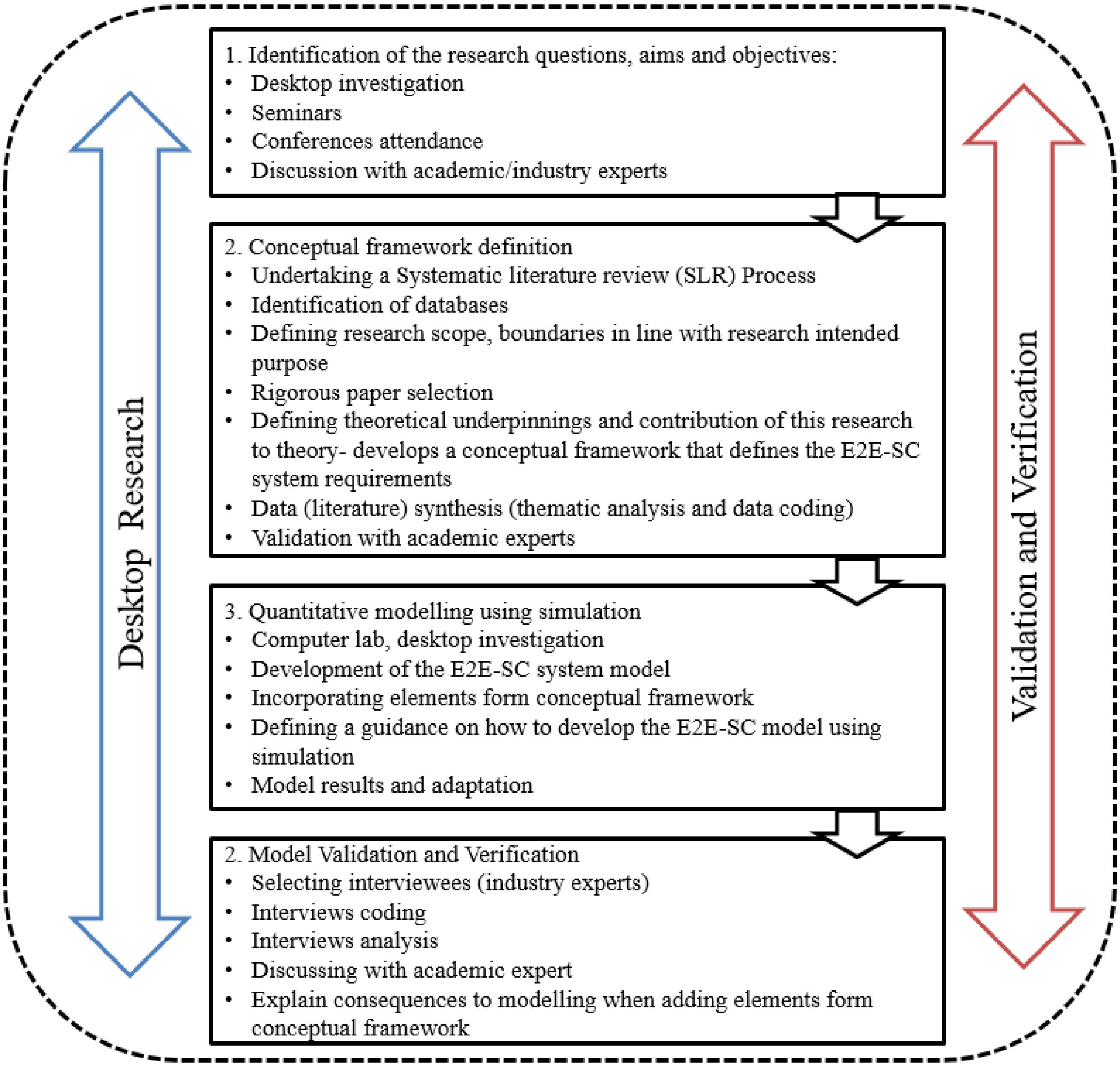


Figure 3.4-1 The research process

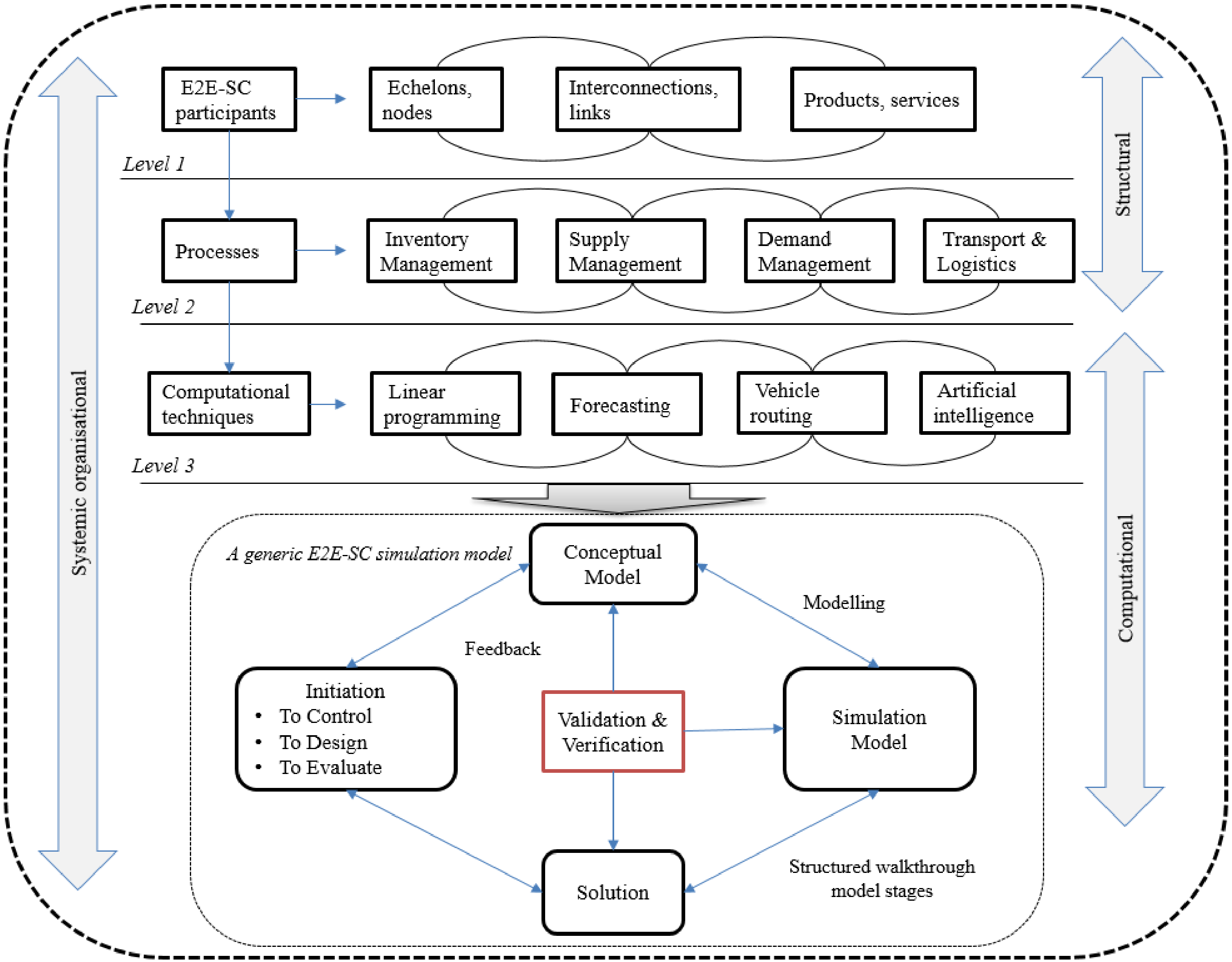
In the following step of the research, a rigorous literature review process was undertaken, which is summarised in Chapter 2. This was underpinned by two important theories for E2E-SC: the system thinking and the complexity theory. In Chapter 2, the explanation and relevance of these two theories is provided as well as the influence of the philosopher Edgar Morin. His understanding of systems combined with ambition of this research, served as an inspiration and resulted in formation of the skeleton for the conceptual framework i.e. structural, computational and systemic organisational.

The elements of the conceptual framework were gathered via literature synthesis and analysis, which were validated with industry experts and this is discussed in Chapter 5. The next step in the research was to define a guide for a scientific model development using simulation where these E2E-SC elements/requirements to be incorporated. The E2E-SC simulation model was developed on the computer, via desktop research, and a full description of the E2E-SC system model development process is presented in Chapter 4. The explanatory use of simulation when developing the E2E-SC model highlights why it is important to consider end-to-end supply chain elements and how adding more elements from the conceptual framework enhances modelling complexity and discusses how this may result in certain outcomes by shedding some light on the conditions under which such outcomes are produced.

Computer simulation or simulation methodology terms are frequently used as one of the most powerful quantitative approaches to investigate and analyse complex and dynamic systems such as E2E-SCs. In Chapter 2, a SLR highlighted simulation modelling techniques used to study these complex systems such as: discrete event simulation (DES), system dynamics (SD), Monte Carlo/Queuing simulation (MCQS), agent-based simulation (ABS) and Hybrid simulation (Hbrd). It has been observed that other methods that are frequently used as decision support tools are hybrid models based on analytical method supported by Simulation Study (AM/SS), where the analytical technique is reinforced by simulation.

These methods are often used in isolation and require a broader scope of investigation to understand the applicability of analytical techniques to model a specific issue within complex E2E-SC systems. Therefore, in the next chapter a deep dive into a hybrid modelling and into a hybrid simulation is presented. A reason to devise specific foci to combined modelling techniques is driven by the complexity observed in the E2E-SC systems at all three pillars: structural, computational and systemic organisational. Analytical methods can reinforce the study by their scientific properties, whereby strengths of OR techniques can be used in simulation models, which on the other hand can address all limitations seen in analytical methods Zulkepli, Eldabi, and Mustafee (2012). This research attempted to address this gap by developing a conceptual framework, which is then amalgamated into the simulation model development process. The link between the conceptual framework and the development of a generic E2E-SC simulation is presented in Figure 3.4-2.

Figure 3.4-2
A generic E2E-SC simulation model and the conceptual framework



The initial stage of the modelling process is to define the model development purpose and a type of the SC under consideration. As for the purpose, this may be to design, control or evaluate the existing strategies within the business and make an informed decision. Here the modelling assumption need to be clarified as well as uncertainties relative to E2E-SC system. The next step in the process takes into account the structure and boundaries of the aforementioned E2E-SC system to clarify these if unknown and also cogitates on the system objectives.

Understanding the main building blocks (SC participants and links between them), processes (such as inventory management, supply and demand management or transport and logistics) and elements of the E2E-SC system is an important part of the model development process. These have been divided into three levels in the simulation model development process following a hierarchical modelling approach, where the top level focuses on the highest level in the modelling hierarchy and a definition of the commonly used constructs, as well as company specified processes and templates (Kelton et al. 2010). The lower level in the modelling hierarchy consists of the application solution templates and other modelling techniques/methods such as linear programming or forecasting.

It is also important to understand the systemic organization and identify all existing uncertainties to adequately inform the modelling assumptions. Once E2E-SC system elements have been defined and the modelling objectives clarified, a conceptual simulation model can be developed. The next steps adhere to the generic simulation methodology, where the modeller defines the specific KPI's, implements the conceptual system model onto computer software and performs scenario analysis. Conceptual as well as computerized model requires validation and verification to ensure that E2E-SC model is a true representation of the real system.

Pirard et al. (2011) affirmed that simulation has been used previously as an effective tool to study complex and dynamic SC systems often operating in an uncertain environment. Byrne and Heavey (2006) noted that despite the existence of widely used analytical methods, the use of simulation is necessary to provide insights into SC behaviour and further highlights the importance of creating models that can be reused and adapted by industrial professionals.

Although, there are various approaches to modelling and different ways to model the same system could be used depending on the purpose of the study, there are few considerations surrounding model development. One of the important sections relative to simulation modelling methodology discussed by various authors is the model development process and steps and activities that this involves (Sargent, 2001; Manuj et al., 2009; Robinson, 2006). Simulation model development process alike the scientific inquiry model (Mitroff et al., 1974) should focus on the following distinct areas:

- Conceptual Model/Conceptual modelling
- Scientific/computerised model development
- Solution/Scenarios
- Reality, Problem, Situation

These are the fundamental areas that should be considered when developing E2E-SC system model. Often modellers or decision maker are required to address a problem, evaluate existing system and develop improvement strategies through different scenarios.

Figure 3.4-2 provided a graphical representation of the logical representation of the E2E-SC system model development logic. Following Mitroff et al. (1974), Banks et al. (1996), Kelton et al. (2010) and Sargent (2013), the proposed approach allows for the development of a hybrid E2E-SC system model that can combine simulation methodology with the knowledge on extended supply chain systems and computational complexity relative to modelling these systemic structures.

3.4.1. Generic model elements

This research conversely appreciates a broad-based system characterization of science and aims to advance the knowledge through designing a conceptual and computerized model based on the building blocks that capture the functionality of an E2E-SC system (epistemology) to better understand it. As discussed in the previous sections, one fundamental framework embraced within this research is that of Mitroff's 'scientific inquiry model', which provided a holistic view and approach to problem solving inquiry. The adaptation of the model developed by Mitroff et al. (1974) purported to enhance the design of this research while embracing the scientific management methodology to operations.

The conceptual framework presented in Figure 2.6.1-1 has been discussed at various points in this research. All generic elements of the E2E-SC system/model are considered in this research at the level of ontological assumptions where the modeller is required to perform a mindful inquiry into the modelling objective. Thus, the applicability of the conceptual framework and its elements. A computer simulation has been perceived by some authors as a computational model representing a system behaviour developed as a part of an experimental research design (Harrison, 1999). In the process of developing a computational/simulation model, all relevant system parts/components (structural elements) and specification of organisation of these parts/components (systemic organisational elements) need to be considered. Likewise, such models would include mathematical equations representing specific rules relating to modelled policies and processes, specifying how the values of variables change at time t+1 as opposed to a given state of a system at time t (Harrison, 1999).

When modelling E2E-SC system, some stochastic parameters can be used, where the uncertainty and noise can be reflected in the model using statistical distributions. This allows to include various uncertainty aspects into a simulation model. After the simulation runs are completed, the results may be subjected to further analysis. Simulations can produce a great deal of data for each variation, including the values of system variables and outcomes for each time period and summary statistics across iterations, as well as the parameter settings and initial condition settings. These data may be analysed in the same manner as empirical data (Rockwell Automation, 2014).

3.4.2. Structural pillar

This pillar considers various E2E-SC structural aspects such as, the number of echelons/nodes; SC levels, various flows within the SC, participants and processes characteristics, etc. These can have adverse impacts on the overall complexity and modelling E2E-SCs (Hwarng et al., 2005). The number of products and/or services offered could further amplify the complexity together with the type and number of processes as well as their structure (Carvalho et al., 2012).

The structural pillar characteristics are presented in Figure 3.4.2-1. Building further on the earlier studies, which were summarised in the Chapter 2, a list of structural elements that need to be considered during the E2E-SC simulation model development process was gathered. All of the elements should be considered prior to scientific model development process, nevertheless a specific number of echelons may be considered depending on the purpose of the project. Therefore, a list of generic elements of the model will not change, but characteristics (attributes) of these elements may be specific to a given E2E-SC system under investigation. The importance is to ensure that all fundamental aspects are not abrogated such as the relative precision of the E2E-SC system boundaries and echelons, number of products/services under review or connections between SC participants. Likewise, attention needs to be given to the model objectives, deterministic parameters as well as key performance measures.

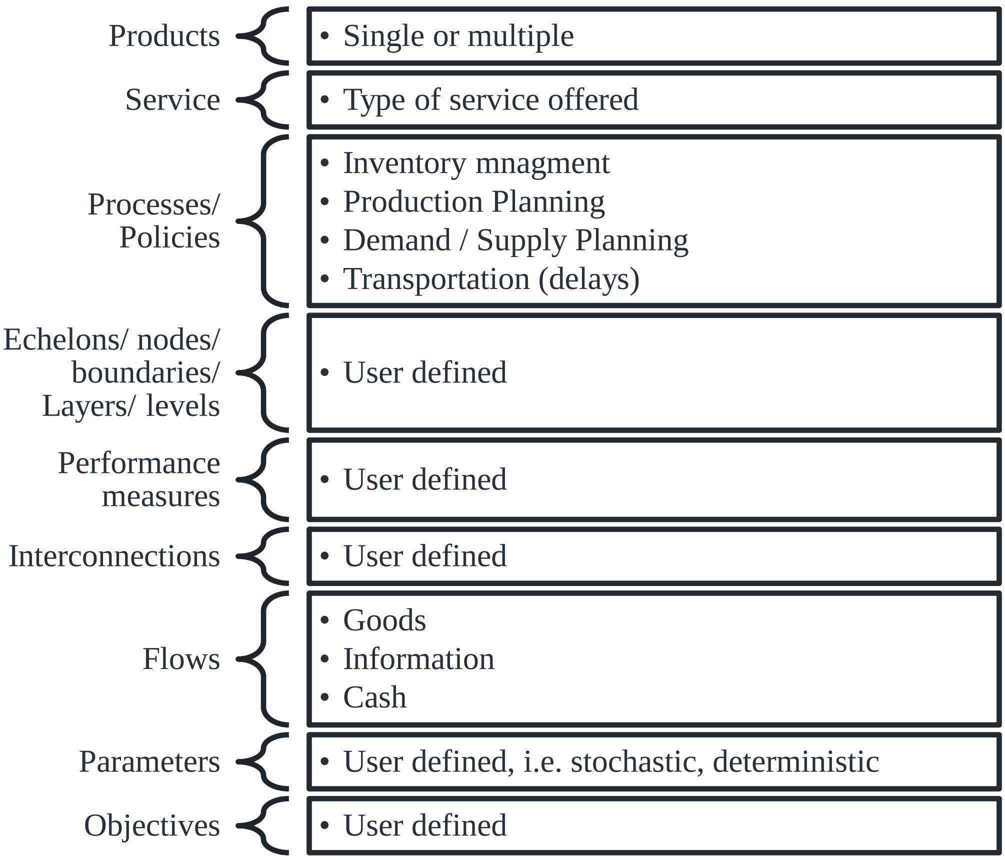


Figure 3.4.2-1 Structural elements characteristics

What came interesting in the literature is the perception and characteristics of relevant E2E-SC processes. The fact of various perceptions behind the generic model for supply chains was also discussed by Grubic et al. (2011), who pointed out on the lack of a well-defined process model that can serve as a context for building an object-oriented model. The scope of their model however, encompassed specific supply chain processes that supported material and information flows between buyer–supplier relationships.

A summary of the most frequently researched processes was presented in Chapter 2, which are considered within this research as a generic and should be considered when modelling any E2E-SC. These are specified in Figure 3.4.2-1 and include inventory management, production planning, demand & supply management and transportation.

3.4.3. Computational pillar

In regard to the computational pillar, this research argues that modelling the E2E-SC should consider computational aspects relative to methods/techniques that businesses use to support the decision-making process. This is particularly relevant while developing a generic E2E-SC system model due to the large number of operational research/management science (OR/MS) methods such as linear programming, forecasting, vehicle routing techniques or artificial intelligence used within businesses. Accordingly, this need to be reflected within the model and accounted for during the simulation model development process.

E2E-SC models are characterized by a high level of complexity; hence the model input and output assumptions and limitations need to be clearly communicated. Statistical distributions are often used as a way to address computational complexity or in the situations where the required data is not available.

E2E-SC models can be abstract with fewer elements focusing on a high level of hierarchy i.e. including echelons only or more specific and detailed spanning several levels, nevertheless modelling assumptions and approximation should be clearly defined for the system and model under consideration providing clarity on model structure and the systemic organization. This will allow for rigorous and transparent research as well as mindful inquiry into the systems' epistemic representation (Bolinska 2013) in order to observe and learn from changes in these systems.

The modeller is usually required to set parameters, relative to modelled processes, number of products, number of echelons, number of key participants, etc. An example of input parameters can be the arrival time of products, or capacity utilisation.

Likewise, the outcome of the simulation run may vary as often in complex systems they represent different behaviour, particularly if stochastic parameters are used. In such situation, multiple iterations are required to access the average system behaviour and draw meaningful explanation of the E2E-SC system model performance in the light of its intended purpose.

3.4.4. Systemic organizational

The systemic organizational pillar refers to the paradigmatic view of the system and captures the multidimensional level of interactions and interdependencies between the system elements. This is derived from ontological perceptions; which view E2E-SC as a physical construct as well as consider E2E-SC as an ideal, heuristic and pragmatic system, designed with predefined aims; to evaluate, improve and control. Figure 3.4.4-1 highlights systemic organisational pillar characteristics. At this level, a thoughtful consideration of the modelling purpose and system under consideration is to be given. This is needed to ensure that the model considers interactions and interdependencies that exist between key participants, nodes, echelons, processes etc.

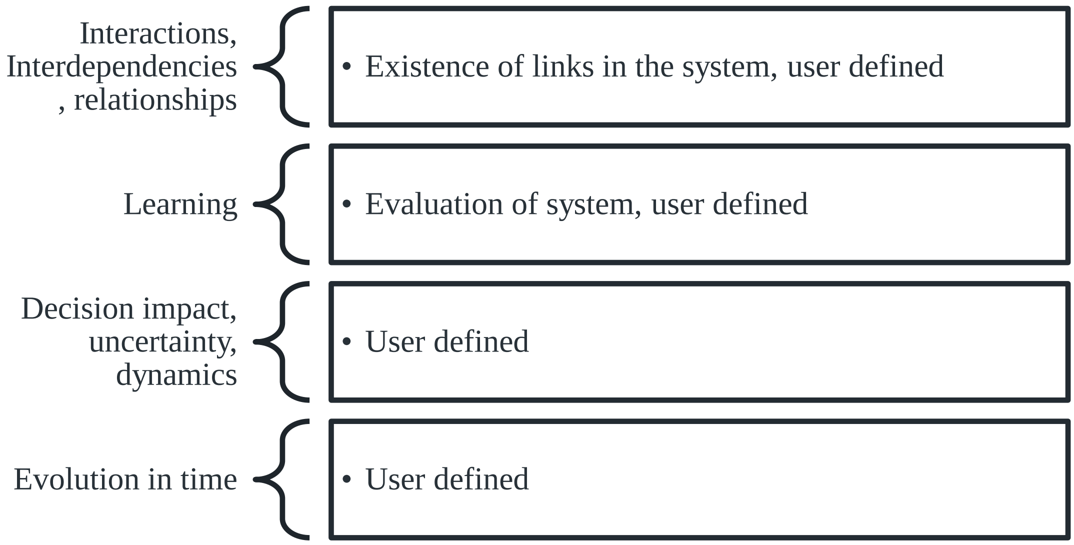


Figure 3.4.4-1 Systemic organisational pillar characteristics

3.5. Chapter summary

The aim of this chapter was to provide a clarity on the research design by explaining the links between its constituent elements. It further advocated the scientific rigor of the research, hence implied the necessity to provide a clear contribution of the conceptual framework to practitioners and academia. This was achieved through deliberation on the philosophical underpinnings and methodological approach that create valued points within the research design. In the next section, a step by step approach to E2E-SC simulation model development process is presented.

Chapter 4

End-to-end Supply Chain System Model Development

4.1. Introduction

The efforts of this chapter are dedicated to provide a detailed overview of the E2E-SC system simulation model development process. The research adopted an integrated methodology founded on principles of modelling, simulation and SCM to emphasise on the importance as well as complexity in modelling E2E-SC systems. A step by step guide to simulation model development is discussed as well as the impact and implications that specific elements from the conceptual framework (Figure 2.6.1-1) can have on simulation model development process.

It has been identified that the simulation methodology is a popular research approach particularly to study complex systems as presented in the work of Bagdasaryan (2011); Cannella et al. (2017); Shapiro (2007b). Simulation allows to replicate a real system using computer software and to perform experimental or scenario analysis on a model instead of a real system (Pidd, 2014; Kelton et al., 2010; Stefanovic et al., 2009; Seila et al., 2003). Although existing research provides a good clarity and fundamentals of simulation modelling, an endeavour undertaken within this research is to provide a new and more sophisticated approach to model an E2E-SC system. This requires an integrated and rigorous approach to modelling process, where multiple ontologies are used to support simulation methodology including validation and verification of all steps to ensure model reliability and replicability.

To validate and verify the applicability of the generic model a twofold approach has been implemented. Firstly, to ensure that the model works as intended the following activities were performed: structured walkthrough through the model elements and sub-models with simulation expert, review of model assumptions, code examination, review of verification procedures, replications analysis, review of results and scenario analysis (Robinson and Brooks, 2010). Secondly, with the help of industry experts from a company 'A', the computerised model was validated in terms of its structural and organisational similarity to the real E2E-SC system and its conceptual representation. This aspect of the research is discussed in Chapter 5.

This chapter discusses the importance of complexity theory and system thinking approach while developing E2E-SC systems simulation models. The research pursued to investigate how to develop a generic E2E-SC system model using simulation. The model development process focusedon ensuring that all generic E2E-SC system elements identified via systematic literature review (Figure 3.3.2-1) were considered. An integrated approach that incorporated DES simulation and OR/MS techniques combined with Microsoft (MS) Excel master data was adopted. The MS Excel master data file contained information that was used to support the E2E-SC system simulation model development process. The following sections will present a step-by-step guideline to a generic E2E-SC system model development process and will focus on answering the following research question:

RQ3. Considering the multidimensional nature of research stream, to what extent the segmented models can be integrated with simulation?

This part of the research will also attempt to address the following two objectives:

- To develop a computerized model using simulation that provides the architecture for combining various modelling techniques.
- To evaluate the implications to modelling when different elements from the proposed conceptual framework are included in the computerised/scientific model.

The chapter will present where complexity can be found in E2E-SC system and how it can impact on simulation model development process.

Simulation methods are frequently used as enablers for analysis and evaluation of effective management strategies within complex end-to-end supply chain (E2E-SC) systems. Most of the simulation methods exist in isolation and appear to have focused on the definite aspects of the system to be modelled and/or a specific SC research agenda. This research recommends an integrated methodology, which also will be referred to as combined or hybrid modelling that combines simulation methodology with knowledge on extended supply chain systems and computational complexity relative to modelling E2E-SC system structures. The study attempted to increase the body of knowledge on modelling E2E-SC systems by proposing a hybrid approach built on the fundamentals of system thinking and complexity theory and reinforced by powerful capabilities of the simulation methodology and mathematical modelling techniques.

The chapter commenced with a classification of SC modelling methods and then provided an overview of the hybrid modelling and hybrid simulation. It discussed the importance of using this approach for modelling E2E-SC systems as well as combined approach between hybrid simulation and OR techniques. Thereafter, it discussed the Arena® simulation modelling environment, explaining characteristics and properties of the software. It continued with presenting simulation modelling definitions that were used in the subsequent chapters. Afterward, a generic E2E-SC simulation model development guideline was presented with focus on hierarchical model elements and description of sub-models and modelling levels. To this extent, the chapter aim was to present a new approach to modelling complex systems linking the conceptual framework, thus the structural/organisational E2E-SC system elements, simulation methodology and discuss computational complexity. Conclusively, it indicated the need for a combined methodology that can combine current computational techniques (OR methods) such as linear programming, vehicle routing problem models or optimisation within a simulation model.

4.2. Classification of SC modelling methods

The extant literature provides a wide range of studies on simulation in business and supply chains, categorising simulation techniques or various subjects of inquiry, researched with support of different simulation tools or techniques. However, SC practise and academia would benefit from a generic model highlighting more efficient methods that can improve the implementation of simulation models in SCs (Oliveira et al., 2006).

Simulation methodology has gained popularity over the years and is now regarded as one of the most powerful approaches to investigate and analyse complex and dynamic systems such as E2E-SCs (Bagdasaryan, 2011). In Chapter 2, a summary of modelling techniques and methodologies used to support decision makers were argued. The review highlighted the importance and popularity of various simulation methods to model complex E2E-SC systems: Discrete Event Simulation (DES), System Dynamics (SD), Monte Carlo/Queuing Simulation (MCQS), Agent Based Simulation (ABS) and Hybrid simulation (Hbrd). Other methods that are frequently used as decision support tools are Analytical Model/Simulation Study (AM/SS), where the analytical technique is reinforced by simulation. These methods are frequently used in isolation and a broader scope of investigation into E2E-SC system and simulation methodology could highlight a range of more sophisticated modelling approaches in this research field.

The research in supply chain modelling is often classified into two main groups: analytical and simulation models (Othman & Mustaffa, 2012). Shapiro (2007b) provides another classification distinguishing between models that are descriptive in nature, developed to better understand the relations within the SC systems and with the surrounding environment. The second group of models defined by the author are normative models that have a decision supporting function and are meant to help managers in making better decisions (Shapiro, 2007b). The first group covers for example; forecasting models, cost and resource utilisation models as well as simulation models, whereas the second group includes optimisation, linear programming, heuristics or hybrid models to name a few.

Modelling involves the use of data and analysis to improve performance of the system under consideration. This often links to the strategic approach adapted by the businesses and ultimately to the specific management theory or theories (Shapiro, 2007b). One of such theories is a system theory, which is often considered in research on modelling complex SC systems and forms a part of theoretical underpinnings of this research (Ghadge, Dani, Chester, & Kalawsky, 2013; Saad & Kadirkamanathan, 2006; Van Der Vorst, Beulens, & Van Beek, 2000; Wangphanich et al., 2010). Theoretical assumptions of the research are important to understand and align the ontological and epistemological position of the research with the correct research methods. Research in modelling supply chain systems often takes a pragmatic approach due to importance of problem solving and in supply chain management due to urgency to improve performance of the entire supply chain (N. Mishra, Choudhary, & Tiwari, 2008).

A continuously growing research in the area of modelling SC systems led to wide research with sophisticated normative models that consider for example system dynamics (Hussain & Drake, 2011), optimisation (Bottani et al., 2015), DES (Carvalho et al., 2012), and hybrid models (Venkateswaran & Son, 2009). When modelling SC systems, four main groups of models can be differentiated as depicted in Figure 4.2-1: analytical models, heuristic models, simulation models and hybrid models. Analytical models are based on OR scientific techniques/algorithms used in demand forecasting, linear programming, optimisation or vehicle routing problem (Shapiro, 2007b).

Heuristic models are often used in problems that require pragmatic solutions, where analytical models seem insufficient and require human intervention in the form of best selection of methods or selection of optimal combination of objects from discrete set of objects (Shapiro, 2007b). These may be classified into common group of combinatorial optimisation models, which may be general purpose or problem specific. In the current research, it is often observed that optimisation methods have some limitations as they are unable to consider impacts of uncertainty, hence they are often combined with simulation methods (Frazzon, Albrecht, & Hurtado, 2016). Advanced heuristic methods such as Genetic Algorithm (GA), Simulated Annealing (SA), Evolutionary strategies, Tabu or Simplex search allow to search for a right fitness solution and are often used when multiple solving strategies are used in synergy to reduce computational effort while calculating solutions (Frazzon et al., 2016).

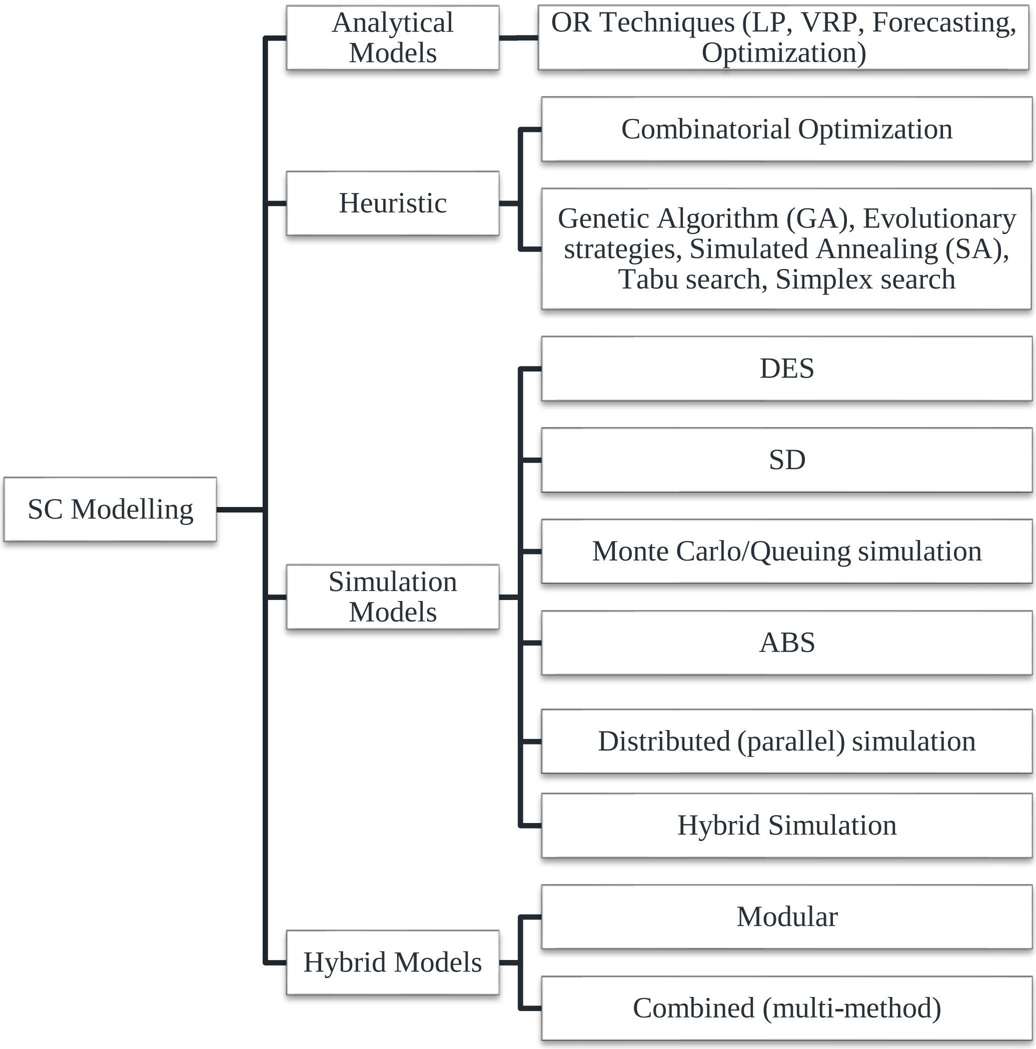


Figure 4.2-1 Classification of supply chain models

Simulation models are used to analyse complex systems, where system input and output may include stochastic variables and unknown number of elements and where the simulation runs over a period of time to generate historic data. These data are then computed into a set of statistics to define a set of performance measures (Altiok & Melamed, 2007). Different simulation models were thoroughly discussed in chapter 2 with some insides into main techniques such as: DES, SD, Monte Carlo, ABS, distributed or hybrid simulation models.

The remaining group in classification of SC models are hybrid models. These include models that were formed from two or more different modelling techniques, which may be within the same category of methods/models or cross categories.

This research assumes that although both terms hybrid model and hybrid simulation can be used interchangeably, there is a difference between hybrid model and hybrid simulation, whereby in hybrid simulation, the combined model includes element of two or more of the simulation techniques. On the other hand, in hybrid models one can observe a combination of techniques, which may or may not include simulation techniques.

The extant research highlights various propositions and frameworks covering different management theories or ontologies focusing for instance on business processes as presented in Grubic et al. (2011). A complex nature of the entire / E2E-SC system and the importance of improving their performance, calls for more powerful methodologies and approaches such as simulation and combined / hybrid modelling approach. Likewise, with the vast research on modelling supply chain systems and lesser attention on the extended properties of these systems, a generic approach is crucial and needed to describe and guide through the main steps in model development process for E2E-SC system (Grubic et al., 2011).

4.2.1. Hybrid modelling combined with OR/MS techniques

This research adapted a cross disciplinary approach incorporating principles of simulation modelling, supply chain management as well as system and complexity theories. The research examined the existing knowledge on modelling E2E-SC systems and defined generic model development steps for hybrid models that incorporate simulation and OR techniques. The hybrid modelling approach has been attracting attention from researchers and practitioners lately with more complex system models observed in the field of supply chain (Onggo, 2015). The current research focused on the E2E-SC systems and explained steps required to develop a hybrid model, where simulation is used as one of the methods.

Some examples of current research adopting hybrid methodology to complex supply chain systems is presented in Table 4.2.1-1. Gnoni et al., (2003) developed a hybrid model to study operational aspects associated with production planning in a vulnerable, automotive four-echelon supply chain. The authors combined analytical, mixed-integer programming (MIP) and discrete event simulation (DES) models to solve lot sizing and scheduling problem in multi-site manufacturing system subjected to capacity constraints and demand uncertainty.

The authors appreciated advantages of using both techniques for modelling complex systems, where the analytical method was used to provide an optimal solution for a defined objective function, for a given set of decision variables and subject to specific constraints. A hybrid approach was adopted to solve lot sizing and scheduling problem (LSSP) aimed at minimising an objective function (sum of setup, inventory and fixed costs). An iterative approach at global and local levels for multi-site production planning was developed. It was observed that computational complexity was increased by sequence dependency in products setup times affected by capacity on line constrained by machine failures. An iterative procedure looked for feasible solution and trade-offs between setup and holding costs at production site. The results indicated that the hybrid, iterative approach led to smoothing of objective function for global optimisation strategy aiming at balancing between set up and holding costs after few iterations hence better economic performance for the case study company. Although there were clear benefits of using hybrid approach in this work, the context of the study did not consider key players in the supply chain and was aiming at improving performance of the focal company only.

Table 4.2.1-1 Examples of research with hybrid modelling approach

Authors	No of echelons	Analytical method	Simulation method	Key hybrid modelling characteristics
Vahdani et al., (2011)	4	Fuzzy set, PERT	-	A hybrid approach developed for supply chain network analysis, based on combining a fuzzy set theory with program evaluation and review technique (PERT),
Gnoni et al. (2003)	3	MILP	DES	Optimisation of Lot sizing and scheduling problem (LSSP), DES model to describe system behaviour under uncertain production variables and evaluate manufacturing performance over time, Adopted iterative procedure for local and global optimisation, Results of global optimisation (Analytical model) are provided to simulation model, which run results are fed back to analytical model for next (r+1) iteration.
Lee et al., (2002)	4	LP	DES	Combined approach; used continuous equations in the DES model
Arns et al., (2002)	4	PN, QN	ProC/B notation	A modelling ProC/B notation used to model SC system and then a hybrid approach based on PN/QN is used to analyse SC performance

Vahdani et al. (2011) evaluated supply chain network (SCN) collapse recovery activity and applied fuzzy triangular numbers to estimate the value of uncertain parameters such as operation times, customer demand and external supply of raw material. The authors developed a multi-stage hybrid model starting from evaluating order fulfilment ability of the SCN, through the collapse recovery possibility and in the final stage a SC simulator was used to dynamically evaluate fuzzy operation times of activities and decisions of fuzzy models on the fuzzy completion of project network as well as SC performance. In this example, the model developed focused on evaluating the network performance and collapse recovery activity and as such could only be used to model problems in statement based on the assumptions provided.

Lee et al. (2002) developed a combined DES and SD modelling approach, which contained state equations to describe system state. The authors classified supply chain elements and connections between them based on their attributes into discrete or continuous, whereby information flow relative to customer orders or inventory levels were considered as continuous elements but transportation as discrete element. The authors argued that combined methodology allows to benefit from strengths of each of the methods. This seems particularly important for complex E2E-SC systems (Onggo, 2015).

In the work of Arns et al. (2002), SC systems are also regarded as discrete event dynamic systems. The authors used a ProC/B notation formalism, a modelling language allowing to combine modelling with SC performance analysis, to describe SC systems as processes. A further semantics were developed to allow for the model to be translated into queuing network (QN) or stochastic Petri Nets (PN) to facilitate SC performance analysis using the existing analysis techniques that are associated with this two modelling approaches. A hybrid approach was applied here to SC performance analysis where the algebraic and numerical analysis were proposed to analyse sub-models and the aggregate result used to replace sub-models to perform a complete model analysis, hence reducing computational complexity.

The current literature would benefit not only from more sophisticated models, but also from having a guideline or procedure highlighting steps required to develop a hybrid simulation model for an E2E-SC system (Oliveira, Lima, &

Montevechi, 2016). Modelling complex E2E-SC systems brings challenges and issues and hybrid models, where simulation methodology can be combined with other OR modelling techniques allow for gaining the benefits of each of the modelling methods (Zulkepli et al., 2012).

The SLR underlined that within OR/MS/OM as well as SCM policies and processes such variables as a lead time or a stock level are important aspects for the extended supply chains. Businesses and decision makers use quantitative models as a decision support mechanism, however in the current environment with more complex, longer and dynamic supply chains, simulation is often employed (Krejci, 2015). The existing publications and books capture various approaches to modelling SC related processes and provide a general knowledge on theoretical and practical applications of simulation and Arena® simulation environment (Kelton et al., 2010; Rossetti, 2010; Altiok and Melamed, 2007; Seila et al., 2003; Banks et al., 1996). These research efforts are often industry specific or focusing on one or two-tier supply chains (Carvalho et al., 2012). These may be attributed to the fact that supply chain related problems are often complex and cannot be solved with one method only. One example of such problem was presented by Saif and Elhedhli (2016), who combined MILP mathematical model to represent economic and environmental effects of cold SC design problem with DES. Simulation was used in their study to define the best control parameters for the inventory system.

The complexity observed within E2E-SC systems derived from their structural and organisational design as well as multidimensional relationships means that the combined application of simulation methods, or hybrid simulation, will allow synergies across techniques and will provide greater insights to problem solving.

This research argues that in the context of complex E2E-SC systems, hybrid simulation is the approach that can deliver benefits through combining simulation techniques (for example: discrete and continuous) with OR/MS techniques due to benefits that each method brings (Onggo, 2015).

Therefore, the development of an appropriate guideline for constructing E2E-SC system models using simulation based on hybrid methodology has been proposed as the contribution of this research. The proposed guide will be discussed in the section 4.4 and will aim to clarify all steps required to develop a simulation model as well as to provide an indication for the method to be used and allow to answer the research question on how simulation modelling can support modelling of an E2E-SC system.

OR/MS techniques are frequently used to support decision maker; however these may be limited in scope and capability when dealing with complex and global SC systems with multiple deterministic and stochastic variables, uncertainty and dynamics of the environment in which they operate. Table 4.2.1-2 provides as summary of various examples, where OR/MS modelling techniques were combined with simulation and analytical models. These models were used to address various SC problems relative to design, control and performance evaluation. Mathematical models were often used to address design challenges relative to deterministic parameters, whereas simulation techniques were adopted to study dynamic input parameters and their sensitivity to evaluate robustness of the SC (De Keizer, Haijema, Van Der Vorst, & Bloemhof-Ruwaard, 2012). Based on the literature presented in the table below, an integrated approach was often used at the level of control and evaluation of the supply chain, where more detailed aspects of the SCM were considered.

Table 4.2.1-2 Examples of OR/MS modelling approaches combined with simulation

Authors	**Analytical Method**				**AI**	**Simulation**	**Key modelling characteristics**
	LP	F	VRP	H			
Saif and Elhedhli (2016)	✓					✓	Distribution; Inventory-location problem A mathematical model (MILP) was developed to represent economic and environmental effects of cold SC design problem. DES was implemented to find the best control parameters for the inventory system.
Masoud and Mason (2016)	✓			✓			A mathematical model (MILP) was developed to address a problem of multi-planning period of production, inventory, and transportation in a two-stage, integrated supply chain system, and then present a hybrid simulated annealing algorithm (HSAA), including a constructive heuristic.
Mousavi and Tavakkoli-Moghaddam (2013)			✓	✓			Simulated Annealing, Tabu search, VR scheduling Distribution networks; Location of cross-docking centres;
Golozari, Jafari, and Amiri (2013)	✓		✓	✓			Hybrid simulated annealing-mutation operator (HSAM); Fuzzy capacitated location-routing problem (FCLRP); Ranking function
Noroozi, Mokhtari, and Kamal Abadi (2013)				✓			Computational intelligence algorithms: Artificial neural network, Hybrid GA; Batch processing scheduling; Learning approach
Lättilä, Karttunen, Korpinen, Föhr, and Ranta (2013)						✓	Decision-making; Forestry; Hybrid simulation; System analysis; Transportation

Shiet al., (2013)	✓			✓		✓	Logistics management, Cross docking; Latin hypercube sampling; Response surface methodology, DES
Yu et al. (2012)				✓			Hybrid GA
De Keizer et al. (2012)	✓					✓	Proposed a hybrid simulation and optimisation model for the fresh product supply chain network design and control problem. Analytical model used to define optimal operational design. Simulation used to evaluate network design, control cost and evaluate SC responsiveness.
Tunali, Ozfirat, and Ay (2011)	✓						Production and distribution planning in supply chain network to satisfy order promising process. Mathematical programming used to optimise production, distribution and inventory at tactical level and production scheduling at operational. Simulation model used to define order promising times based on data input from analytical model.
Merkuryeva and Napalkov (2009); Merkuryeva and Napalkova (2009)	✓			✓	✓		Genetic algorithm; Response surface-based meta-modelling; Supply chain cyclic planning
Dong and Li (2008)				✓		✓	Dynamic modelling; Heuristic control strategy; Hybrid simulation tool
De Sensi, Longo, Mirabelli, and Papoff (2006)	✓			✓	✓	✓	Ants Colony System; Modelling; Optimization; Simulation
Ko, Ko, and Kim (2006)	✓					✓	Distribution network; Hybrid optimization/simulation; Third party logistics
Shang et al. (2004)	✓				✓		Optimisation that incorporates Taguchi technique and response surface methodology

The next section will focus on hybrid simulation models, discussing current developments in this sector and applicability of this method to modelling E2E-SC systems. A summary of hybrid simulation research illustrated an overview of studies that combined two or more simulation models or simulation models with other modelling techniques. The existing research offers multiple examples, highlighting the benefits of using hybrid or combined methodology, however it would benefit from explanation on which are the main elements that should be used when modelling E2E-SC systems and what are the requirements to develop a generic model. Therefore, the current research takes on a challenge to provide the answer to the above questions.

4.2.2. Hybrid simulation

Hybrid simulation is regarded in this research as a modelling approach that combines two or more simulation modelling methods such as DES, SD or/and ABS (Onggo, 2015). Table 4.2.2-1 presents hybrid simulation papers selected during SLR (shaded colour) as well as other literature in this field of research. It provides some of the approaches used when modelling complex systems. As combining simulation methods is often used to study complex systems, it deemed important to discuss the work undertaken in this field and the applicability of such methodologies to modelling E2E-SC systems.

A combined or hybrid modelling approach may vary depending on the research purpose and context. Fleischhacker, Ninh, and Zhao (2015) conducted a research that developed a class of multi-echelon inventory models for clinical trial supply chains combining analytical models with simulation. The authors argued that combining research methodologies will prevail in the future research, where for example analytical models can be used to generate input to the simulation model and allowing to capture more real-life complexities. This point is considered in this research as one of the aspects to be considered during the E2E-SC model development process.

Hybrid simulation is more frequently used in studies on complex SC systems, where single methods may be limited, hence more beneficial seems using multiple methods (Frazzon et al., 2016; Zulkepli et al., 2012). Frazzon et al. (2016) developed a linear programming mathematical model with deterministic variables and DES model that mimics disturbances in production and logistics operations (using stochastic variables) of a global SC and the obtained SC performance results were subjected to control algorithm. The authors used a Genetic Algorithm (GA), which is a heuristic that is based on agent-based modelling, to compare results of the DES model with desired SC behaviours to define the right production schedule.

Venkatesvaran and Son (2005, 2009) and Son and Venkatesvaran (2007) developed a hybrid model based on non-linear optimisation model, heuristics, as well as system dynamics (SD) and discrete-event simulation (DES). They saw a need for a sophisticated integrated architecture to model hierarchical production planning in the SC systems. Their model was interfaced through high level architecture (HLA) where functional and process sub-models were supported by IDEF (Integrated Definition) system definition technique. The model was supported by use of multiple COTS software such as; Powersim ® for the SD model, Arena for the DES model and AMPL® for the optimisation model, wand all were integrated via HLA/RTI. A positive response of the architecture to the demand variations was observed after the experiment was implemented in the two-product and two-facility manufacturing enterprise.

Table 4.2.2-1 Hybrid simulation research characteristics

Authors	No of echelons	Analytical Method	Simulation method	Area of research
Rooeinfar, Azimi, and Pourvaziri (2016)	5	LP, GA	DES	SC network, production-distribution,
Frazzon et al. (2016)	3	LP, GA	DES	Production and logistic processes
Krejci (2015)	3	-	ABS, DES	Humanitarian logistics; SC coordination
Onggo (2015)	3	-	DES, SD	Blood SC, Elements of hybrid model presented: modules, module interface and updating rules
Rabelo et al., (2015); Rabelo et al., (2007); Rabelo, Eskandari, Shalan, and Helal (2005)	3	Analytic hierarchy process (AHP) technique, Integration Definition for Process Modelling (IDEF0)	DES, SD Continuous	Manufacturing system, Modular approach, SD model with connected with SCOR based DES models
	4	2 stage stochastic LP	ABS	Sustainable SC network, risk management, iterative optimisation and ABS simulation
Sel and Bilgen (2014)	2	MILP heuristic	DES	Production and distribution planning in soft drink industry; Rolling horizon heuristics;
Nikolopoulou and Ierapetritou (2012)	3	MILP	ABS	Production and distribution planning, transportation in chemical industry, Iterative approach to combine optimisation with ABS simulation
Cigolini et al. (2011)	3	-	C++, Java, VB programming	Object-oriented meta-model, Push and Pull planning approach; Petri Nets used to represent sub-models
Son and Venkateswaran (2007); Venkateswaran, Son, Jones, and Min (2006)	2	Optimisation	SD, DES	HLA used as in a hybrid distributed simulation, Vendor managed inventory (VMI)

Bai and Wang (2008)	3	-	DES, SD	Hybrid dynamic system; Vendor managed inventory (VMI)
Chatfield et al. (2007)	Not specified	-	ABS, DES, C++ & Java programming	Object-oriented modelling, modular design, parallel and distributed modelling
Pathak et al.(2007)	Not specified	Univariate analysis, Multinomial logistics regression (MLR)	ABS, DES	To investigate how SN topologies, evolve a theory-based framework is developed that combines aspects of complex adaptive systems theory, industrial growth theory, network theory, market structure, and game theory
Manzini et al. (2005)	Multi-echelon	-	DES, Continuous, Visual Interactive Simulation (VIS)	Design and management of extended SC with focus on distribution and order processing
Reiner (2005)	Not Specified	-	DES, SD	Quality management integration with SC processes in Telecom industry. DES results used to input to SD model.
Wartha, Peev, Borshchev, and Filippov (2002)	Not Specified	optimisation	UML-RT Hybrid Simulation kernel of AnyLogic	SCM processes including production and distribution
Young Hae Lee and Kim (2000)	Not Specified	LP	DES	SCM processes including production and distribution

Krejci (2015) combined ABS and DES models sequentially whereby the outputs of the first one was used as inputs to the second one. ABS are often used in studies where the human element or decision making is required in combination with operational techniques. A similar approach was undertaken by Chatfield et al. (2007) and Pathak et al. (2007). Onggo (2015) drew attention to a synchronisation mechanism needed between different simulation models when developing hybrid models. The author emphasised that one of the synchronisation algorithms from parallel simulation can be used or HLA-RTI (High level architecture – Run Time Infrastructure) software, which was also used by Chatfield et al. (2007) and Venkateswaran and Son (2009). Hybrid simulation research is growing in popularity and this research methodology is frequently selected in OM and SCM studies, where researchers and/or decision makers appreciate the benefits of using this modelling approach. Table 4.2.2-1 illustrated examples of hybrid simulation research, which drove the following summary:

- Hybrid modelling and/or hybrid simulation are used to address complex SC problems, which cannot be realistically modelled using a singular approach, hence combined methodology brings benefits and strengths of each individual method (Krejci, 2015; Onggo, 2015).
- Combination of analytical and simulation methods allows to account both deterministic and stochastic aspects of SC system and its inherent complexity.
- Simulation-optimisation is more frequently used approach to address complex OM problems such as production-distribution, while incorporating various SCM processes and policies (Younget al., 2000; Nikolopoulou & Ierapetritou, 2012; Wartha et al., 2002).

- Hybrid simulation is supporting modular design principles. A challenge relative to this approach is seen in defining an interfacing approach and updating rules to combine methods and/or models (Onggo, 2015).
- Iterative process between models in the hybrid approach can be supported by AHP-RTI software (Onggo, 2015).
- Heuristics such as GA, SA, Tabu and Simplex search or evolutionary strategies are used in optimisation methods combined with simulation to search for near optimal solutions (Frazzon et al., 2016).
- OR/MS techniques are used in both analytical and simulation models particularly at the operational and tactical levels. DES approach prevails in modelling operational and tactical SC levels, while SD is more often used at a strategic level (Rabelo et al., 2007; Tako & Robinson, 2012).
- Computer programming allows to develop a sophisticated object-oriented simulation (OOS) models that can incorporate various theoretical underpinnings and combine multiple modelling methods (Chatfield et al., 2007; Cigolini et al., 2011; Wartha et al., 2002)

Hybrid simulation is more frequently used in studies on complex SC systems. The popularity of this research methodology is accredited to its attributes, which are important for decision makers when analysing and evaluating extended SC systems.

4.3. ARENA simulation modelling environment

There are various simulation tools used for modelling purposes. International Journal of Simulation Modelling (2015) provides a list of selected discrete event simulation software amongst which are: AnyLogic, Arena, Automod, eM-Plant SIMUL8, WITNESS or ProModel that are available for decision makers perusal. Dagkakis and Heavey (2016) reviewed the state of the art in Open Source DES software used in modelling manufacturing, services, SC and logistics and argued that all commercially available DES packages as well as free cloud-based packages can be used for various practical applications and all have a similar simulation engine, however may differ in the user interface, program coding, visualization (2D or 3D) or cost of the commercial license. Limitations that Commercial-Off-The-Shelf (COTS) bring are around customisation due to lack of access to source code, lack of modularity and reusability of models and components (Dagkakis & Heavey, 2016). However, a selection of the simulation tool is only one of the steps within simulation methodology and the model development process.

Within this research, Arena simulation software has been chosen as one of the most robust and powerful tools for modelling complex system often used in studies on SC systems (Wu et al., 2013). Arena is an advanced simulation environment that allows modelling, graphically animating, verifying and analysing complex systems (Rockwell Automation, 2013). Arena software was also predominantly chosen in the selected studies within SLR, which could be due to its attributes and suitability for modelling complex systems.

There are two ways of working with Arena; first is relative to the development of simulation models based on the existing set of template panels and modules, which takes place in model window; and the second provides architecture for developing new template panels, which is performed in template window. Referring to the former, a new model can be created in Arena in a model window, where set of existing panels such as; Basic Process, Advanced Process, and

Transfer Process can be used to create simulation models (models then can be saved as. doe files). These are also available in the template window and their role is to support modeller during creation of the logic for the newly developed template panels, which will be explicitly discussed in the later part of this chapter.

For more information on the model building process and general knowledge on Arena simulation environment an interested reader is directed to Kelton and Law (2001) or Arena product manual, which can be found under Help in Arena software. Arena software is available as a student version for teaching simulation to students and building small models up to 40 blocks and 150 entities at a time in the model. For bigger models, the fully functional academic licensed version is required.

Particularly important feature of the software, available in the fully functional academic version is a Template Development environment, which provides capability for the design of new templates consisting of panels of modules and related modelling constructs. This requires navigation to the template window, where the process of creating new templates can commence. To this extend a modeller can at any point attach to or detach from the Project Bar all relevant template panel object files (.tpo files), which are supportive during the process of defining a module logic.

4.3.1. Arena® simulation software

Arena® simulation software was chosen for this research due to its powerful capabilities and applicability to model complex supply chains systems. There are various studies on complex SC systems, which chose Arena software as a modelling environment (Azevedo & Sousa, 2000; Carvalho et al., 2012; Cigolini, Pero, Rossi, & Sianesi, 2014; Gumrukcu et al., 2008; Karaman & Altiok, 2009; M. Mishra & Chan, 2012; F. Persson & Araldi, 2009; Tannock et al., 2007; Vamanan et al., 2004). Another example when Arena simulation software was used is Song, Li, and Garcia-Diaz (2008), who applied metamodel simulation methodology to multi-echelon SC problem to statistically analyse input-output parameters. An overview of the modelling software is provided hereafter to allow the reader to follow all steps described within this and relative sections of the thesis with ease and clarity. A further guidance on aspects relative to simulation modelling in Arena® and particularly template development is offered by Rockwell Automation within Arena's Software under Help>Arena Product Manuals>Template Developer's Guide. Likewise, there are various textbooks that provide comprehensive knowledge on Arena® simulation modelling environment for instance: Kelton et al. (2010), Seila et al. (2003) or Rossetti et al. (2011). Although, generic textbooks focus primarily on the simulation model creation and development, they often go beyond model building activities and provide advanced knowledge and explanation on technical principles behind such modelling constructs. There are fewer textbooks available that explain on how simulation methodology can support modelling complex E2E-SC systems. When dealing with an inherent uncertainty, the approach required is to focus on theoretical underpinnings and what these tell about the system under investigation and how can we apply this properly grounded knowledge into practise. This calls for more research on modelling approaches to model complex E2E-SC systems.

Arena architecture also allows for template development whereby customised modules and/ or models can be created. However, this requires an understanding of a programming language and the software itself to reflect on such constructs as well as an access to the professional version of the software. Template development is not considered in this research, nevertheless this has been recognised as an opportunity for a future work.

Although, modelling in Arena® can be performed in many ways, where the same operation can be modelled using various approaches depending on the skills and creativity of the modeller, when it comes to complex systems a broad knowledge on various modelling techniques, spanning across various disciplines is required. This research argues that combining modelling techniques is necessary to address all aspects of complex E2E-SC systems (Lee et al., 2002).

To this end the existing panels of modules are often used to develop SC related models, where Arena can be customized to include:

- External MS Office files whereby the software can communicate with Excel spreadsheets and Access databases for inputting or outputting data.
- Automation with the help of Visual Basic for Application (VBA)
- New modules development using Template Development in Arena Professional Edition

These features of the software provide a scope for extending the basic models and development of more robust, hybrid models, allowing for integration of existing mathematical models or/and existing information technology developments to provide a comprehensive replica of the complex systems such as E2E-SC.

4.3.2. Definitions

This section of the research provides some definitions relative to Arena® simulation modelling environment that will be used throughout the chapter. To this extend some generic definitions can be useful as they are used in both model window to build simulation models and in template window to create new modules, and these are presented below (Rockwell Automation, 2014):

- *entity*- relates to something that is distinct in existence, for instance within SCs it can be customer, goods or products, documents, components or parts that go through a process or other activity like queue or holding.
- *module*- is a construct that has operands and its underlying logic leads entity through the module, any time that module instance is placed in the model window. Modules are used to create models and are selected from template panel.
- module *definition*- all information about particular module i.e. module structure, data used within such module and animation, which are stored in the template panel library (.tpo) file.
- *module* instance- placing a module in the model window.
- logic window- is the modelling logic associated with a module instance in the model window and the data generated by the module.
- model logic- is the modelling logic associated with the model in Arena®.
- operand- can have two contexts; [1] refers to building simulation models and it is the dialog box in any module instance, which contains one or more changeable values (also called Field), and [2] refers to a template design, where the operands (changeable values fields) are defined/created by placing an object in dialog design window.

4.3.3. Hierarchical properties

Arena is characterised by a hierarchical structure, which permits building complex simulation models by providing an access to template panels and analysis modules depending on the need of the study (Kelton et al. 2010; Pidd 2004). A top-down model can be built, whereby a modeller can start with easier top-level system design, which then can be developed by designing sub-models. The advantage of this concept is that many sub-models can be modified without the need to change the entire model. This results in fewer errors due to minimal changes to the system hence better model reliability (Seila et al., 2003). This part of the research aims to underline how combining modules to represent supplier operation can form a model that can stand on its own or be used as a part of extended supply chain (sub-model).

Hierarchical feature of the simulation software also indicates that modules are defined using other modules, which is beneficial as some part of the processes or the sub-models once developed and verified can be used to build new higher-level modules. On the highest level in the modelling hierarchy lies the definition of the commonly used constructs, as well as company specified processes and templates, which need to be developed by a modeller. The lower level in the modelling hierarchy consist of the application solution templates, which are pre-defined set of panels, developed to satisfy specific modelling requirements for example to create a model replicating packaging operations incorporating models from Packaging template panel i.e. Machine or Convey.

The next levels in the simulation hierarchy considers the use of existing models from generic Basic Process panel through Advanced Process and Advanced Process Transfer to reach Blocks and Elements panel that allow for greater level of model flexibility and details. On the bottom of the hierarchy is User-Written simulation language or C/C ++ Code, where very detailed aspects of the developed model can be incorporated (Seila et al., 2003).

In Arena, the base modules in the hierarchy represent SIMAN simulation language, which utilises two panels: Blocks and Elements. The modules in the Block panel are used to generate a SIMAN model file (.mod), which commonly use the same naming convention as other Arena modules (i.e. Create, Access, Delay, Branch etc.), perhaps due to the similar functional capabilities. Blocks are structural parts of the module logic used during template development and are enhanced by Elements; which hold more information such as resources, queues or counters; written in SIMAN experiment file (.exp) and corresponding to data modules in other Arena modules panels. The existing Arena panels (Basic Process, Advanced Process etc.) contain modules with a predefined set of operands, which were built using Blocks and Elements.

However, if the structure of the existing modules within the panel are not sufficient and do not meet the modelling requirements then a modeller can develop their own templates utilizing hierarchical attributes of the Arena modelling architecture as well as following template development principles. When modelling complex systems, a consideration needs to be given to a various structural, computational and systemic organizational aspects, which directly or indirectly indulge the process of abstracting a system. This research appreciates the importance of holism and provides a framework, which identified generic E2E-

SC system elements to be used for modelling using simulation. SC systems are specific artificial constructs created and developed by humans yet operating based on various cross-disciplinary principles.

4.4. Simulation model characteristics

Manuj, Mentzer, and Bowers (2009) propose eight-steps guide through the design, implementation and evaluation of simulation models in logistics and supply chain, which corroborates generic simulation methodology with stringent requirements to maintain research rigour. These steps as well as recommendations from Sargent (2013); Kelton et al. (2010); Pidd (2004); Banks et al. (1996) and Kleijnen (1995) are considered during model development process within this research and are presented hence forth.

A generic simulation model was developed in Arena, and various simulation books as well as Arena's Smarts (a library of simulation models and tutorials covering a range of topics and suggestions on how to model in Arena), where used as a guidance. The inherent complexity found in E2E-SC system was discussed and its impact on model development process was demonstrated. The study illustrated how modules in Arena can be used to replicate an E2E-SC system consisting of suppliers, manufacturers, DC, retailers and transportation with their inherent processes, objectives, variables, constraints and possible other consideration. A generic guideline to E2E-SC system model development process was followed, specifying for instance, model assumptions, number of variables used, number of resources and their levels, stochastic as well as deterministic variables or organisational aspects such as number of different stock holding point. To fully apprehend the hierarchical functionality of Arena® simulation software a series of sub-models were developed. This designated process of combining modules to represent supplier operation formed a model that can stand on its own or be used as a part of extended supply chain.

Development of an E2E-SC model is not a trivial exercise and although some generic aspects relative to modelling systems would be applicable here, consideration should be devised to the establishment of governing rules. This is to devise a set of assumptions that would clarify the model scope and guide the modelling process. E2E-SC systems can be very diverse with varying level of complexity, which ultimately has a big impact on the development of models that replicate these systems. Hence the important question is: what are the elements of a generic E2E-SC system/network? The question itself can be quite broad in scope and without specified assumptions one could expect the answer to be replicable or generalised to all possible SC systems that are in existence.

One way to answer such question would be to group SCs by type of industry i.e. retail, automotive, oil industry, construction etc., as those could possibly have similar characteristics (Serdarasan, 2013). In this research, the focus was placed on the theoretical underpinnings and methodological approach, which defined the selection of the literature for review within a specified scope. Another important factor to consider was a level of details used to develop a conceptual framework and the scientific (computerised) simulation model. When considering the higher up level in the modelling hierarchy and/or the level of system abstraction, the more generic E2E-SC elements and characteristics are revealed (Venkateswaran & Son, 2004).

In defining E2E-SC system, this research considered the extended nature and the entirety of structural, computational and systemic organizational properties of such systems. This dictated a variety of possible solutions and options when designing E2E-SCs with much less modelling approaches available to reflect all facets of these systems. The proposed conceptual framework provided an understanding of the E2E-SC system constituent elements and at the same time showed its inherent complexity.

A further attention is required and more examples on how to model an E2E-SC system or network. Although, simulation has been frequently used to address OM, OR/MS issues it has often focused on singular or limited participants in the SC or key processes and operational techniques. Findings from the SLR and developed conceptual framework indicated which structural, organisational and computational elements should be incorporated during generic simulation model development. For instance, demand fluctuation, lead time or stock level are important aspects affecting performance of E2E-SC and as such should not be abrogated during model development process.

4.4.1. An E2E-SC model steps

The intention of this part of the thesis is to provide a detailed overview of the E2E-SC model development process. One important aspect that this research considers is an end-to-end representation of a SC system/network, hence the impact of problem specification/issue on hand or modelling purpose on all players in the SC. Looking from OM perspective, an example of such problem can be defining capacity requiremetns at all nodes within the SC so business objectives are met and profits are maximised (Makatsoris & Chang, 2004). This requires mapping the long term (strategic), medium (tactical) or short term (operational) demand forecast and supply to identify future capacity needs, assess options and

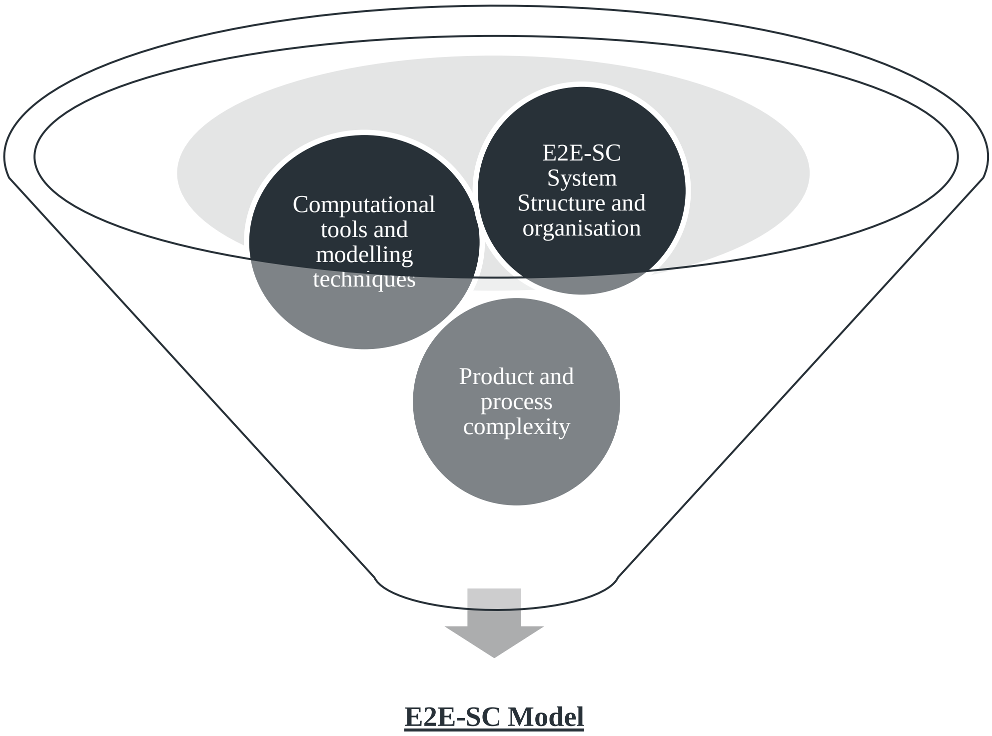


Figure 4.4.1-1 E2E-SC model elements

finally propose recommendations. The challenge in modelling an E2E-SC relates to complexity, which is found along the entire chain. For instance, products that businesses usually supply within one model may be subjected to various processes that could also involve multiple other businesses i.e. transportation, warehousing or distribution centres.

The research adopts an interdisciplinary approach and combines the knowledge on E2E-SC systems and simulation methodology with system thinking and complexity theories to highlight the implications brought upon by computational complexity when modelling these complex supply chain systems. One of the contributing elements of the research is around challenges and issues observed during simulation model development process and the impact of adding more elements/aspect from the developed conceptual framework. Derived from system thinking and complexity theory, the knowledge on modelling E2E-SC systems and its structural and organisational components was developed. Findings from SLR indicated that a system concept is often applied in SC research (Ballou, 2004; Lambert et al. 2004), system dynamics (Disney & Towill, 2003; Mula, Campuzano-Bolarin, Díaz-Madroñero, & Carpio, 2013) or cybernetics (Ashby 1964).

One way in which this research can support decision makers and academics is by extending the existing work on simulation modelling in SC systems. This can be achieved by evaluating and analysing an E2E-SC system simulation model development process steps and deliberating on the main aspects contributing to the complexity of such models. Simulation model development process stages are built on the multidisciplinary approach combing knowledge on E2E-SC systems/networks (Mishra & Chan, 2012), simulation methodology (Kelton et al., 2010), system thinking and complexity theoretical underpinnings (Ekinci & Baykasoglu, 2016; Morin, 1978; Yates, 1978) with principles of scientific inquiry model (Mitroff, 1974). The proposed modelling framework stems from multiple dimensions and provides a sophisticated approach for simulation modelling, where a cross functional knowledge and expertise is used to draw a mindful inquiry into a subject matter and problem at hand. The conceptual framework and its underlying pillars were developed through SLR and have recognised complexity elements as main factors affecting E2E-SC system performance and the main reason for simulation use in first place.

A simulation model development process consists of four main stages: conceptualisation, model development stage, simulation model execution and model implementation and scenario analysis (Çetinkaya, Verbraeck, & Seck, 2015; Banks, Carson, & Nelson, 1996). The existing methodologies provide a set of methods, techniques and tools often summarised under guidelines and approaches to simulation modelling study development and execution. Some studies looked at the modelling and simulation from software engineering perspective as observed in Balci (2012), where the author reviewed the project life cycle framework for large scale complex simulation projects.

The aim of the framework proposed by Balci (2012) was to describe the organisation of processes, product work, quality assurance, validation and verification as well as all project management activities that are part of simulation project development, use of M&S application, its maintenance and reuse. Çetinkaya et al. (2015) focused on the transition from conceptual to computerised model and emphasised that limited studies provide clarity on how to address a sematic gap between these two stages in simulation study. The results of their research delivered a model-driven development for simulation modelling framework in support of model continuity and formal transformation from conceptual framework into executable simulation model. The Table 4.4.1-1 provides step by step guide to E2E-SC system model development incorporating elements from the conceptual framework (Figure 2.6.1-1) and underpinned by methodological approach based on Mitroff's scientific inquiry model (Figure3.3.2-1) to simulation model development process.

Table 4.4.1-1 Steps for modelling E2E-SC systems using simulation

Level 1	Level 2	Level 3	Characteristics
Step 1 Conceptualisation	Problem Specification	SC Model Purpose	To Control To Design To Evaluate
	Conceptual Model Development	Structural Elements	SC type (divergent, convergent, single echelon, tree type SC, hybrid) SC configuration (Number of echelons) Processes/policies under review System interconnections and boundaries Number of links Flows under considerations Number of products
		SC Organisation	Dynamic system aspects Define system uncertainty System interdependencies (functional dependencies, interfaces, etc.) Characteristics of links
Transformation from conceptual to scientific model			
Step 2 Modelling	Scientific Model development	Modelling Objectives	To Optimise To Analyse To Solve (link to Performance Indicators)
		Model variables	Discrete Continuous Hybrid
		Computational aspects of the model	Input/output parameters Model assumptions/approximations Data type: stochastic vs deterministic Mathematical techniques/algorithms
		Data Collection	Data requirements and data source Data collection and storage method
		Modelling tool selection	Software Packages: DES- i.e. Arena, SD- i.e. iThink, Stella Hybrid- combined approach Programming Languages: Python, C, Fortran, C++, Java
		Model Validation & Verification	SC experts (subject experts) Structured walkthrough model
Step 3 Model Running/Solving	Simulation Run	Run Parameters	Run time units Number of replication and replication length Length of replication warm-up period
	Solve the model	Simulation results	Extract the solution provided. Define form of reports.
Step 4 Implementation and scenario analysis	Implementation	Model directions for use	Monitor model performance after implementation. Specify structural and organisational parameters that can be changed without affecting model intended purpose
		Experimental designs	Re-run model based on subset of collected data
	Analysis of results	Select appropriate technique for input/output analysis	Present analysed results. Evaluate solution i.e.: - Design of Experiment, - Analysis of Variance (ANOVA), - Comparative analysis, - Sensitivity analysis. Discuss model solution considering modelling objectives.
		Model and modeller behaviour	Use existing knowledge to analyse model behaviour and modellers cognitive reflection. Provide model limitations. Provide recommendation for model use.
Post Implementation evaluation			

The purpose of this part of the research is to discuss the main elements of the simulation model development process by amalgamating a cross functional knowledge in field of simulation modelling and E2E-SC systems focusing on systemic properties and complexity theory. The generic framework for modelling E2E-SC systems using simulation is building further on the existing literature and dwells on four general stages of the simulation model development process and aims to answer the following research question:

RQ2: How simulation methodology can support the modelling of a complex E2E-SC system.

The application of computer science is an important part of this research since most of the simulations are executed on the computer software and all technological advancements to software functionality have a direct impact on the capability of the existing tools and techniques. In the next subsections, the framework stages and characteristics will be provided and discussed.

4.4.2. Model design initiation and concept development

The first stage in the simulation model development process is a model conceptualisation, where a modeller or a decision maker defines a model intended purpose. This can be a specific problem that requires immediate attention or an improvement proposal to the existing processes or activities.

E2E-SC system is a complex set of participating organisations and businesses interconnected and interacting with each other and operating within a certain boundary (Wang, Zhang, & Kinsner, 2010). The system boundaries can be difficult to define due to its numerous elements, building blocks or parts, which are subject to continuous change over time. The state of an E2E-SC system can be represented with quantitative or qualitative variables. The organisational behaviour of such structure represents a condition of change over time due to internal reactions between system elements and in relation to other system states (Patel & Nagl, 2010).

At this stage, modelling purpose is defined, which may involve system design, control or evaluation. Defining a modelling purpose may be reflected in various ways and involve numerous activities such as defining the problem or an E2E-SC system under investigation and developing a conceptual framework, before moving to scientific model and simulation study goals. These preliminary activities may involve an investigation into E2E-SC boundaries and links between key participating organisations and mapping SC network structure and organisation to recommend the best location and number of facilities. The initial stage in the modelling could focus on evaluating, which processes and policies require attention in the light of external strategic changes or operational uncertainties such as demand or lead time fluctuation (Hung et al., 2004). These may be about globalisation and extending scope of operations as well as internal structural changes led by decision makers to benefit from profit improvement and cost saving strategies.

4.4.3. Problem specification

Various simulation guidelines define problem specification as a start of the simulation project. Williams and Ulgen (2012) advised that the problem statement should refer to numerical values and could potentially be aligned with key performance indicators. The authors explained that this is an important stage in the simulation project lifecycle as it allows to clarify the issue on hand and align with business needs or modelling purpose. This is also supported by Rossetti (2010), who reiterated that regardless of the modelling reason, one of the critical aspects is to define a set of performance measures.

The problem specification in this section refers to simulation model as well as E2E-SC system. A simulation model serves as a mean to design, control or evaluate the SC, and in such is developed to support needs of a decision maker. The model should be a true representation of a real SC system, hence the problem statement where available should be based on an existing problem, or alternatively the key performance indicators can be used as areas for improvement. Here the focus in on the complex E2E-SC and simulation models, however, severity and complexity of the problem needs to be clearly understood as various alternative methods to simulation can be employed.

The problem statement will be tailored to the needs of businesses and the structure of an E2E-SC will look different depending on the location of decision makers who may consider their company position as focal and have different views on the membership and the network structure. With the continuous growth of the structural and organisational complexity in the supply chain, the problem on hand can become intractable for the theoretical approaches hence simulation methodology is often used to support in modelling uncertainty market characteristics (Hung et al., 2004).

4.4.4. Conceptualising the research

Conceptual modelling step is an important part of any simulation study. The main purpose of this step is to provide a system description and specify the objectives, inputs and outputs as well as content of a non-software specific model along with assumptions used to create the model (Robinson, 2014). The design of conceptual model can be affected by multiple aspects, whereby the level of abstraction or in other words the level of simplification is often regarded as critical when replicating a real system. A conceptual modelling definition considered in this research is in line with Robinson (2014) and is focusing on simulation modelling of an E2E-SC. The definition is further complemented by the efforts of this research in the form of key elements that define structure and organisation of an E2E-SC whether in existence or not.

The key structural, computational and systemic organisational elements were identified through the SLR as E2E-SC system requirements and formed the conceptual framework for this research. In a nutshell, the conceptual framework presented in Figure 2.6.1-1 is instrumental in developing a generic modelling procedure for E2E-SC models using simulation. Structural and systemic organisational aspects were incorporated in the conceptual model step as the main areas of any E2E-SC that a decision maker is required to include or exclude, providing sufficient level of assumptions and linking with the study and model objectives. Pillars of the conceptual framework were further validated with industry experts and the conceptual framework validation is discussed in Chapter 5.

A computational pillar and its inherent elements were found more relevant for the 2nd phase, which is the modelling step and are further discussed in the scientific model development section. In line with definition provided by Robinson (2014), this research assumes that conceptual model is developed in separation from computer model and in fact the first one is used as a generic set of theoretical and practical concepts that support development of scientific/computer model.

A conceptual model is a base or foundation for developing computerised models in any modelling environment. Within this research the conceptual model describes a list of elements that constitute an E2E-SC a system. The list is depicted in Figure 4.4.4-1 below and includes the E2E-SC participants, processes and computational techniques.

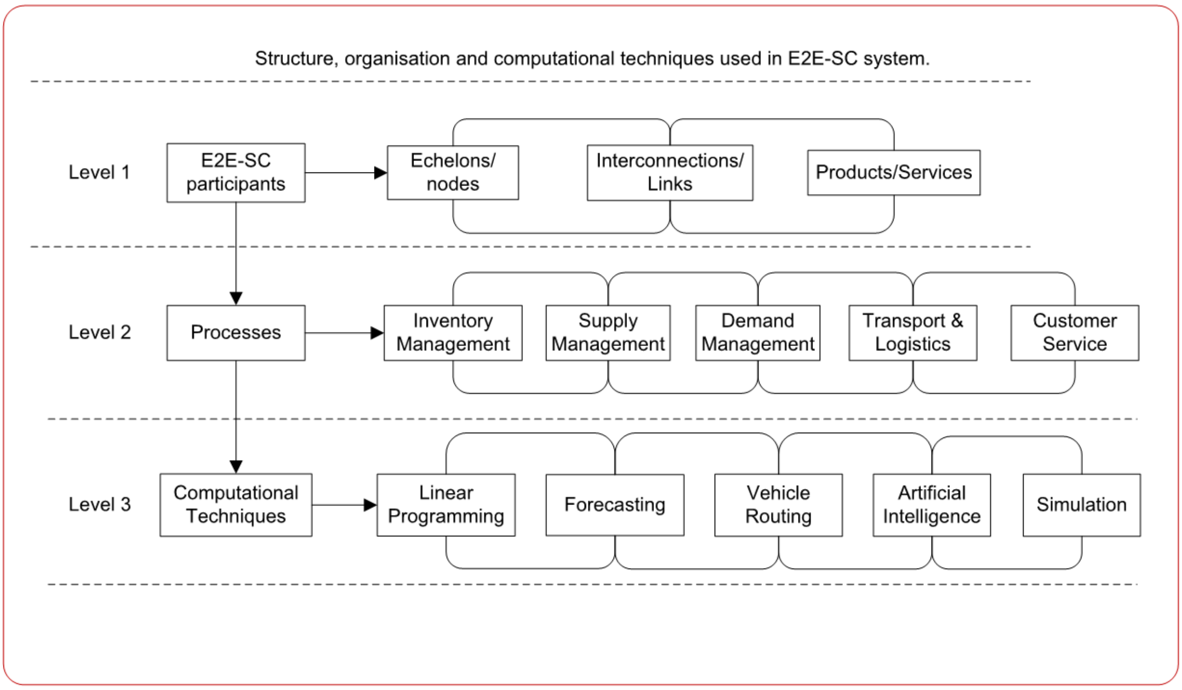


Figure 4.4.4-1 Levels in E2E-SC system model

Considering generic E2E-SC system elements presented in Figure 2.6.1-1, this research described an E2E-SC from a holistic perspective and classified its elements into three levels (Figure 4.4.4-1), whereby the structural characteristics come as a top-level view, linking the organisation to its key participants; echelons/nodes, links, products/services. Level two defined a set of processes to be considered when modelling an E2E-SC, and level 3 defined OR/MS techniques that are used to manage, control or design an E2E-SC and its strategic, tactical and operational policies. The Figure 4.4.1-1 aimed to provide a guide on how to design an E2E-SC conceptual model. In the next section, a generic E2E-SC conceptual model will be discussed and in the following sections, this will be transformed into a scientific computer model design in Arena simulation software.

In the generic E2E-SC conceptual model consideration has been given to number of SC participants, which formed a set of echelons, that is supply node, make node, deliver node and customers node. In a simulation model development process, a modeller was required to describe an E2E-SC under investigation, present the linkages between the nodes and to define the boundaries of the system as well as to define environment/market consideration (Georgiadis & Athanasiou, 2013). Moreover, as often observed in the literature (Cannella et al., 2017; Das & Dutta, 2013; Shockley & Fetter, 2015) type of products and services needs to be defined, and whether a singular or multi product supply chain will be modelled.

4.4.5. Generic E2E-SC model characteristics

This section of the research is focusing on presenting the generic E2E-SC model and its elements. Inspired by work of Hwarng et al. (2005), Vieira and Junior (2005), Pundoor and Herrmann (2007), Tipi (2009) and Van Der Vorst et al. (2009), this research will focus on discussing the scientific model developed in Arena for an E2E-SC network that is composed of four echelons: external key materials suppliers, manufacturer, distribution centres and retailers also known as countries with focus on logistical processes. The number of participating parties is not restricted. A hierarchical modelling approach has been adopted while developing structure of the supply chain system under consideration, which is also in line with principles defined in Supply Chain Operations Reference (SCOR) model. The model is developed based on E2E-SC system structural, computational and systemic organisational aspects identified via SLR in Figure 2.6.1-1. The model is inspired by work of Hwarng et al. (2005), Vieira and Junior (2005), Pundoor and Herrmann (2007), and Van Der Vorst et al. (2009) and in Chapter 5 model validation with industry experts is discussed. To this extend model is only reflecting the reality by referring to the work of the above authors as well as work summarised via systematic literature review. Contribution of this research will be discussed accordingly.

The generic E2E-SC network structure presented in Figure 4.4.5-1 below aims to replicate an E2E-SC of a fast-moving consumer goods (FMCG) and includes four suppliers (S), one manufacturing site (M), two distribution centres (DCs) and 6 retailers (R). Supplier 1, Supplier 2 and Supplier 4 have the same specification and supplier 3 includes subassembly of materials. Each supplier manufactures and delivers one key component apart from Supplier 1, who supplies two components. All four suppliers deliver key materials to the manufacturer M1 based on orders and the predefined schedule. M1 processes the information and in line with both upstream and downstream supply chain requirements produce and delivers FG based on orders and the predefined schedule to DCs or directly to retailers.

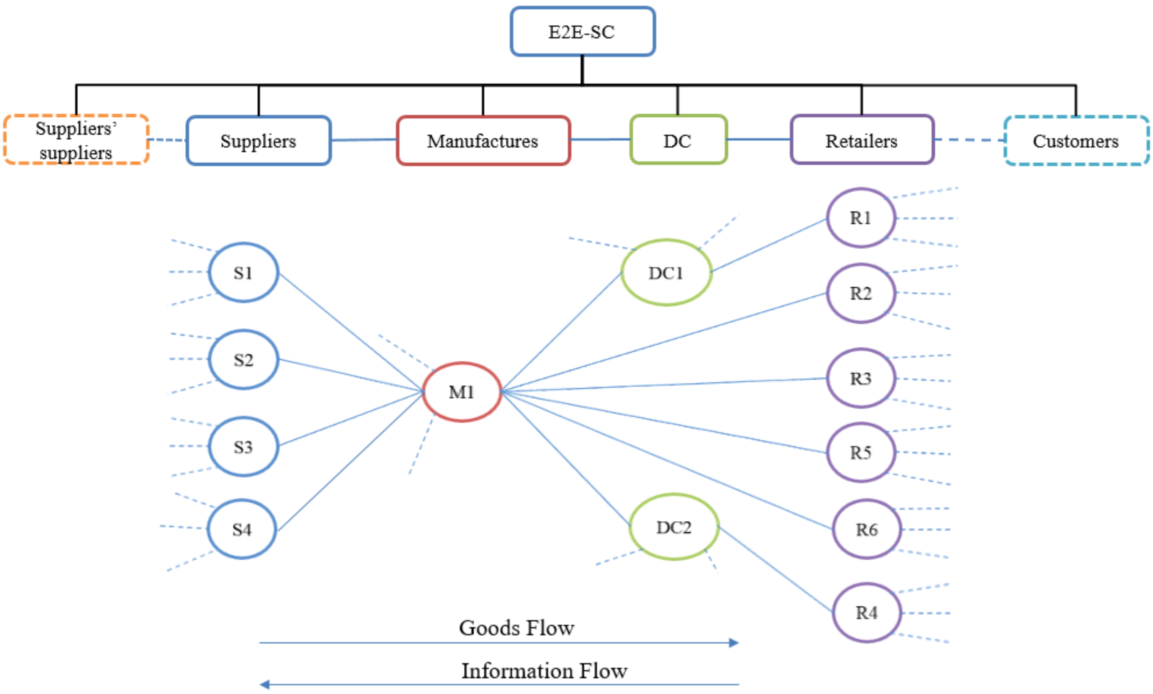


Figure 4.4.5-1 An example of a generic E2E-SC structure

The E2E-SC structure in this example is a tree type, however due to modular design the structure can be further extended by adding more participants depending on the scenarios and the purpose of the modelling. The objective of the model is to evaluate the E2E-SC system performance and provide suggestions for improvements. The key performance indicators used to evaluate the E2E-SC system model performance were based on recommendations provided in the Arena's software user guide and included as follows (Rockwell Automation, 2014):

- Entity related performance measures: time, cost and quantities in various system stages.
- Queue and Process related performance measures: time, cost and quantities in various process stages.
- Resource related performance measures including user defined average total operating costs:

- Average stock level
- Average stockholding cost
- Average shortage cost
- Average demand backlog
- Average time in the system
- Average capacity utilisation (CU)

There are certain assumptions and simplifications included in the model. The model only considers key materials that are subject to capacity constraints on line. The demand for the key components is uncertain and statistical distributions are used to reflect this in the model, which are based on the historical data. The assumptions are that each supplier has dedicated lines with limited capacity, but other lines can be added if enough demand is present. The key components can be used in multiple products. The manufacturing plant has a specific number of lines with limited capacity. This model involves multiple products. Transportation is provided by the logistics company, which is a part of the business. Both suppliers and manufacturing plans use inventory management policies and stock holding levels are dependent on the level of expected customer service. Demands for the FGs are stochastic and are represented in the model with the help of statistical distributions. The lead time for key materials and FG is stochastic as well. In the generic model, the focus is on the flow of information and goods in the system. However, the average total operating costs has been defined by the user in the components and finished goods inventory control sub-models.

4.5. Simulation model development

This section provides details of the simulation model development process in Arena and describes all models, sub-models and modules used. Challenges and issues associated with an E2E-SC simulation model development are not only attributed to the lack of visibility and understanding of the structure and organisation of the entire end-to-end SC system, but also driven by a complex nature of these systems and modelling implication often reaching to amalgamate knowledge from various disciplines like computer engineering, OM or OR/MS. Therefore, to reflect all relevant aspects of an E2E-SC, hierarchical features of the Arena simulation environment are considered and panel of relevant models has been developed.

This section focuses on the generic E2E-SC system simulation model logic and description of hierarchical structure of models. To this extend a modular design has been implemented and development of sub-models in Arena®, where various sub-models can be reused, that is can stand on its own as a separate, individual model depending on the needs of the modellers and/or business requirements.

4.5.1. Model implementation

A simulation model developed for this research was implemented in Arena software version 14.7 and MS Excel 2016. Arena was used to model logistical activities in the E2E-SC system relative to flow of goods and information. Multiple models and sub-models were developed to replicate a FMCG supply chain network. This research adopted an integrated methodology approach, combining Arena simulation models with MS Excel, which is often referred to as a hybrid methodology or hybrid simulation and detailed evaluation of literature in this area was presented in section 4.2.

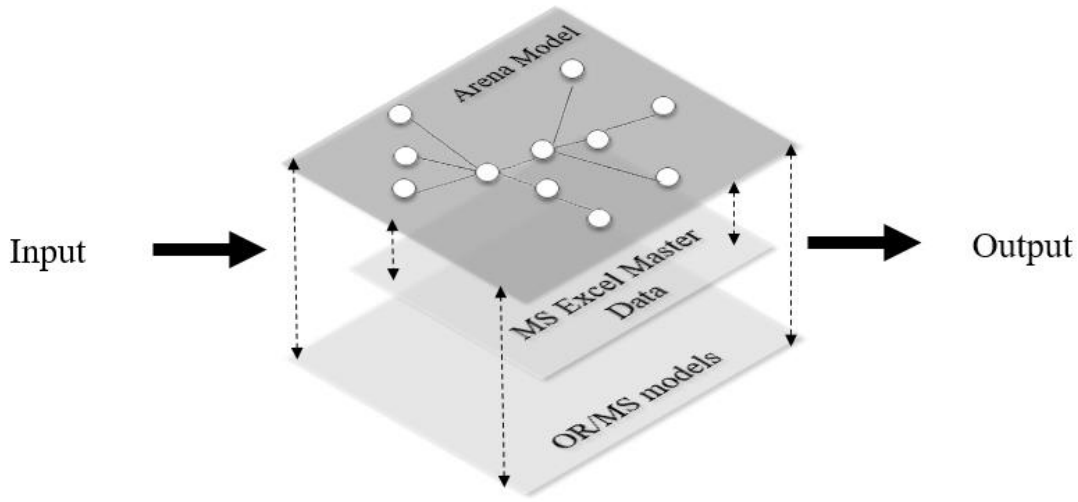


Figure 4.5.1-1 Arena's interaction with MS Excel Master data and OR/MS models

A combined approach used in this study was based on integrating the Arena model and MS Excel database and supported by OR/MS models as shown in Figure 4.5.1-1. The data input to the Arena simulation model, MS Excel and OR/MS models are user defined and dependant on a specific E2E-SC system. The structure of the Arena model will depend on the data input as well as the structural, system organisational and computational information gathered in the MS Excel and OR/MS models used, which again will vary depending on the E2E-SC system being studied.

MS Excel spreadsheet was designed with the aim to support decision making process as well as to provide a necessary help during simulation model development process such as to help in capturing portfolio and products architecture, supply and demand structural facets of an E2E-SC. Moreover, the ambition was to create a document which would allow a quick data extract from business software applications such as Interspec or SAP. The MS Excel Master Data document structure featured key SC elements such as Bill of materials or cost structure, hence included all information regarding product architecture, suppliers, markets served as well as capacity at suppliers and at the manufacturer. Likewise, demand data and other data such as inventory management information were kept in Excel files. A hybrid modelling approach involved OR/MS data input from the Excel file into the Arena model relative to inventory holding policies or optimal routing configuration. Similar approach where Arena and MS Excel were used in combination was presented in Carvalho et al. (2012) and Pundoor and Herrmann (2007).

Hybrid approach can be used in studies that consider gaining benefits from multiple modelling or research methods. One example of such approach can be observed in Pundoor and Herrmann (2007), who adopted hierarchical modelling approach and combined Arena model with MS Excel via VBA to allow read-write files as and when required. Arena can be interfaced with other applications such as Visual Basics or C++ and this could be viewed as an opportunity to automate the modelling process (Kelton et al., 2010). However, any alterations to the model would require an expert knowledge in computer programming, hence was not sought for this research.

In the current research, the generic E2E-SC system structure was defined in Arena simulation models, where flows of materials and orders (information) were reflected based on the information gathered in the MS Excel master file. Likewise, all functional and procedural aspects of the E2E-SC were captured in MS Excel. The data that were recorded in MS Excel master data file, were accessed to describe such activities as product architecture, supply and demand data and capacity identification for each node. Some of the data were used to map an E2E-SC structure and organisation and some other as numerical data input to the Arena modules and models. Generic nature of the MS Excel document proved useful as a stand-alone file to map E2E-SC organisational and structural system aspects. OR/MS models were developed separately to define the optimal inventory policy or distribution of goods, which will be discussed in this section as well.

4.5.2. MS excel master data

MS Master Data file has been developed to support modelling an E2E-SC in Arena. The MS Excel Master Data file is managed at the level of Product Technical Set (PTS), which is a classification of products at a higher level than stock keeping unit (SKU) level data to ensure relevant product information and details for tactical and strategic E2E-SC analysis. PTS in this research refers to FMCG industry and to each family of products in the business that share the same product format or product line technology.

PTS is the highest aggregate unit for which capacity needs to be maintained. For example, in group of products, the brand related Category A component shape and design will dictate the grouping of individual SKUs as one specific PTS. In the Master Data file, a capacity for a variant or SKU is not defined at this level, but the aggregate capacity for the group as one entity.

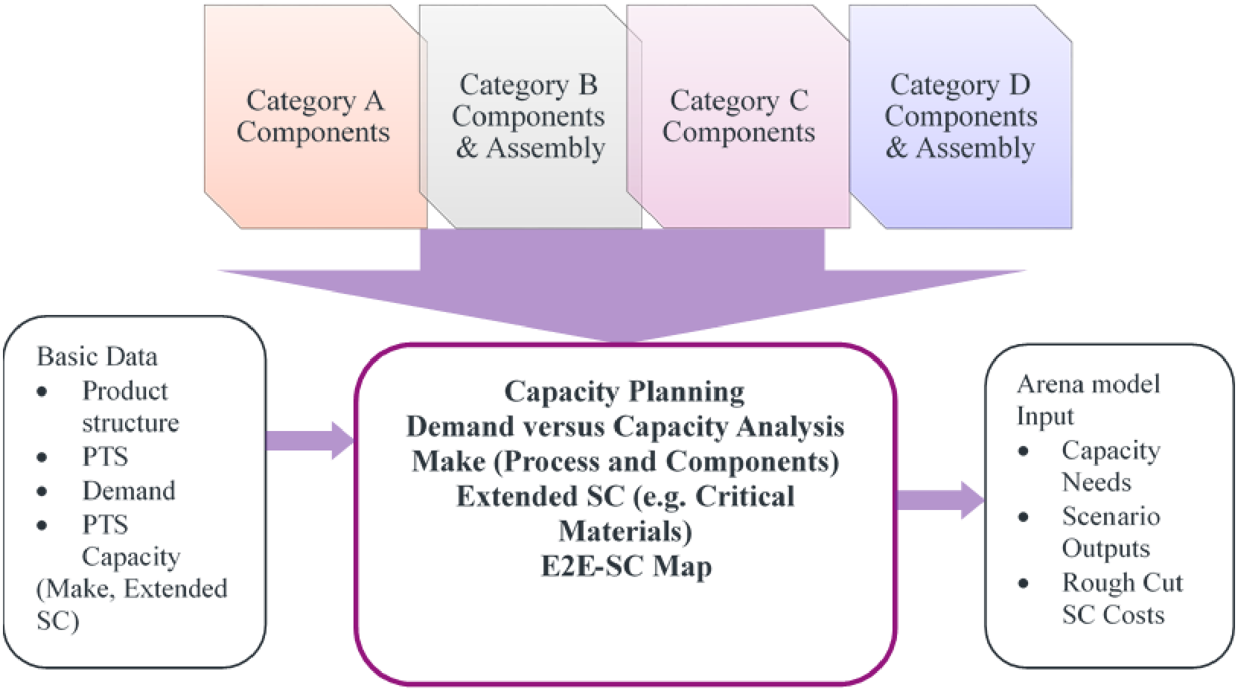


Figure 4.5.2-1 Master Data Design Architecture

The Master Data document can have multiple analysis modules depending on the number of key critical components and technological processes used to make them (Figure 4.5.2-1). The master data document is designed to support the modeller and enable data collection and analysis, for example:

1) Category A components: Definition of packing lines capacity and utilization analysis

2) Category B components: Definition of Category A (and assembly) capacity and utilization analysis

3) Category C components: Definition of another components capacity and utilisation analysis

4) Category D components: Forecast for pre-defined critical raw materials in each category

The master data does not mandate the use of all the four modules and the user has the choice to use some or all the modules in line with the modelling aims and objectives. The file has been created in MS Excel and validation tab was created with the list where the relevant naming conventions can be added to support data entries when populating the Master Data modules. As such, correct and relevant entries in lists are crucial for successful use.

Masterdata lists cover the following aspects of an E2E-SC as presented in the Table 4.5.2-1:

Table 4.5.2-1 Masterdata listing specification

Material Types	User defined (fixed values)
Key Materials	User defined (categories of components)
Material ID	Raw, Pack (fixed values)
Manufacturing Plant	User defined
Clusters	User defined
Categories	User defined
Years	User defined
Product Family	User defined
Technological Process	User defined
Market specification	User defined
Brands	User defined
Supplier	User defined
Capacity Identification Group	User defined, for may only apply to some components
Pack Size	User defined
PTS	User defined, the level at which capacity analysis is run (mandatory).

Some examples of data requirements for each module in the Master Data document with dummy data is presented below.

1) Product Packs Master (Figure 4.5.2-2)

The Product Pack master defines the various PTS, pack sizes and specific gravity for each brand.

	A	B	C	D	E	F
7	Brand or Marketing Platform	Product Technical Set	Technologica l Process	Pack Size	Specific Gravity	Date Supplied
9	Product 1	Technology 1	Type A	100	1	02/07/2017

Figure 4.5.2-2 Product Pack Master

1) Product Architecture (Figure 4.5.2-3)

The Product Architecture defines the "mini-BOM" for each PTS. It only lists the key materials of interest in modelling for both Raw and Pack. "Material Type" classifies each key material as either "Category A" or "Category B" (or any other business-related user defined classification). Items classified as "Category A" will be used for capacity analysis in section relative to Category A components assembly.

The product architecture can be specified for each country or a common architecture can be defined for all countries in a market cluster. The product architecture should be specified for all countries in a market cluster (if there are differences in BOM e.g. key materials), a product architecture can be defined with "All" in the Country field. This ensures that the tool records product architecture for all countries correctly for each market cluster. The modeller can also specify the product architecture for all pack sizes in each PTS as defined in Product Packs master.

	A	B	C	D	E	F
2	Market Cluster	Market Specification	Brand or Marketing Platform	Product Technical Set	Technological Process	Pack Size
4	Cluster 1	County 1	Product 1	Technology 1	Type A	100

	G	H	I	J	K	L	M
2	Material ID	Material Type	Key Material	Shared	Raw Mat Inclusion%	Per UoM	Date Supplied
4	Pack	Material A1	Key Material 1	TRUE		1	02/07/2017

Figure 4.5.2-3 Product Architecture Master with dummy data

1) Finished Goods Supply Module Data (Figure 4.5.2-4)

Finished Goods Supply Module defines the product supply matrix for each brand-PTS-Market Cluster combination. Users can define more than one sourcing unit by choosing the %allocation value.

	A	B	C	D	E
7					
8	Brand or Marketing Platform	Product Technical Set	Technological Process	Market Cluster	Manufacturing Plant
10	Product 1	Technology 1	Type A	Cluster 1	Factory 1

	F	G	H	I	J	K	L	M	N
7	Qtr 1 2017	Qtr 2 2017	Qtr 3 2017	Qtr 4 2017	Qtr 1 2018	Qtr 2 2018	Qtr 3 2018	Qtr 4 2018	
8	% Allocation	% Allocation	% Allocation	% Allocation	% Allocation	% Allocation	% Allocation	% Allocation	Date Supplied
10	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	02/07/2017

Figure 4.5.2-4 Finished Goods Supply Matrix Master with dummy data

2) Category A Supply Module and Category B Supply Module

This master defines the supply matrix for all Category A/ Category B components per PTS-Manufacturing Unit combination. The modeller is required to define the supply matrix for all Category A/ Category B components as defined in the Product Architecture.

3) PTS to Capacity Identifier (Optional, required if Category B supply matrix is used)

This is a special master for capacity analysis of Category B components. In the case of Category B components, the capacity bottleneck could be a unique technology that may span multiple PTS (shared capacity). Hence, this master maps the PTS to this unique identifier. In the data templates, the user should normally enter Category B capacity at capacity identifier level rather than at PTS level.

4) Ex-works Costs (Optional, if cost analysis is in modelling scope)

This master captures the average transfer price per MU-PTS combination, which can be used for reporting of total product costs (ex-works plus transportation, warehousing and other costs i.e. tax). The individual data is as per the typical classification in transfer pricing and the data should be readily available from SC Finance in each MU. It is recommended that the most recent transfer price is used for data entry. The MS Excel Master Data was developed based on the participant observations in the Company A. The modules structure and Master Data (MD) tool design reflected E2E-SC system modelling structural and organisational elements that were identified during the research as useful in developing a simulation model. The MD tool has been further developed from the previous experience that the researcher had with the Company A during which the researcher undertook the work-based learning. A generic MS Excel database has been developed and the tool is used in this research for the purposes of simulation modelling and will be here forth referred to as MD. The consideration behind the MD development is further discussed further in the following sections. The next sections of this research aim to deep dive into details of the E2E-SC Arena simulation model.

4.5.3. Model initialization and data input requirements

A data input is an important consideration in any model development process. This plays a critical role in any simulation study due to inherent computational complexity relative to use of statistical distributions and large amount of data that simulations can generate. The data input, model logic and model output are important facets that need to be clearly understood, verified and validated by modeller and industry experts to ensure that the model represents reality as intended. Although system thinkers may argue that it is impossible to represent an entire system as it would mean to reflect its natural links to the external environment, a reductionist approach allows to focus on the critical supply chain element and consider approximations. The approach taken in this research aims to consider structural elements of an E2E-SC system, which are derived from simplicity and reductionism also known as holism as well as systemic organisational, which takes an account of the knowledge generated by the parts and a whole of the system.

During the model development process, some of these data are entered in the Arena model while some others are entered in the Excel MD file corresponding to each participant in the E2E-SC. To develop a generic simulation model, the following data are needed:

• Structural representation of the supply chain system under consideration. This requires mapping the supply chain and understanding what processes are used within each node. This has been discussed in the section 4.4.5.

• Organisational representation of the E2E-SC network. This requires description of business policies and processes that integrate all functions across the entire supply chain (Pundoor, 2002). The aim is to include generic processes, business policies and managerial techniques in the modelling and analyse in more detail whether they purport to improve the supply chain performance as a whole. To do so, processes and related policies for an E2E-SC network were identified via SLR in Chapter 2 and were considered in the conceptual and scientific models:

- number of inventory holding points,
- inventory holding policy type at each holding point,
- inventory information sharing policies,
- demand requirements,
- lead time requirements,
- capacity utilisation at each producing node,
- production-distribution policies (order processing, replenishment etc.),
- control and risk management policies.

4.6. E2E-SC system model logic

This section describes an E2E-SC model logic in Arena. The E2E-SC system can involve multiple participants, who may have conflicting objectives, however having a common aim to deliver the final product into the hands of ultimate customers. Three types of flows are considered in the model: materials flow, information flow and cash flow. Materials flow involves movements of raw materials through the supply chain, materials conversion into FG and delivery to the final customer. This also may involve materials processing or assembly.

The flow of information refers to control logic that checks the stock levels and defines the appropriate policy depending on the business requirements. This is often defined by the decision maker/modeller. The cash flow refers to the backward financial flows in the supply chain and ensuring that there is enough cash to cover daily operating expenses (Comelli, Féniès, & Tchernev, 2008). The cash flow is not considered in this research due to added complexity.

There are two ways to approach model development process: it can be bottom up or top down (Kelton et al. 2010). This research highlights how modules within Arena® can be used to model supply chain structural elements that is a set of suppliers, manufacturers, DCs, retailers and systemic organisational connections between these key nodes typical to bottom up approach. Likewise, key processes and policies can be included for instance lead time and different stock holding points.

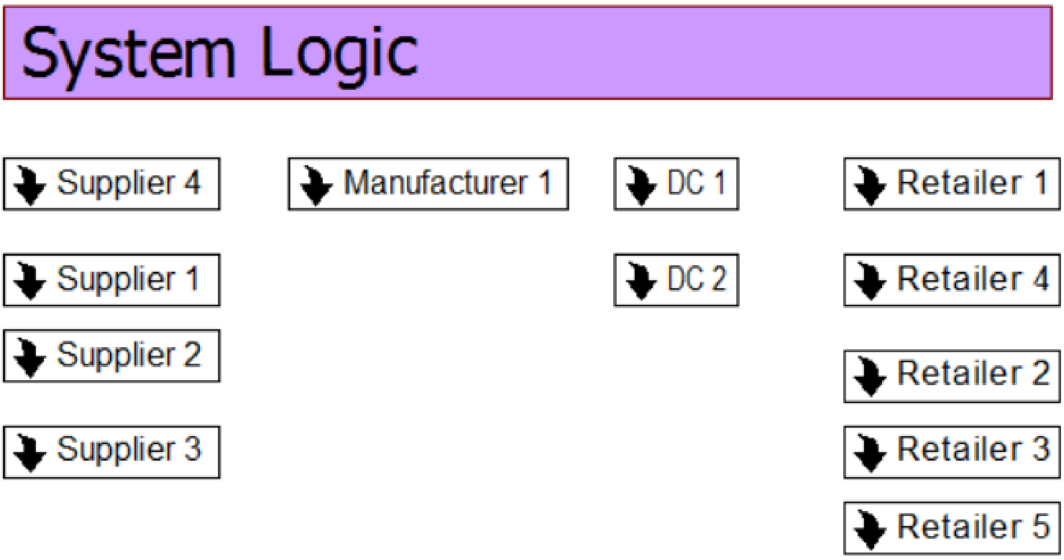


Figure 4.6-1 E2E-SC system Model in Arena Level 1

A level 1 structure of the Arena model is highlighted in Figure 4.6-1. It has been developed using sub-models and in each sub-model a set of modules are put together and connected using their interfaces to master data file. So, each participant in the supply chain has a defined characteristic recorded in the master data. The supply chain simulation model consists of sub-models that correspond to the modules in the following Arena's template panels: Basic Process, Advanced Transfer and Advanced Process. The sub-models are built at the strategic and tactical level. The Excel files and macros perform operational and planning activities. Execution is carried out in Arena with enabling processes modelled in MS Excel and serving as input to the simulation either in the form of Excel data or parameters in the Arena model (Pundoor & Herrmann, 2007). Arena model is developed based on modular design with the aim to reuse the sub-models with minimal alterations. MS Excel master data allows to consider multiple products at the PTS level and focusses on key critical materials that are subject to capacity constraints. The next sections defined the modelling objectives.

4.6.1. Objectives of the model

The modelling objectives for this work are:

• To develop a computerized model using simulation that provides the architecture for combining various modelling techniques.

• To evaluate what modelling implications can arise when different elements from the proposed conceptual framework are included in the computerised/scientific model.

The research strives to define which supply chain elements can be added to the simulation model as generic and which are business specific. Likewise, the purpose of this work is to evaluate if by following the proposed guide to E2E-SC model development, one can design a simulation model and adapt to a specific supply chain system.

4.6.2. Supply model

Supply model considered flow of materials/key components and defines processes relative to their production, delivery and order fulfilment. In the generic supply model two categories of elements can be identified: (a) structural elements and (b) control elements. The structural elements aim to replicate the logic in Supply model, whereby the raw materials arrive to the supplier, they are assigned arrival time and delays are recorded to account for additional activities relative to booking goods in. The raw materials are then processed, and numbers of produced components are recorded. The control elements of the model are responsible for triggering the right inventory level and scheduling delivery upon receipt of orders from the customer, which in this case is the manufacturer. There are two sub-models that perform these control functions; “Supply 1 Routing” and “S1 Inventory Control”.

Similar supplier model structure to Vieira and Junior (2005) is presented in this research in the sense that there is a defined number of suppliers delivering components to the manufacturer, based on the orders requirements. The supply models in this research are composed of four suppliers, which supply five different types of components to a single manufacturer. The assumption is that each component undergoes a production process at the supplier and resources are seized, delayed to account for production time and released upon process completion. A process module is used to represent a production line resource requirements and capacity utilisation performance measures are recorded. Each component can be used in assembly of one or multiple Product Technology Sets (PTS), and production of FG is represented in the “Manufacturer 1” sub-model.

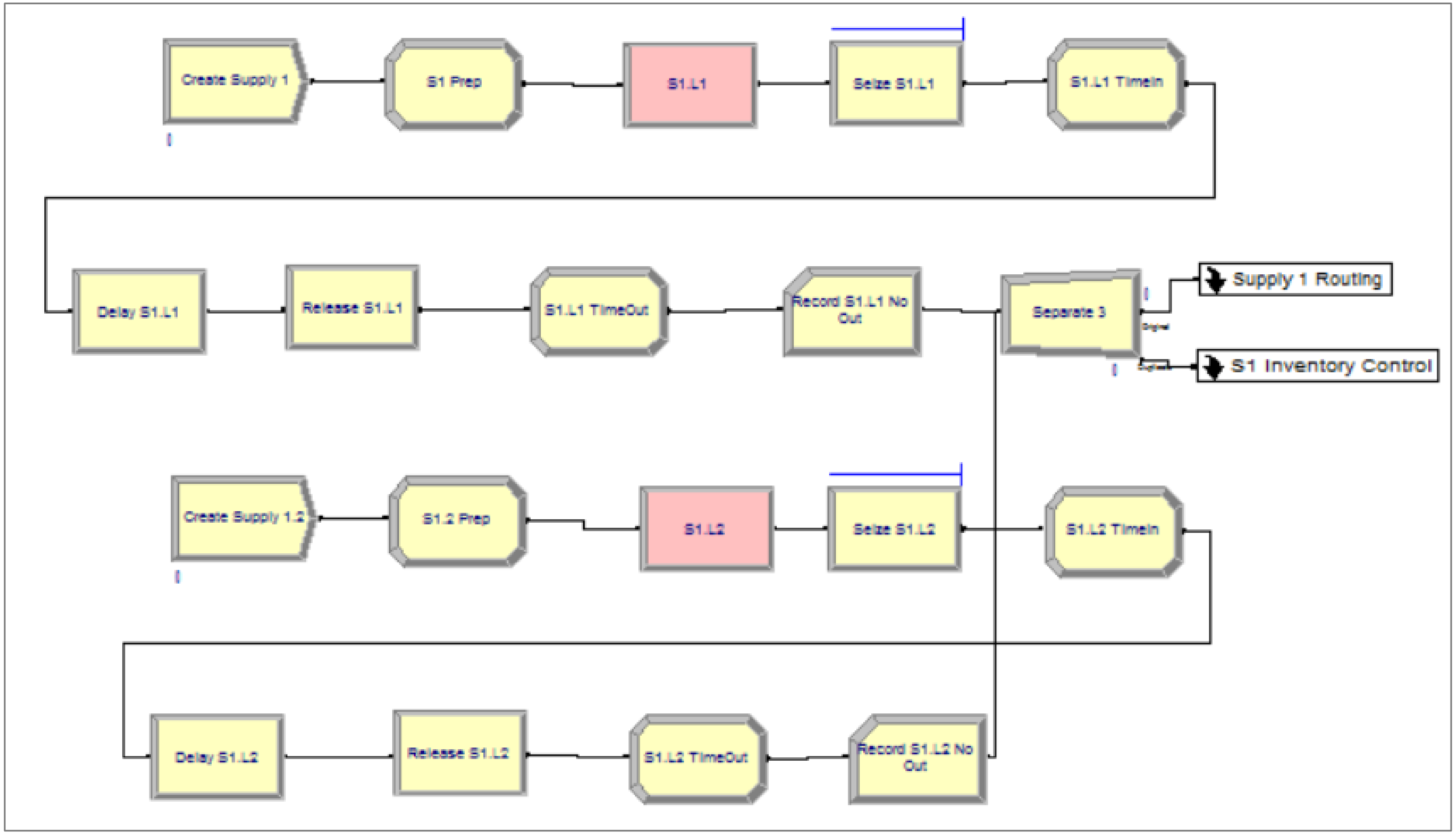


Figure 4.6.2-1 "Supply 1" sub-model in Arena replicating production of key components

Figure 4.6.2-1 highlights Arena modules that were used to develop the logic of the “Supply 1” sub-model. The structure of the “Supply 1” sub-model was based on the MD file and were used as an input to the Arena model. The number of suppliers of the key components as well as supplier capacity utilisation and supplier location were captured in the MD file. The information recorded in the MD file was used as an input to the Arena sub-models. Each supplier sub-model was constructed in a similar way capturing generic elements as resource availability, capacity utilisation, production and delivery lead times. Some suppliers may produce more than one product and may be delivering components to more than one manufacturer. In the example illustrated in Figure 4.6.2-1, the supplier has two lines producing two different components: line one makes Component 1 and line two makes Component 5. The model logic is initiated by a create module, which reflects the demand requirement for each of the components. A detailed description of the “Supply 1” sub-model is presented in Appendix 3.

The complexity in modelling supply side of the E2E-SC system can be enhanced by many components and varying requirements to process these components. Likewise, individual components may be unique for one PTS or shared across two or more PTSs. Some components may need to be assembled before delivery to the manufacturer or may be produced on different lines with different capacity availability. In the example presented above the supplier manufactures two components on two separate lines following a push policy.

Both components are then scheduled for delivery to the manufacturer, based on a defined sequence. The “Supply 1 Routing” sub-model for Supply 1 is depicted in Figure 4.6.2-2.

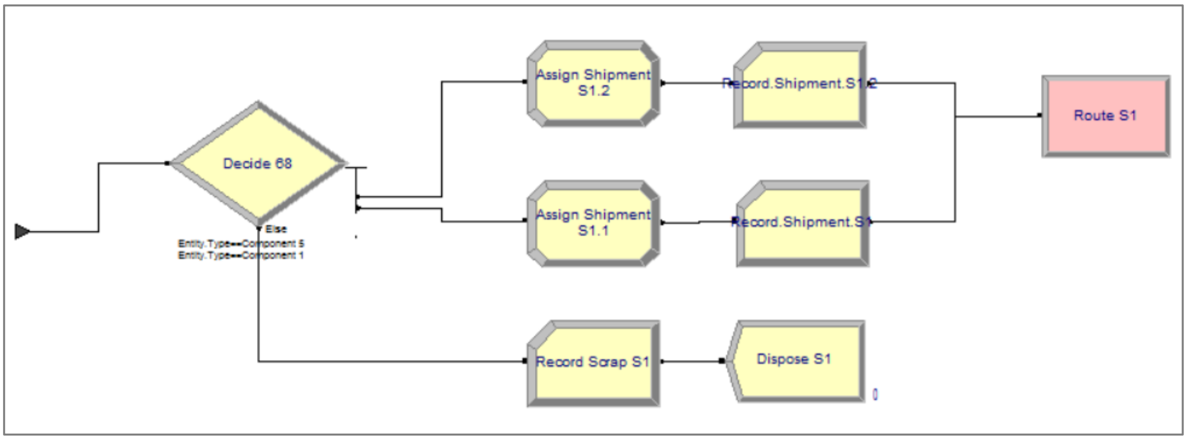


Figure 4.6.2-2 “Supply 1 Routing” sub-model logic in Arena

In the decide module (Figure 4.6.2-3) user makes decision based on condition hence “N-way by Condition” is selected in the “Type” operand. In this example, entities are directed to the next module based on the entity type conditions. The entity called Component 5 is directed to the “Assign Shipment S1.2” and the entity called Component 1 is directed to “Assign Shipment S1.1” module.

There are two true branches leaving the Decide module, which are linked to two assign modules, where entities are subject to assignment. The top one (Figure 4.6.2-4) assigns an Entity.Sequence for the Component, 1 which is defined in the “Sequence-Advance Transfer” data module as “SeqS1.2” that follows steps to Station “S5_Receipt”. The “Assign Shipment S1.1” module in Figure 4.6.2-4 defined the entities sequence as “SeqS1.1” in the Sequence data module with the next step leading to “S1_Receipt” station.

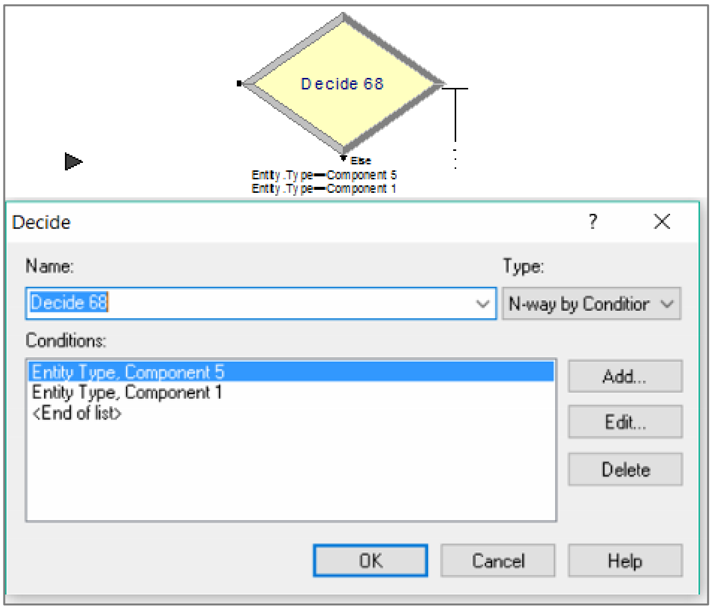


Figure 4.6.2-3 Decide module and its operands

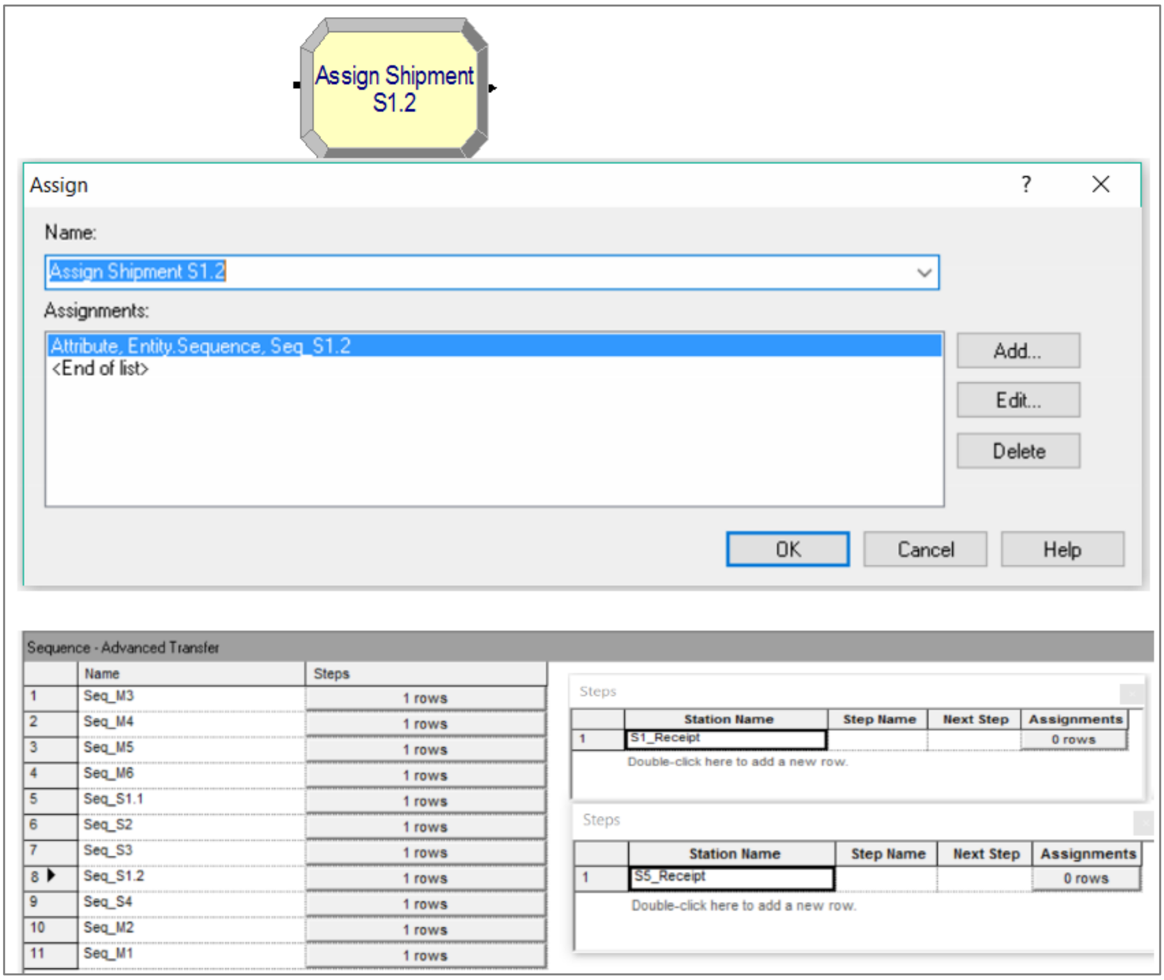


Figure 4.6.2-4 Assign shipment S1.2 module and its operands and the sequence data input from Advanced Transfer panel.

The number of Components 1 and Components 5 is then recorded in the "Record" module and both type of entities are sent to the "Route" module. As illustrated in Figure 4.6.2-5, in the "Route" module, the routing time is defined, and destination operand set to "By Sequence".

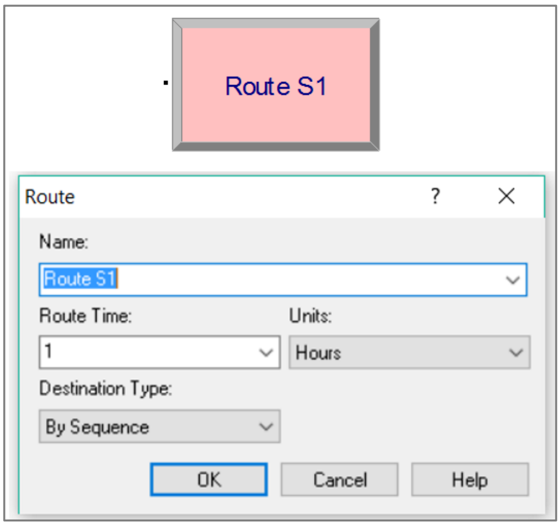


Figure 4.6.2-5 Route module and its operands

The same logic applies to other suppliers apart from supplier 3, who has different structure of operations as assembly of subcomponents occurs there. The "Supply 3" model logic is presented in Figure 4.6.2-6 below.

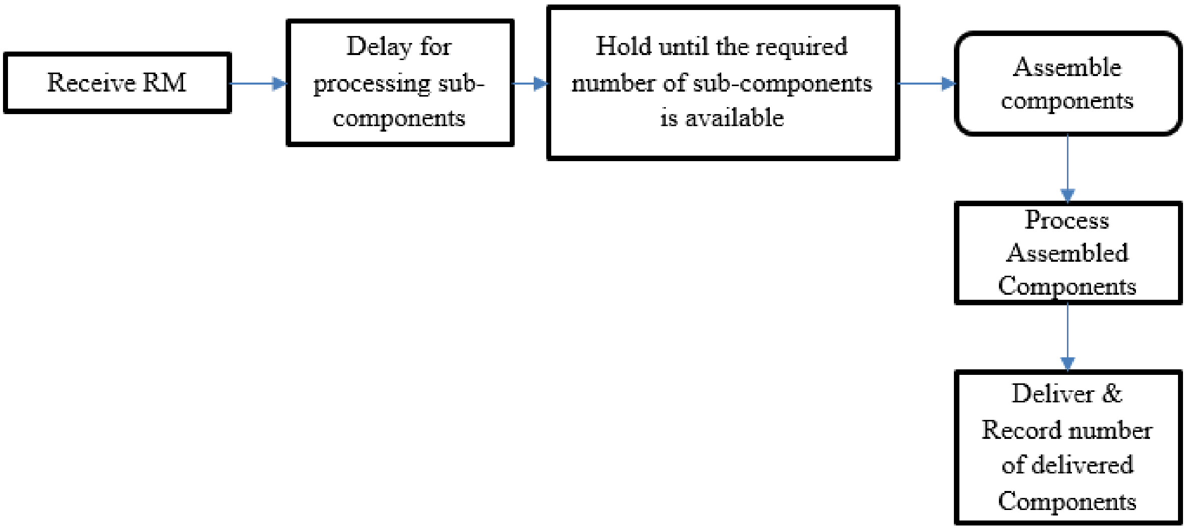


Figure 4.6.2-6 "Supply 3" model logic

In the "Supply 3" sub-model, there are two flows of two sub-components (Component 3.1 and Component 3.2), which are batched into one Component 3 and only Component 3 is dispatched to the manufacturer. All supply models are linked to a route sum-model and are dispatched to the manufacturer. Likewise, each component is linked to inventory evaluator control sub-model where inventory levels are recorded.

4.6.3. Make model

The manufacturer of finished goods is considered here as a focal company that receives key components from suppliers, performs necessary checks and assembles them into finished packs based on the product structure defined in the MD file. The make model logic is presented in Figure 4.6.3-1.

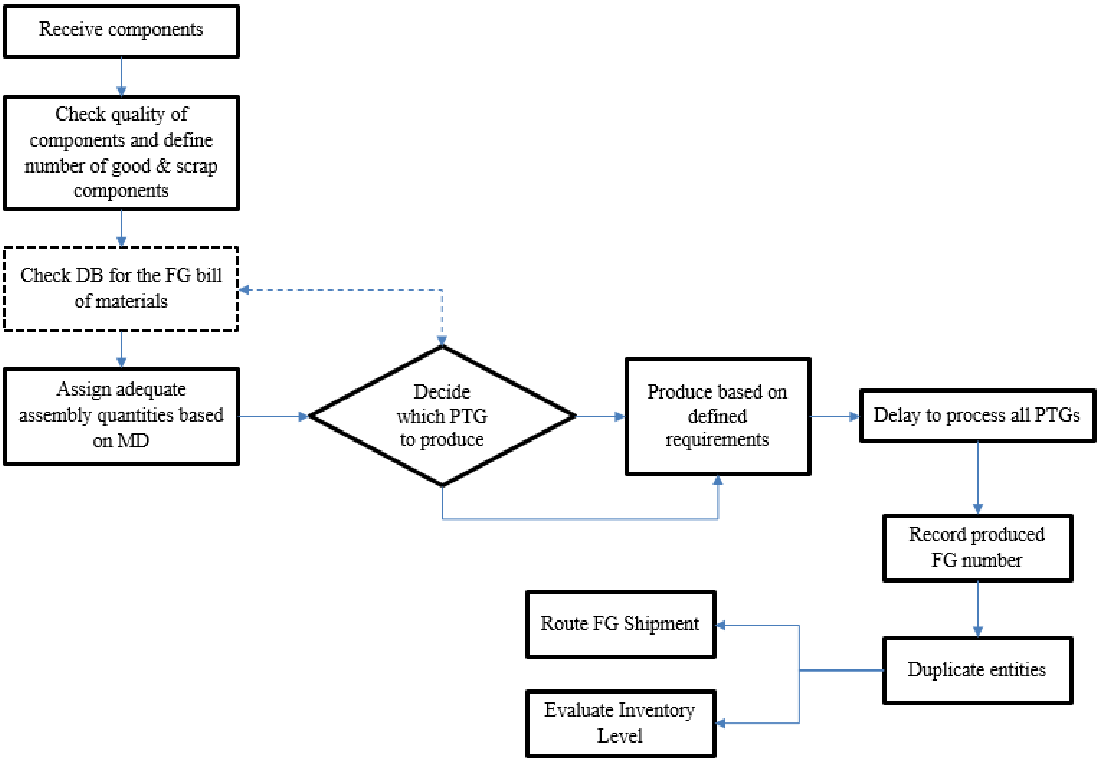


Figure 4.6.3-1 The Make sub-model logic

All products are assembled at the PTS level and a priority of production is defined by the modeller based on the business requirements. A time delay is included in the model to reflect FG processing and preparation for shipment to customers. Number of FG produced at “Manufacturer 1" (M1) is recorded in the Record module and all entities are duplicated and sent to two different sub-models: “Routing M1.FG” and “M1.FG Inventory Control”. All PTS are dispatched to customers and end recipients of the supply chain via “Routing M1.FG1” sub-model. Inventory levels of each product is evaluated in the “M1.FG. Inventory Control” sub-model, where all duplicated entities are directed. The Arena’s “Manufacturer 1” make model logic is presented below in Figure 4.6.3-2 (Please note that the figure is for illustration purpose only and detailed description of the model sections is presented below).

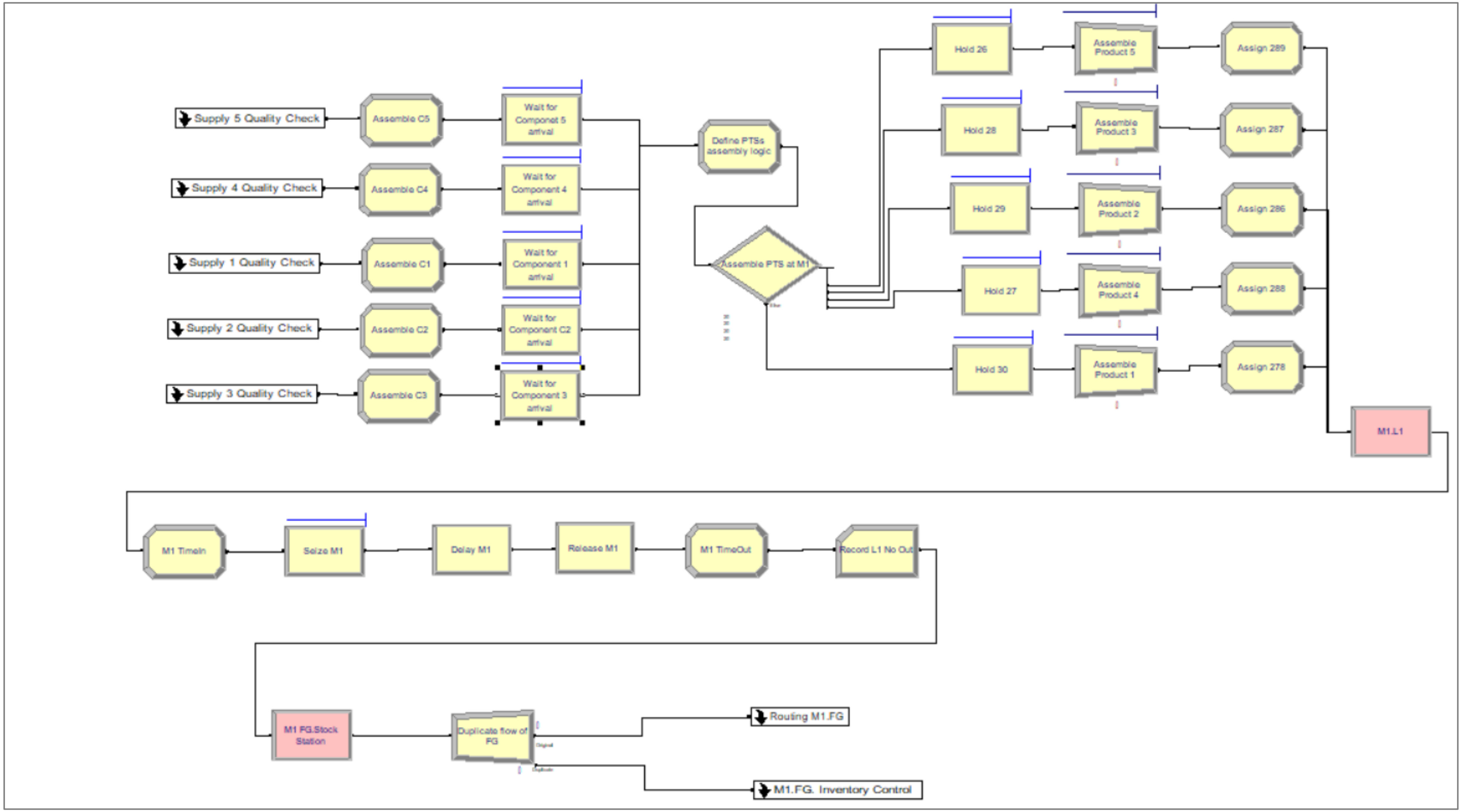


Figure 4.6.3-2 “Manufacturer 1” model logic in Arena at level 2

In this example, all parts are quality checked and defined number of rejections is recorded. There are five supply quality check sub-models, which have the same model structure and each of the key components is routed to a dedicated sub-model to undertake components quality checks. Only components that pass the quality check are allowed for the assembly. In the "Delay to S1 Inspection", the entity (component 1) is delayed to account for inspection time and the allocation is defined as value added time. The Component 1 is then directed to decide module, where the modeller defines the probability of the inspection pass or fail and both rates are then recorded in the record modules. The "Supply 1 Quality Check" sub-model is presented below in Figure 4.6.3-3. A detailed overview of each of the modules is presented in Appendix 4.

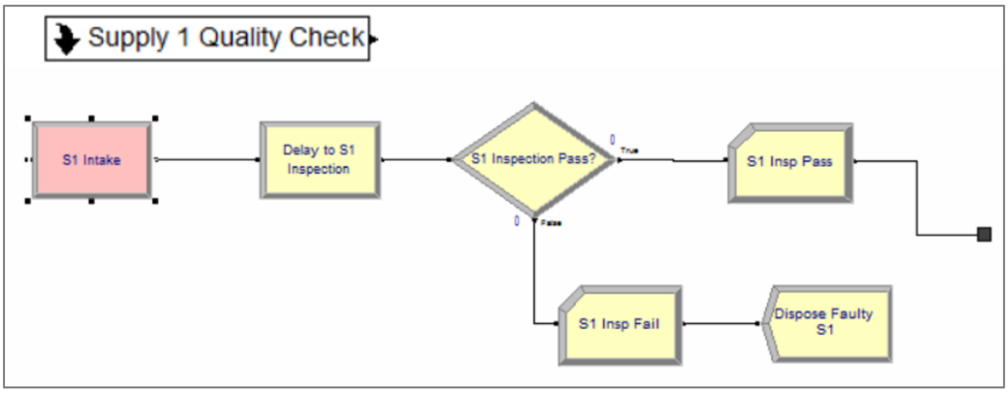


Figure 4.6.3-3 "Supply 1 Quality Check" sub-model logic

Each of the five-supply quality check sub-models are linked to five "Assign" modules called "Assemble C1, C2…C5" (Figure 4.6.3-4). These modules are used for assigning new values to variables and entity attributes, in the case of Component 1, a variable "vCount_1" is assigned a new value 1. This is replicated across other assign modules for entity specific variables. A similar assignment is recorded for an entity attribute, which in case of Component 1 is "aCount1" with the new value given as 1. A letter "v" is used in front of each variable and a letter "a" in front of entity attribute name to differentiate between variables and entity attributes, which may have the same or similar naming convention.

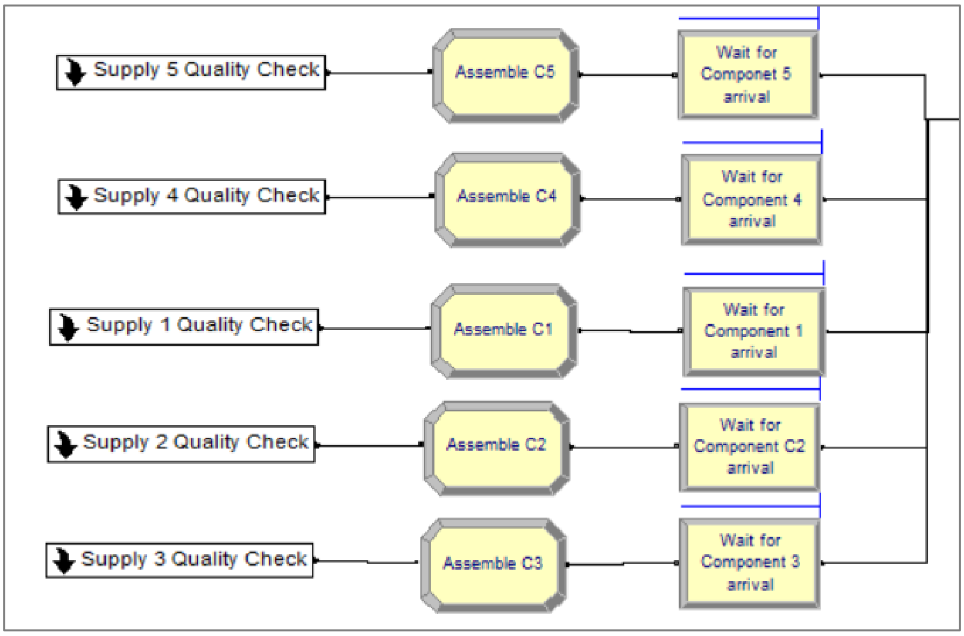
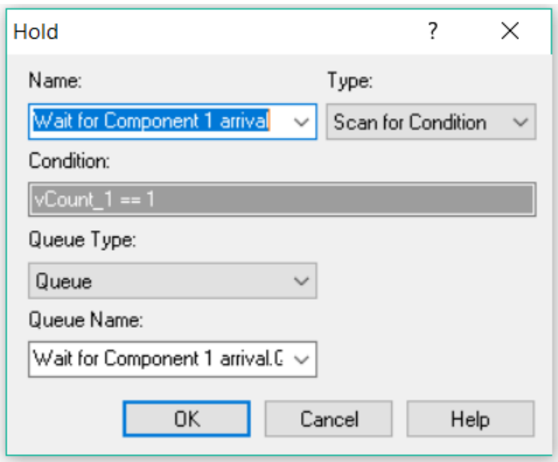


Figure 4.6.3-4 Quality Check submodules linking to Assign and Hold modules.

A hold module (Figure 4.6.3-5) was linked to the assign module to ensure that the correct number of entities is prepared before entities are batched. In the type operand, a "Scan for condition" option was selected, and a condition defined using Arena's expression builder to define variable current value depending on the number of components required to assemble a given PTS format, which were defined as follows:



vCount_1 == 1

vCount_2 == 1

vCount_3 == 1

vCount_4 == 1

vCount_5 == 1

Figure 4.6.3-5 Wait for Component 1 arrival Hold module operands.

If the requirements were to use more than one component for the assembly of PTS this could be changed in the hold module by specifying the condition. All hold modules were responsible for holding entities until the condition specified was fulfilled and then entities were released to the next step in the model, which defined PTSs assembly requirements (Figure 4.6.3-6).

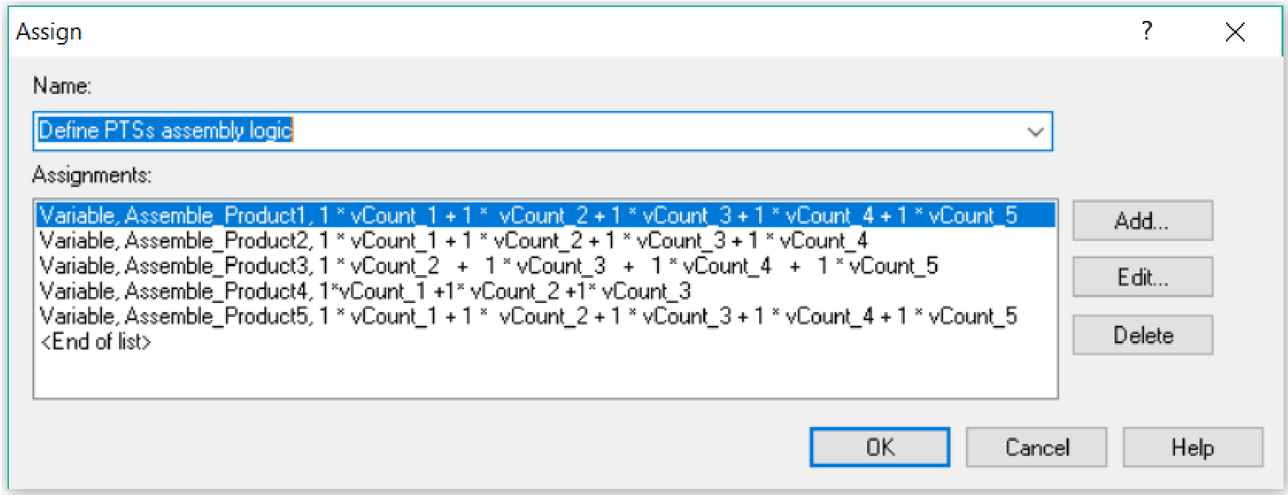


Figure 4.6.3-6 Assign PTSs assembly logic

In the “Define PTSs assembly logic” assign module multiple assignments were defined. Each assignment was relative to different PTS and the number of assignments depended on the model scope. In the exemplary model presented in this section of the thesis, there were 5 PTSs that were considered (Figure 4.6.3-7).

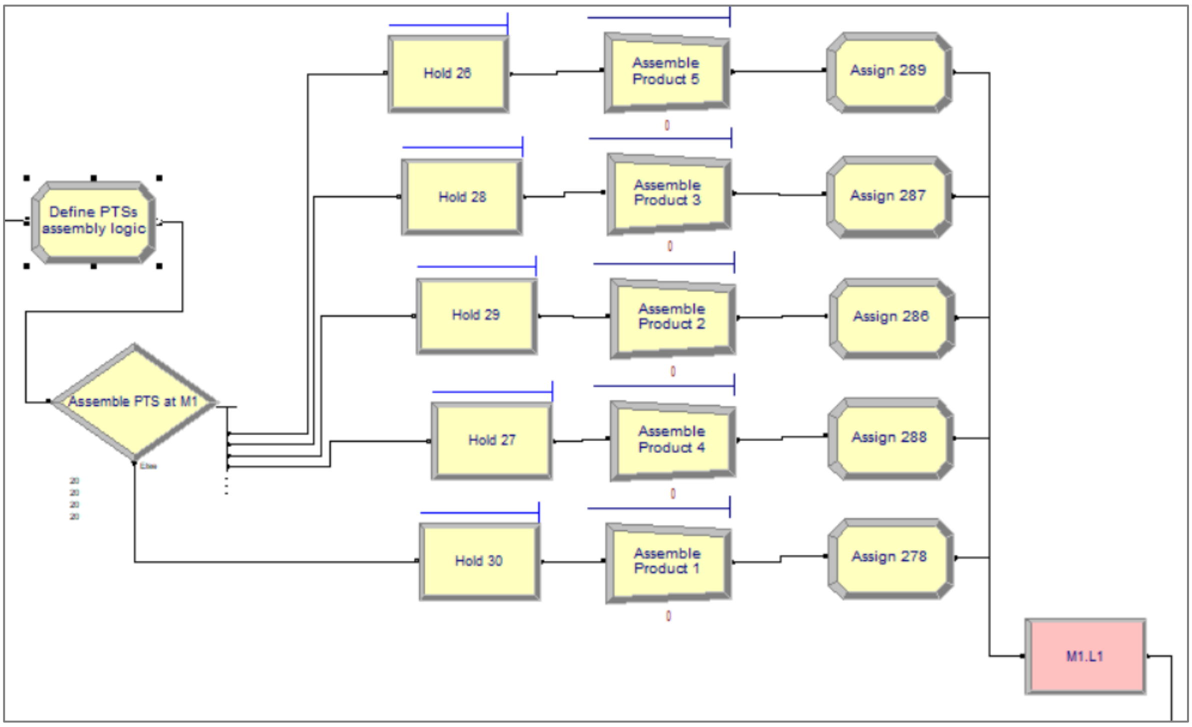


Figure 4.6.3-7 Product assembly section in the "Manufacturer 1" model

The decide module was used to allow for decision-making processes in the system. The modeller could define a priority list for each PTS assembly, but also this module was selected due to its attributes that allow to make decisions based on one or more conditions or based on one or more probabilities (e.g., 70% true; 30% false). As illustrated in Figure 4.6.3-8, to direct entities to the right direction a "N-way by Chance" type was used. There were four true exits and one false exit, each having equal distribution of 20% probability of happening.

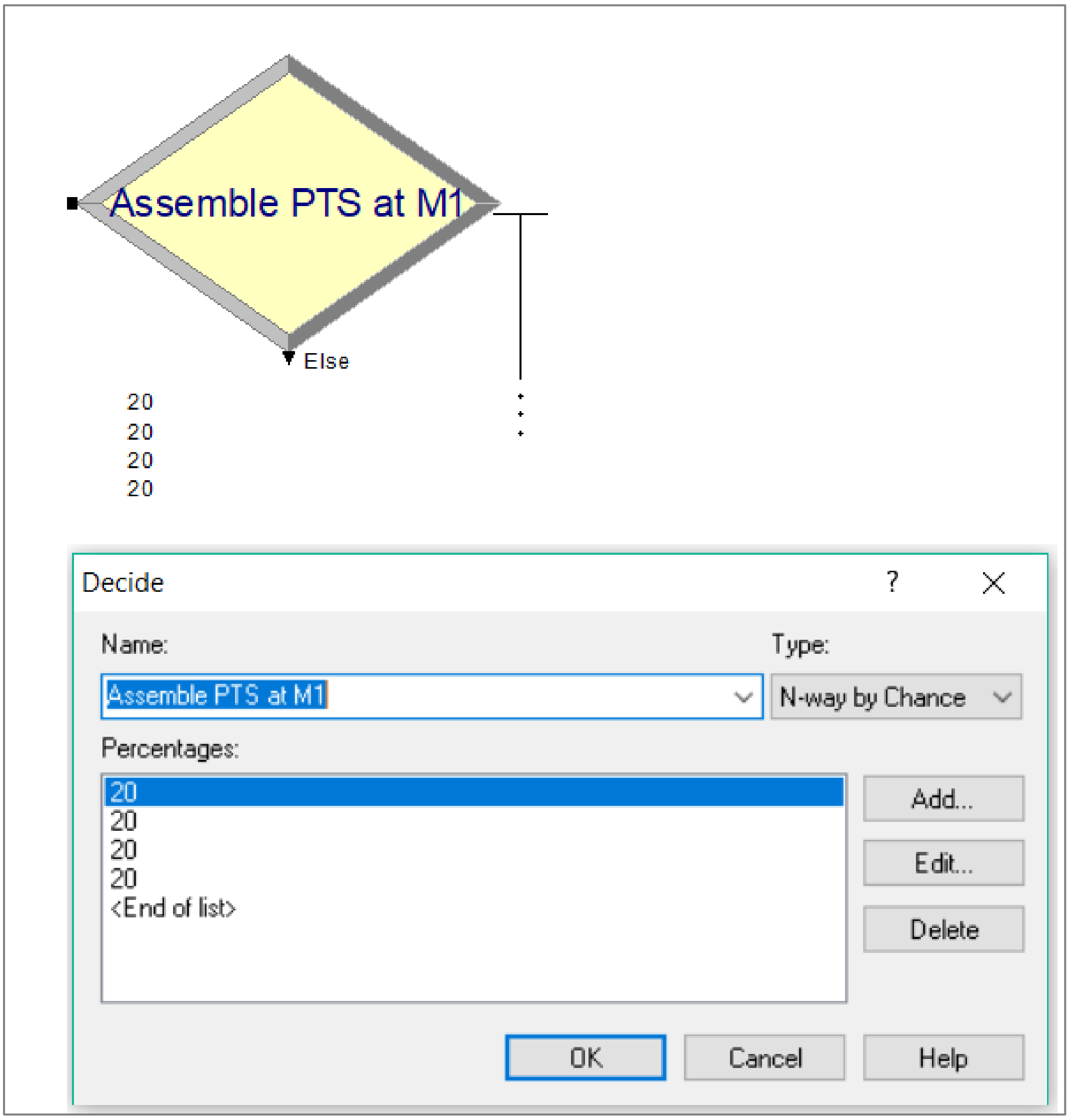


Figure 4.6.3-8 "Assemble PTS at M1" decide module

Each of the 4 True branches exiting from the "Assemble PTS at M1" decide module was linked to 4 hold modules ("Hold 26, 27,28 & 29") succeeded by 4batch modules ("Assemble Product 2, 3, 4 & 5") and then 4 Assign modules ("Assign 286, 287, 288 & 289"). The False branch of the "Assemble PTS at M1" decide module was similarly liked to "Hold 30" hold module and then to "Assemble Product 1" batch module and finally "Assign 278" assign module (Figure 4.6.3-7). In the hold modules arriving entities were held until a relevant number of entries to form a PTS was present. Subsequently, in the batch module a condition for permanent batch size was defined as depicted in Figure 4.6.3-9.

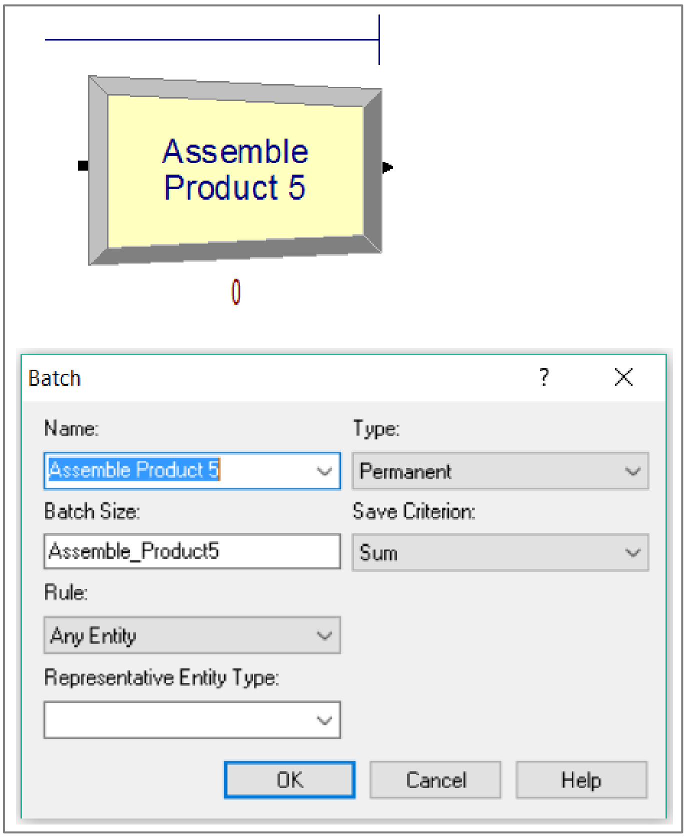


Figure 4.6.3-9 "Assemble Product 5" batch module

Entities arriving to each Batch module were placed in a queue until the required number of entities was accumulated. This was defined by a batch size operand, which was populated with the relevant expression that was defined in the assign module in Figure 4.6.3-6. The operand type was selected as permanent and a new entity/PTS was sent to an assign module. Each Batch module was linked with an assign module, where entities pictures were defined as well as entity type (Product 1,2…5).

All assign modules were linked to a station module called "M1.L1", from where entities were directed to seize ("Seize M1"), delay ("Delay M1") and release

("Release M1") modules used to model processing time and capacity utilisation at the manufacturer. This was captured in the final section of the make model in Figure 4.6.3-10.

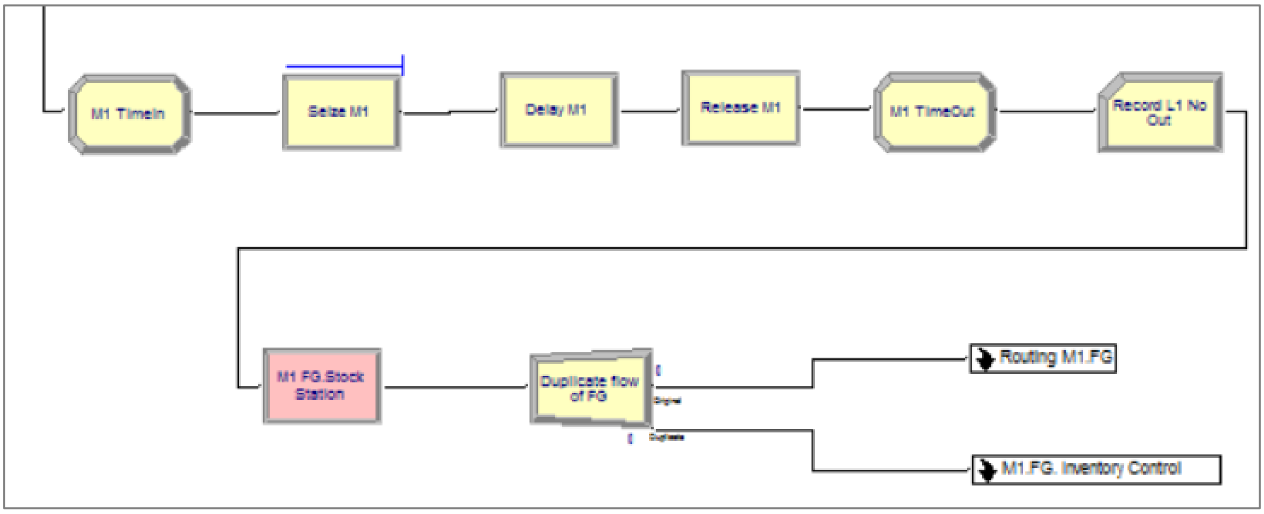


Figure 4.6.3-10 Processing section of the "Manufacturer 1" sub-model linking to routing and inventory evaluator.

All entities were assigned a Time in, which was set to the current simulation time, TNOW. In the "Seize M1" module, "Type" operand was selected as "Resource" and the resource name was defined as "M1.Line1". The time required for the processing on the manufacturing line was modelled in the delay module "Delay M1" and when the delay time elapsed, the resource was released ("Release M1" module), time in production recorded and entities moved to the "M1.FG. Stock Station". The inclusion of the station module helped with the model run animation, which can facilitate evaluation of the model applicability and help during model validation step (Kelton et al. 2010).

From the "M1FG. Stock Station" entities were directed to "Duplicate flow of FG" module, which was used to copy the incoming entities into multiple entities, with percentage cost to duplicates specified as 100% and the number of duplicates defined to 1. The original branch of the duplicate module was linked to "Routing M1.FG" sub-model in Figure 4.6.3-11.

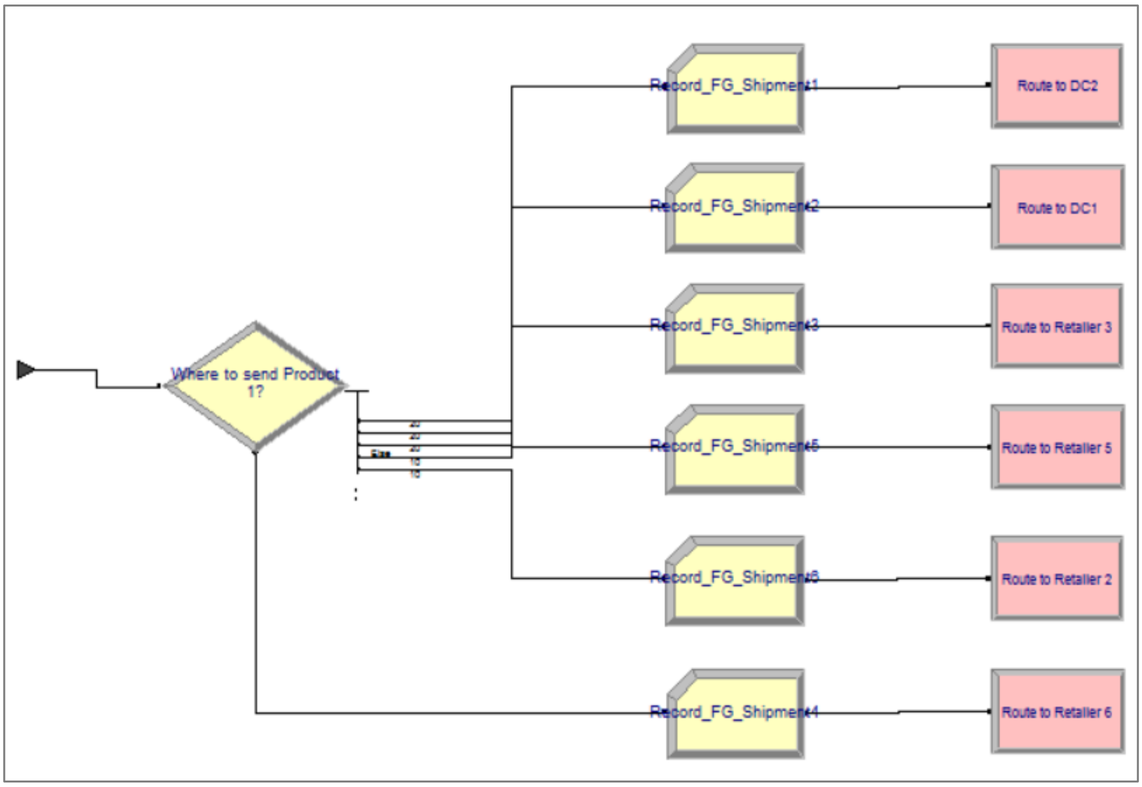


Figure 4.6.3-11 "Routing M1.FG" sub-model logic

Similar approach was taken as in the "Supply 1 Routing" sub-models whereby a decide module was used to define shipping requirements and N-way by Chance operand "Type" was selected and probabilities defined. This aspect of the model could be developed further and was identified as potential connector to the analytical model, where a separate vehicle routing model could be developed, and the results of the analytical model combined with the simulation model. In this example routing was defined as probability in percentages. Four "True" branches from the decide module were linked to four record modules and 4 route modules. The false branch was linked to the fifth record module followed by route module.

Figure 4.6.3-12 "M1.FG Inventory Control" sub-model logic

All entities were subject to the same routing logic based on probabilities, yet in the real environment this may vary significantly and therefore a further development of the model would be required to allow for multiple conditions to be assigned depending on such constraining factors as vehicle utilisation, lead time, demand requirements or market flexibility. This was identified as an area for further research.

A duplicate branch from “Duplicate flow of FG” module was connected to “M1.FG inventory Control” sub-model that was further developed from Kelton et al. (2010). The sub-model (Figure 4.5.3-12) was developed using modules from block and elements panels. This sub-model looked into inventory evaluation for each entity that moved through the system. The inventory up to level policy was adopted to reflect inventory I(t) performance over time. This type of inventory review policy is referred to as (s, S) in the literature (Kelton et al., 2010).

4.6.4. Distribution model

Physical distribution and materials management are part of logistics managements, which is an important element of the E2E-SC system. Distribution is relative to a flow of goods and information in the system / model. It can be defined as an efficient transfer of goods through the supply chain network to satisfy customer requirements and business needs in a cost-effective way (Rushton, Croucher, & Baker, 2017). Rushton et al. (2017) highlighted major components found in logistics and distribution as transportation, warehousing, inventory, packaging and information. All these functions require systemic planning and coordination not only of their own processes within their node but also cross functional alignment and collaboration with external links. Rushton et al. (2017)

emphasised on the total logistic concept, which considers various elements that are covered by logistics and distribution category as one integrated system. This concept is particularly important for this study as each E2E-SC system includes multiple linkages between key participants and external environment.

Shi et al. (2013) highlighted five main steps relative to distribution centre operations which were: receiving, sorting, storing, retrieving and shipping. The authors further argued that by adopting cross-docking optimisation method the logistical operations can be improved and the business can benefit from consolidated outbound operations. The authors combined DES with metamodel based optimisation, which was reinforced by Latin Hypercube Sampling (LHS) and Bootstrapping techniques used to search for optimal solutions.

Analytical models are frequently adapted in studies relative to operational problems in supply chain systems. Complexity observed in these systems calls for more pragmatic and sophisticated solutions to solve them. Therefore, often simulation methods are employed in combination with analytical models to allow for most effective modelling solutions.

This study considered developing a generic distribution model, which considered the following activities as presented in the Arena model below: “DC1 Station”, “Seize Resource DC1” resources, “Assign Time In”, “Delay for Processing DC1”, “Release Resource DC1”, “Assign Packing Time” and “Route to initiate order processing DC1”.

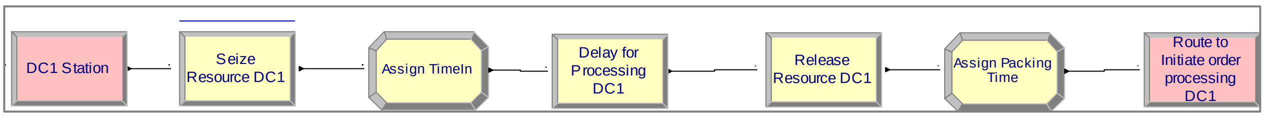


Figure 4.6.4-1 Distribution model logic in Arena level 2

In the distribution model presented in Figure 4.6.4-1 only entities sent to "DC1 Station" arrived. Some entities were shipped directly to the retailers or second distribution model. Extant literature provides many examples of the specific issues relative to distribution or production-distribution process. Specific activates such as cross-docking (Shi et al., 2013), transhipment problem (Tiacci & Saetta, 2011), pack size constraints and spatially-correlated demand (Yan, Robb, & Silver, 2009), uncertainty of customer orders and equipment performance (Ahire, Gorman, Dwiggins, & Mudry, 2007), loading dock requirements (Gill, 2009) or batch ordering policies (Karaman & Altiok, 2009) amongst many others were not included in this research. Nevertheless, the generic model was deemed applicable for further work and extension to any specific problems.

4.6.5. Retailer model

At the downstream of an E2E-SC was located the ultimate recipient of finished goods (FG), the consumer. Consumers purchased finished goods via online or physical attendance to markets/shops. Consumers purchase pattern recorded over time provides a data input for market demand models.

In this example, demands were based on constant value, nevertheless for real case studies this would need an exact data input sets, collected over period, which then could be run through input data analyser to define the best data fit to ensure that the most exact statistical distribution was used. An alternative option would be to read data values from the file, which Arena's functionality allows to perform. The demand can be based on the past data or it can be a combination of historical, current and forecasted volumes. To support this step, various foresting techniques can be used to understand the demand behaviour and to predict the optimal forecast volumes. Arena allows a multiple runs and various scenario comparisons based on the data input depending on the business needs. The retailer model logic is presented in Figure 4.6.4-1. Each retailer model included the following sub-models: FG processing model, customer demand model and order processing model.

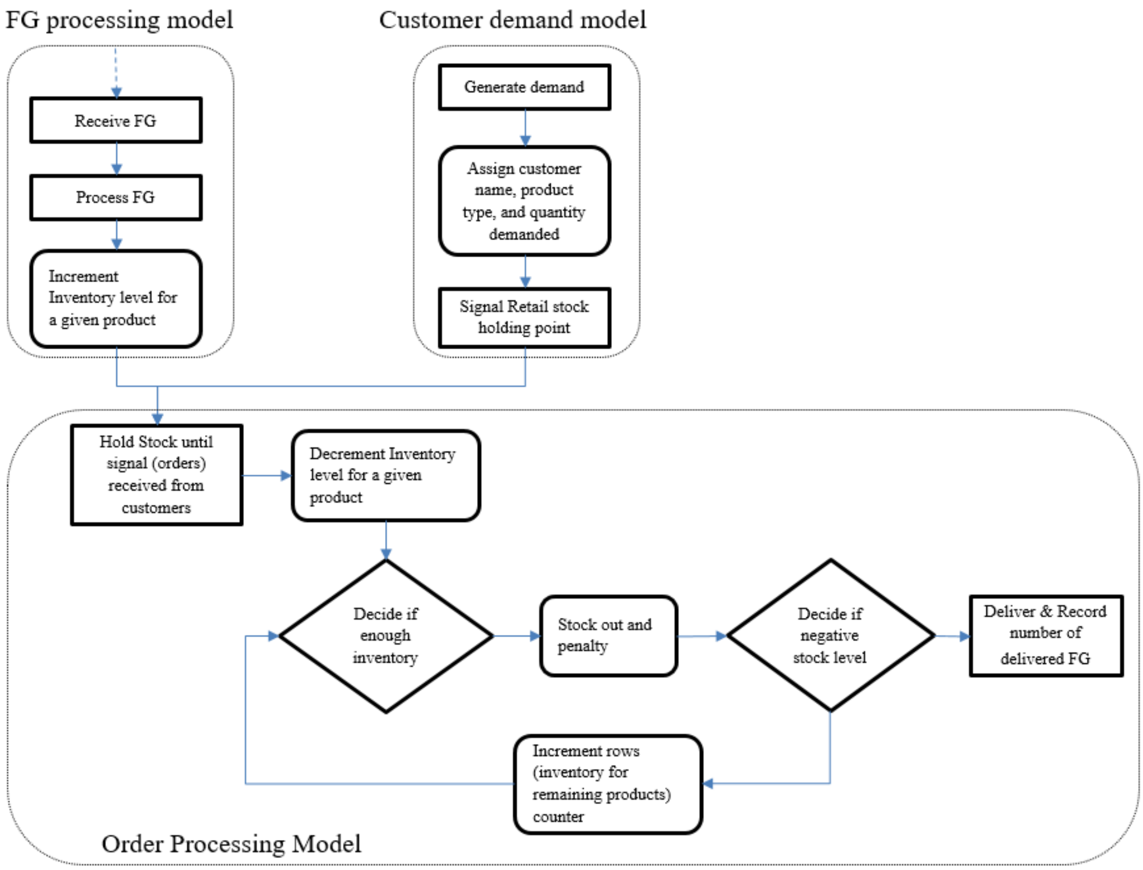


Figure 4.6.5-1 Retailer model logic

The Arena model for demand generation is presented in Figure 4.6.5-2. In Arena, this activity was modelled using the following modules: create, assign, signal and dispose. In the example of Retailer 1, five models were populated to replicate the demand pattern and to model order quantities requested by customers for five products. The demand was created for each product in create modules based on the sales pattern observed in the retail. Assignments were then defined in each of the below models providing the quantity of demand requirements for each product requested by customers.

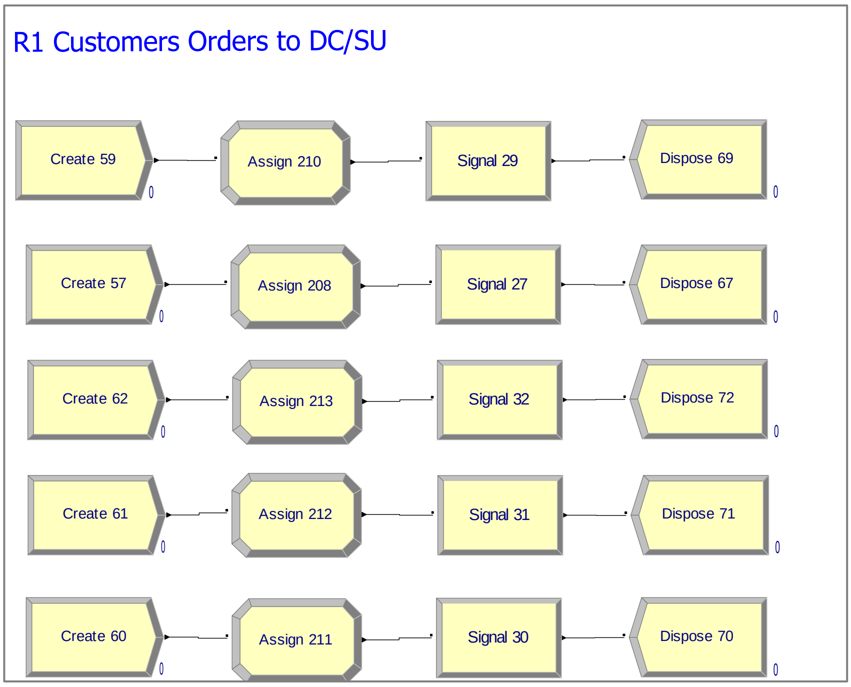


Figure 4.6.5-2 Retailer 1 Customers demand requirements model logic

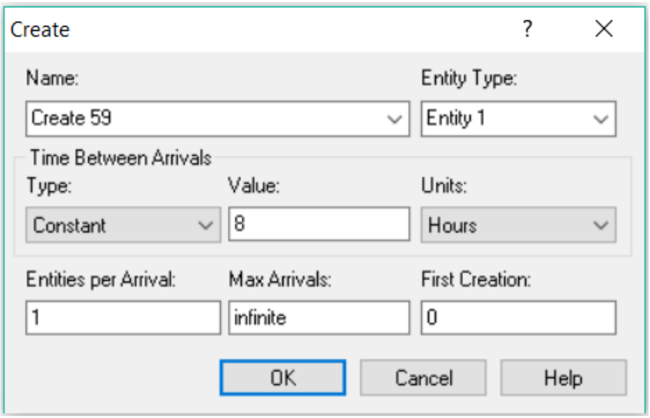


Figure 4.6.5-3 Create module operands values

As depicted in the Figure 4.6.5-3, the demand generation model logic started with the create module, where demand pattern was defined using statistical distribution. Following this, in the assign module an attribute called "Customer" was defined with the value 101. Likewise, the product type and demand quantity for this product were assigned (Figure 4.6.5-4). Each retailer/customer was defined a specific numerical identification.

A quantity of each product demanded by the customer was defined in the Arena model by assigning a product specific variable, for instance; the variable called “QtyP1” was used to define the quantity of Product 1 demanded by the Retailer 1 customer number 101. Other variables were defined in the variable spreadsheet in Arena to reflect quantities needed for each product number i.e. P1, …, P5.

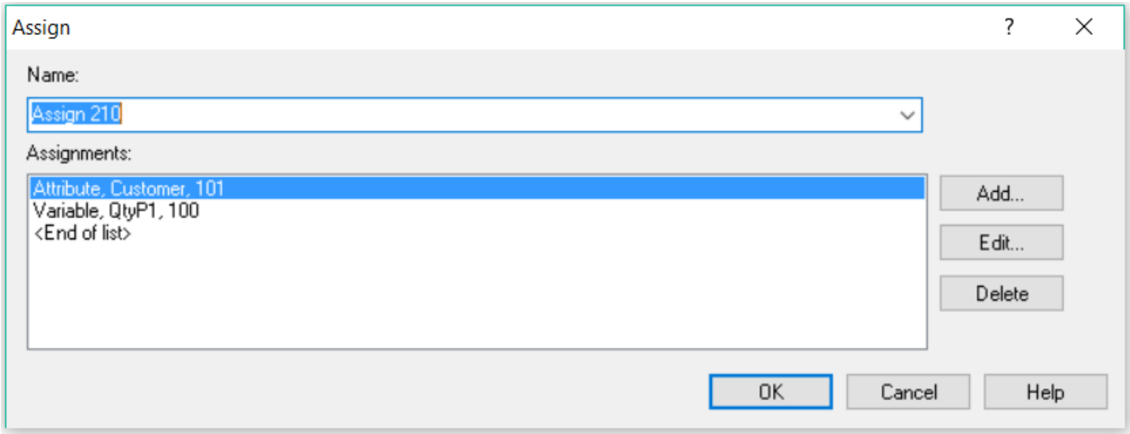


Figure 4.6.5-4 Assign module operands values and assignments

A Signal module was used to send a signal value to a Hold module in the model in Figure 4.6.5-5. In the example of Retailer 1, any time demand was generated and an entity arrived at a Signal module, the signal was evaluated and the signal code 101 was to initiate orders processing at the Retailer 2 customer. The “Hold until orders received from R1” module operand “Type” was set to Wait for Signal with the value 101, which was Retailer’s 1 customer identification number. This triggered the release of inventory and orders processing at the Retailer 1 (as specified number of entities were present).

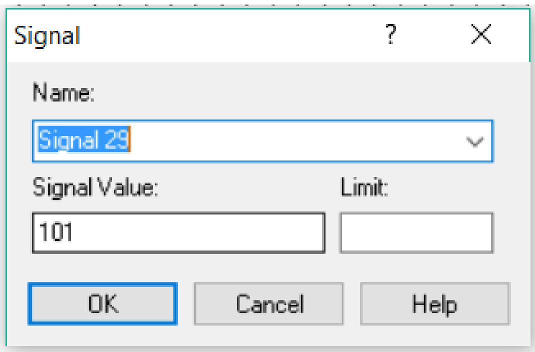
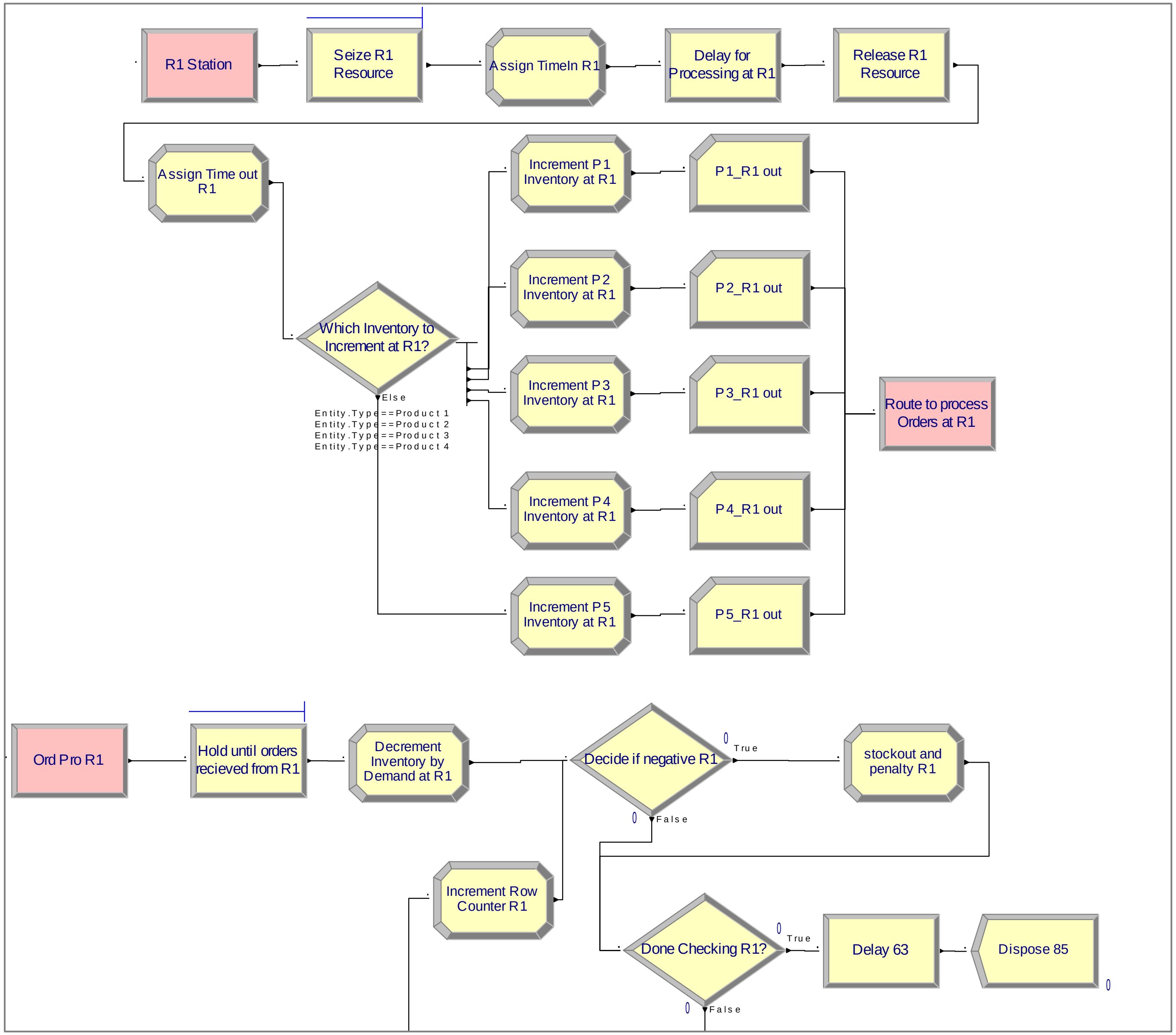


Figure 4.6.5-5 Signal module operand values

The model represented the flow of FGs in the system and the flow of information that was subject to control logic, where inventory levels for each product were decremented by demands requirements. The orders processing model logic is presented in the Figure 4.6.5-6 below.

Figure 4.6.5-6 Orders processing model logic



The model commenced with the “R1 Station” module and was linked to Seize module called “Seize R1 Resource”. In the Seize module one resource named “ResourceRetail1” was allocated to all entities passing through the model. To measure processing time, the “Assign TimeIn R1” module was used, and the attribute Tin was assigned with the value TNOW. This was complemented with the delay module whereby an expression “DC1ProcessingTime” was used to reflect the Delay Time. Subsequently, a Release module was added to release unit of the “ResourceRetail1” resource that entities previously has seized. This module was linked to an assign module, where an attribute “TimeInPack” was assigned a new value of TNOW-Tin to model duration of the orders processing at the Retailer 1. Following the assign module, a decision-making logic was modelled in the decide module, where the N-way by Condition based on the entity type was selected (Figure 4.6.5-7). This module was selected to allow to increment the inventory for each of the five products in the subsequent assign modules.

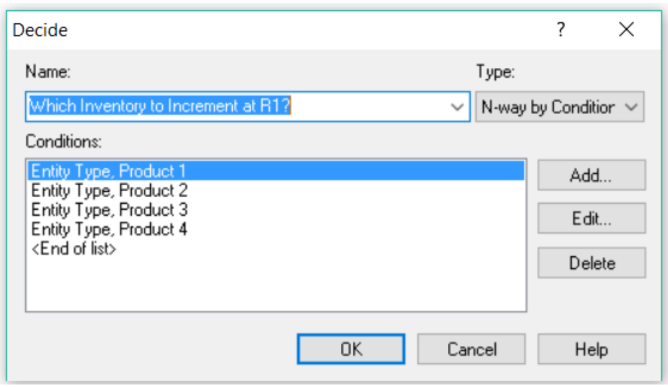


Figure 4.6.5-7 Which Inventory to Increment at R1 module logic

Each of the five assign modules were linked to one of the branches in the preceding decide module. Assignments in each of the five modules were carefully added to ensure that the correct inventory was incremented for each of the five products (Figure 4.6.5-8). A variable array 1D was used to model multiple products.

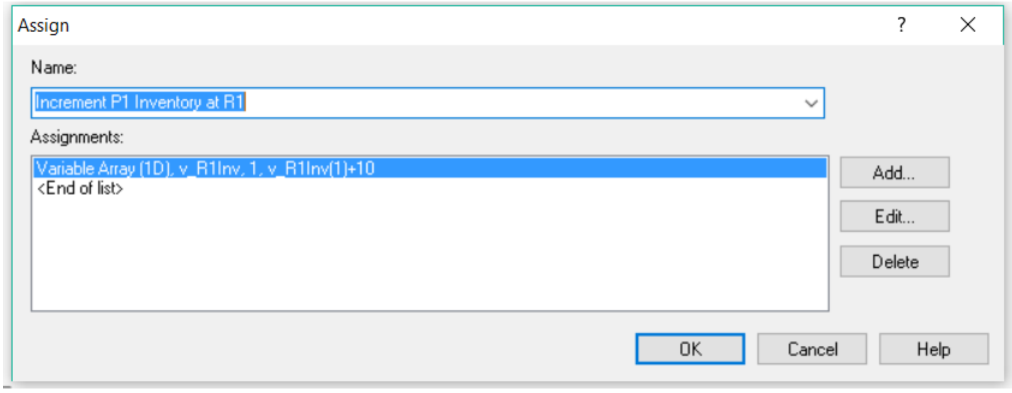


Figure 4.6.5-8 Increment P1 Inventory at R1 module operand

When making a variable assignment, the variable specified should be automatically added to the Variable spreadsheet if not already defined by the modeller. The same logic applied to variable arrays except for the row and column dimensions of a variable array, which needs to be specified in the Variable spreadsheet before running the simulation. In this example, there are 6 retailers and therefore six variable arrays 1D were used to capture inventory levels at each of the six retailers (v_R1Inv, …, v_R6Inv), stock outs at each of six retailers (v_Stockout_R1, …, v_Stockout_R6) and lost revenue at each of six retailers (v_LostRevenue_R1, …, v_LostRevenue_R6). There were five products offered to each of six retails, therefore each of the above retailer specific variables were defined five row dimensions for these variable arrays. The variable array 1D called "v_R1Inv" was used to increment the inventory in the "Increment P1 Inventory at R1" assign module, where the inventory of Product 1 was incremented by 10 (v_R1Inv (1) +10). All variables used to model orders processing at retailers are captured in Table 4.6.5-1.

Table 4.6.5-1 Variables spreadsheet used to model orders processing at retailers

Name	*Rows*	*Columns*	*Data Type*	*Clear Option*
Customer Name	6		Real	System
v_LostRevenue_R1	5		Real	System
v_LostRevenue_R2	5		Real	System
v_LostRevenue_R3	5		Real	System
v_LostRevenue_R4	5		Real	System
v_LostRevenue_R5	5		Real	System
v_LostRevenue_R6	5		Real	System
v_R1Inv	5		Real	System
v_R2Inv	5		Real	System
v_R3Inv	5		Real	System
v_R4Inv	5		Real	System
v_R5Inv	5		Real	System
v_R6Inv	5		Real	System
v_Stockout_R1	5		Real	System
v_Stockout_R2	5		Real	System
v_Stockout_R3	5		Real	System
v_Stockout_R4	5		Real	System
v_Stockout_R5	5		Real	System
v_Stockout_R6	5		Real	System

Incremental inventory for each of the five products were recorded and entities were routed to "Ord Pro R1" station. Once a signal was received indicating customer orders, the inventory was decremented by the demand amount as recorded in the assign module in Figure 4.5.5-9. The inventory of each of the five products was decremented by the orders received.

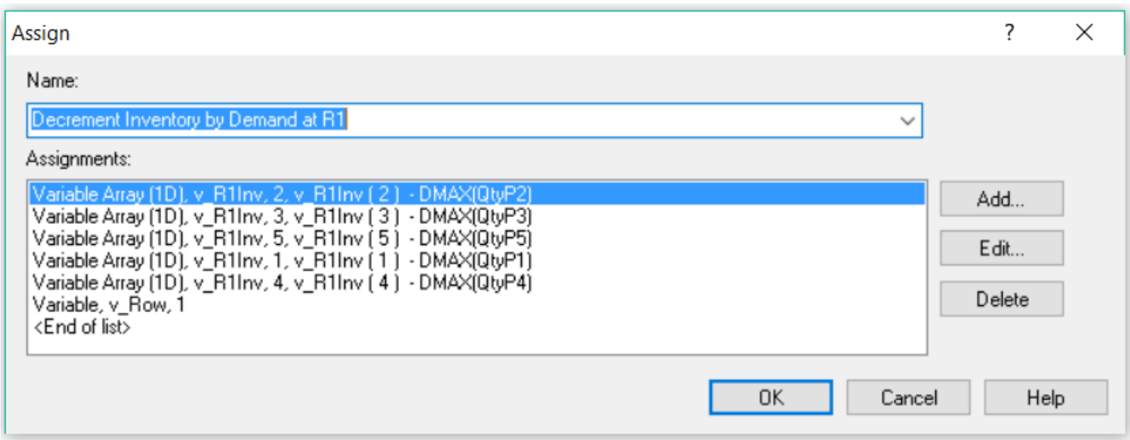


Figure 4.6.5-9 Decrement Inventory by Demand at R1 module operand

In the following “Decide if negative R1” decide module, a decision-making process took place whereby if the inventory was negative stock outs occurred and penalties were assigned to each of the products in the “stock out and penalty R1” module. All entities entered final stage of the model, which was delay and dispose.

4.7. Simulation results

In this section of the thesis simulation run parameters are defined and evaluation of the simulation results is provided. A summary of the data used in simulation run relative to the described above model logic is presented below in Tables 4.7-1 to 4.7-8. At this stage of the research, data input and simulation run results are evaluated. Model testing and operational validity will be presented in Chapter 5. The data selection/input used in this model were random and were hypothesised to test model validity and verify if the model fulfils its intended purpose (Sargent, 2013). To discuss the external validity of the simulation model, the future work would aim to use a real data instead of hypothesised parameters values and so to evaluate the model performance (Meredith et al. 1989). The E2E-SC simulation model developed in this research is generic and therefore the data input and output are hypothesised, based on random inputs. The initial models’ values were defined based on constant values to allow for visual observation and quick evaluation of model performance. As acknowledged by Carvalho et al. (2012) the simulation warm-up period is very important as short warm up may introduce bias into simulation the results or useful data can be wasted if warm up period is too long. The approach taken in this research is in line with Carvalho et al. (2012), whereby a graphical method was adopted and the visual inspection of timeseries of the simulation outputs evaluated to ensure output reliability. After completing a few runs a total simulation run was set to 1000 hours which is similar to the one used in Carvalho et al. (2012). The aim of this model was to consider the entire category of products that consisted of various product families. Similarly, the model focused on the generic aspects such as capacity at each node of the E2E-SC system and focused on its key critical components. It can be observed that during data collection process some required data to perform simulation may not be readily available due to their sensitivity, insufficient sample or due to not been collected by the company under investigation, which can be a constraining and limiting factor (Rossetti, 2010). Hence the use of approximated values within the model reduces its fit to the actual phenomena and increases the risk of irrelevance. Consequently, all such input values would be recorded and closely examined by the industry experts.

The current model considered the flow of five products through the E2E-SC system with emphasis on five critical components (Component 1, …, Component 5). The arrival of all supplies was constant with 1 unit arriving every 1 hour. Supplier 1 supplied two components: Component 1 and Component 5. The model logic for the third supplier considered two sub-components (S3.1 and S3.2), which were batched to create one Component 3. Both sub-components were arriving at the Supplier 3 also at a constant rate with a value of 1 and with the time between arrivals assigned at 1 hour. All components were processed according to the statistical distributions presented in Table 4.7-1, before they were delivered to the manufacturer 1. The delivery time was recorded for each of the suppliers as a delay with normal distribution with mean of 2 and standard deviation of 4 hours.

Table 4.7-1 Supplier input data

Suppliers	Identifier	Value	Units	Additional Data
Supply Arrival	Component 1 Component 2 Component 3.1 Component 3.2 Component 4 Component 5	1 unit 1 unit 1 unit 1 unit 1 unit 1 unit	Hour Hour Hour Hour Hour Hour	
Supply Processing	PrepTime PrepTime	0.2 0.2	Hour Hour	Delay Delay
Deliver Supply	Delay S1.L1 Delay S1.L2 Delay S2.L1 Delay S3.L1 Delay S4.L1	1 1 1 1 1	Hour Hour Hour Hour Hour	

Table 4.7-2 Manufacturer input data

Manufacturer	Identifier	Value	Unit
Delay to Inspection	Delay to S1 Inspection	1	Hour
	Delay to S2 Inspection	1	Hour
	Delay to S3 Inspection	1	Hour
	Delay to S4 Inspection	1	Hour
	Delay to S5 Inspection	1	Hour
Passing Inspection	S1 Inspection Pass?	99.5%	n/a
	S2 Inspection Pass?	99.5%	n/a
	SS Inspection Pass?	99.5%	n/a
	S4 Inspection Pass?	99.5%	n/a
	S5 Inspection Pass?	99.5%	n/a

Table 4.7-3 Distributors input data

Distributors	Identifier	Value	Unit
Delay for Processing DC1	DC1ProcessingTime	0.1	Hour
Delay for Processing DC2	DC2ProcessingTime	0.1	Hour
Route to Customers	DC1	1	Hour
	DC1	1	Hour

Table 4.7-4 Retailers input data

Retailers	Identifier	Value	Unit
Processing	Retail1Processing	1	Hour
	Retail2Processing	1	Hour
	Retail3Processing	1	Hour
	Retail4Processing	1	Hour
	Retail5Processing	1	Hour
	Retail6Processing	1	Hour

Table 4.7-5 Resource spreadsheet view in the Basic Process Panel

Name	Type	Capacity
Dispatch Operative	Fixed Capacity	1
FactoryOperative	Fixed Capacity	1
ResourceRetail1	Fixed Capacity	1
ResourceRetail5	Fixed Capacity	1
ResourceRetail6	Fixed Capacity	1
S1.Line1	Fixed Capacity	1
S3.Line1	Fixed Capacity	1
M1.Line1	Fixed Capacity	1
S2.Line1	Fixed Capacity	1
ResourceRetail4	Fixed Capacity	1
PackageMan1	Fixed Capacity	1
PackageDC2	Fixed Capacity	1
ResourceRetail2	Fixed Capacity	1
ResourceRetail3	Fixed Capacity	1
S4.Line1	Fixed Capacity	1
S1.Line2	Fixed Capacity	1

Table 4.7-6 Inventory evaluation data input

Variable Name	Value
Inventory LevelS1 (…,S5)	10
Little s	5
Big S	10
Setup CostS1 (…,S5)	32
Incremental CostS1 (…,S5)	3
Unit Holding CostS1 (…,S5)	1
Unit Shortage CostS1 (…,S5)	5
Interdemand TimeS1 (…,S5)	EXPO(0.1)
Evaluation IntervalS1 (…,S5)	1
Delivery LagS1 (…,S5)	UNIF (0.5, 1.0)

At the manufacturer, the received supplies were subject to a quality check, which was reflected in the model as a delay with given values as well as the percentage of the components that passed quality check presented in Table 4.7-2. Only high-quality components were sent for production process. At this stage of the model each of the three types of the supplied components was used in the batching module to create products P1-P5. The time delay for production and processing for each participant in the E2E-SC were defined. Each of the five products were then moved (recorded in the model as delay of 1 hour) to the finished goods storage area, and ultimately delivered to distributors and retailers with the transportation process recorded as a delay of 1 hour. The routing from suppliers to manufacturer was based on the predefined sequence based on Arena's N-way by chance condition, which allowed for any number of conditions or probabilities to be specified as well as an "else" exit (Arena Help File, 2013). Routing from the manufacturer to the distributors and retailers was based on the random configuration, however this point can be addressed by use of vehicle routing model in the combined application with OR techniques. This is another area where mixing modelling techniques can support modelling an E2E-SC.

The data required for the simulation may be obtained from various tools that use other modelling techniques. For instance, to devise sequential routing to customers, a vehicle routing problem and associated algorithms can be used. Therefore, further model developments will consider ways of mixing modelling techniques with simulation to achieve a best E2E-SC system model performance.

The experimental simulation model was run for 1000 hours. The output of the simulation run was based on one replication and provided the following information about the key performance indicators:

1) Relative to entities

a) Time related indicators such as value added (VA) time, wait time, transfer time, other time and total time
b) The number of entities (components, product) entering and leaving the system
c) Entities WIP values

2) Queues in the system

d) Waiting time

e) Number waiting

3) Resources in the system

f) Instantaneous and Scheduled Utilization, which considers number of busy, scheduled and seized resources

4) Records data and information as defined in the Arena's "Record" module, which refer to collection of statistics

The results of the simulation run are presented below. Simulation allowed to reflect the delay that occurred as materials/goods were moving along the E2E-SC system. The simulation allowed to capture operational performances of the SC participants as well as the entire SC system relative to i.e. resources utilisation, processing time or time spent in the system.

The number of entities that entered the model is presented in Table 4.7-7. Simple values were used to allow for step by step review of the model logic and its intended purpose. By evaluating the below table, the total number of Components 1,2,4 and 5 were in the range of 2239 and 2254, but the number in of Component 3 was significantly lower (1484), since this part was assembled from 2 different sub-components which had a time delay to account for the assembly process.

Table 4.7-7 Number of entities created in the simulation run

Number In	*Value*
Component 1	2241.00
Component 2	2254.00
Component 3	1484.00
Component 3.1	1334.00
Component 3.2	1334.00
Component 4	2248.00
Component 5	2239.00
Entity 1	1320.00
Inventory Evaluator	1001.00
Inventory EvaluatorS1	1001.00
Inventory EvaluatorS2	1001.00
Inventory EvaluatorS3	1001.00
Inventory EvaluatorS4	1001.00
Product 1	344.00
Product 2	415.00
Product 3	416.00
Product 4	587.00
Product 5	364.00

The entities wait time is summarised in Table 4.7-8 and entities transfer time in Table 4.7-9. An observation can be made that component 3 wait time was ~ 0.5 hour, but the average wait time for finished goods was 44.43 hours. This may be attributed to the fact that each of the finished goods required a defined number of different key components and only were assembled if all required components were present.

Table 4.7-8 Entities wait time

Wait Time	*Average*	*Half Width*	*Minimum Value*	*Maximum Value*
Component 1	0	0.000000000	0	0
Component 2	0	0.000000000	0	0
Component 3	0.048816568	0.025672791	0	3
Component 4	0	0.000000000	0	0
Component 5	0	0.000000000	0	0
Inventory Evaluator	0	0.000000000	0	0
Inventory EvaluatorS1	0	0.000000000	0	0
Inventory EvaluatorS2	0	0.000000000	0	0
Inventory EvaluatorS3	0	0.000000000	0	0
Inventory EvaluatorS4	0	0.000000000	0	0
Product 1	48.37488968	(Insufficient)	0	324.5
Product 2	44.15870112	(Correlated)	0	320.7
Product 3	42.69097371	(Correlated)	0	330.7
Product 4	40.15794726	(Correlated)	0	328.7
Product 5	46.78343374	(Correlated)	0	335.9

Table 4.7-9 Entities transfer time

Transfer Time	*Average*	*Half Width*	*Minimum Value*	*Maximum Value*
Component 1	0.003984064	0.003901843	0	1
Component 2	0.002944063	0.003441102	0	1
Component 3	0.00443787	0.005100666	0	1
Component 4	0.004916421	0.005983768	0	1
Component 5	0.004975124	(Correlated)	0	1
Inventory Evaluator	0	0.000000000	0	0
Inventory EvaluatorS1	0	0.000000000	0	0
Inventory EvaluatorS2	0	0.000000000	0	0
Inventory EvaluatorS3	0	0.000000000	0	0
Inventory EvaluatorS4	0	0.000000000	0	0
Product 1	3.150159744	(Insufficient)	0	7
Product 2	2.621693122	0.170876807	0	6
Product 3	2.608465608	0.172575108	0	6
Product 4	2.101886792	0.149179023	0	5
Product 5	3.096969697	0.179680887	0	7

The capacity utilisation for each of the resources used in the model is presented in Table 4.7-10. Upstream the supply chain the capacity utilisation at suppliers and manufacturer is very high with no spare capacity available. On the other hand, based on the model inputs, the downstream of the supply chain shows low capacity utilisation.

Table 4.7-10 Capacity utilisation for each resource

Instantaneous Utilization	*Average*	*Half Width*	*Minimum Value*	*Maximum Value*
Dispatch Operative	0.00	(Insufficient)	0.00	0.00
FactoryOperative	0.00	(Insufficient)	0.00	0.00
M1.Line1	0.9950	(Insufficient)	0.00	1.0000
PackageDC2	0.01840000	0.002916973	0.00	1.0000
PackageMan1	0.01990000	0.002264588	0.00	1.0000
ResourceRetail1	0.01990000	0.002395862	0.00	1.0000
ResourceRetail2	0.01020000	(Insufficient)	0.00	1.0000
ResourceRetail3	0.02010000	0.002023281	0.00	1.0000
ResourceRetail4	0.01840000	0.003125085	0.00	1.0000
ResourceRetail5	0.01150000	(Insufficient)	0.00	1.0000
ResourceRetail6	0.01920000	(Correlated)	0.00	1.0000
S1.Line1	1.0000	(Insufficient)	0.00	1.0000
S1.Line2	1.0000	(Insufficient)	0.00	1.0000
S2.Line1	1.0000	(Insufficient)	0.00	1.0000
S3.Line1	0.6658	0.004043774	0.00	1.0000
S4.Line1	1.0000	(Insufficient)	0.00	1.0000

Other aspects relative to simulation model run results will be further discussed in the validation chapter. Likewise, the data input changes impact on the E2E-SC system performance will be evaluated. Table 4.7-11 provides a graphical representation of the simulation run results. This helps in understanding of the E2E-SC system performance relative to components, products and processes performances.

In the graphical representation of simulation results, the inventory levels for all key components as well as finished goods is provided. In this example, a periodic inventory evaluation is adopted and decisions regarding key materials or FG ordering is based on this inventory policy. The graphs below represent the inventory level at any time in the simulation run for each of the 5 components, which were all initiated to 100. The variable in this model is the function of I(t), where the inventory level is depleted for instance in the case of “Component 1” by the variable “vCount_1”. The variable “vCunt_1” is the number of components that was delivered to the manufacturer and passed the quality check. Some of the components i.e. “Component 1” and “Component 2” are more frequently used then other components and therefore the replenishment is more frequent as observed in the graphs. Based on the data input, the inventory levels performance measures allow for visual observation of the state of the inventory, clearly visible when dropping below zero. This demonstrates the practical applicability and potential to develop and enhance the graphical representation of such performance measures into a dashboard allowing to control the E2E-SC as well as for better planning and designing of these complex systems.

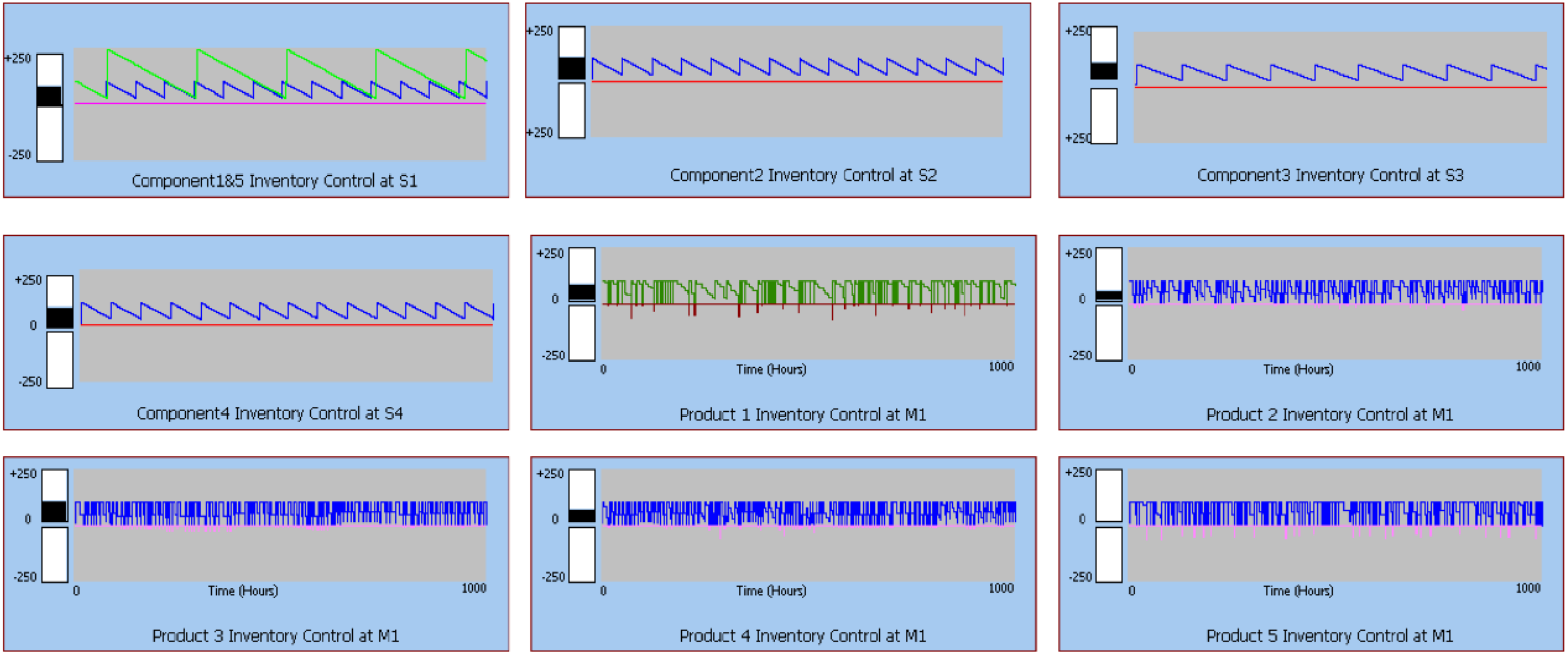


Table 4.7-11 Graphical representation of results

4.8. Chapter summary

This chapter presented a step by step guide to develop a generic E2E-SC system simulation model in Arena. Also, the requirements for modelling these complex systems were discussed. The overall aim of the chapter was to answer the research question regarding the extent to which simulation methodology can support the modelling of complex E2E-SC systems. The simulation is a powerful tool to allow for evaluation of the E2E-SC system performance measures over time. Nevertheless, its capability may prove limited when adding more products and processes to the E2E-SC system. The complexity observed in the structural, computational and systemic organisational elements of an E2E-SC requires sophisticated modelling techniques that allow for mixing simulation with other techniques. A generic approach to an E2E-SC system model development process using simulation was defined to support modellers and decision makers who would like to understand the behaviours of such systems. E2E-SC system is very complex and only to include generic elements require a set of assumptions and approximations as well as combined approach where other modelling techniques can be adopted for instance to provide data input to the simulation model or allow to interactions with other systems or tools. Simulation, allows to graphically represent performance measures, which may be useful in an E2E-SC system/model behaviour evaluation based on results.

Chapter 5

Validation, Verification and Research Reliability

5.1. Introduction

This section of the thesis is dedicated to review reliability and validity of the research design (Saunders et al., 2015). The research considered reliability as an approach to yield consistent findings based on the logical steps in the literature synthesis techniques or analysis procedures (Easterby-Smith et al., 2012b). Validity on the other hand is about ensuring that the research findings are in line with the intended purpose of the research (Saunders et al., 2015).

To ensure research reliability and validity, this chapter will validate the conceptual framework, and will verify and validate the E2E-SC model developed using computer simulation. This will be achieved in this chapter by addressing the following objectives:

1. Interviews with industry experts to discuss the model structural, computational and systemic organisational elements of the conceptual framework.
2. Critical evaluation of the E2E-SC simulation model to arrive to the conclusion and provide suggestions for improvement.

The chapter began with a brief introduction and progressed to elaborate the objectives that were set to ensure the research reliability and validity. A set of interviews were conducted to validate research conceptual framework and the generic step by step guideline to the E2E-SC simulation model development process. A critical evaluation of the validation process for a generic simulation model is provided and further examined in the light of the E2E-SC simulation model that was created as a part of this research. The chapter will continue to discuss validation limitations and will conclude with recommendation for a combined approach to modelling the E2E-SC systems using simulation and providing suggestions for further work and improvements. The next section will discuss reliability of the research findings. In this research, findings are gathered in the form of the conceptual framework and generic requirements for modelling E2E-SC when using simulation.

5.2. Reliability of research findings

Robinson (2014) argued that validation and verification is about increasing the confidence in the model, so it can be used to support decision making. The author avowed that it is impossible to prove that simulation model is valid. Consequently, any research intentions are to provide a reliable and valid source of information by offering logical set of statements and tactics. The current research ensured that this is achieved by validating the conceptual framework (1) and the E2E-SC simulation model (2) by addressing the following points (Saunders et al., 2015):

- Concept validity- the research employed a rigorous SLR approach that led to the composition of the conceptual framework. These formed generic requirements for modelling E2E-SC when using simulation. A guideline for creation of the generic E2E-SC system model using simulation was then presented. The conceptual framework as well as steps in the simulation model development process are being validated via interviews with industry experts.
- Internal validity of the conceptual framework- derived from data synthesis step within the SLR, where the researcher employed pattern matching activity and undertook a rigorous literature review process building further on the work of Shafer and Smunt (2004) to classify the most frequently studied aspects of an E2E-SC from product and process perspective. Subsequently, using logical

connection between various elements these were classified into three pillars: structural, computational and systemic organisational.

- External validity – which is often referred to as generalisability. Saunders et al. (2015) explained that this element of the research validity seeks to examine whether the research findings apply to other settings or organisations. In the current research, this aspect of the research validity shown to be rather a difficult task due to challenges relative in creation of the E2E-SC simulation model. This point in research validation will be achieved by focusing on the generic E2E-SC system requirements that should be used when constructing the simulation model and this was reached through four interviews with industry experts.

The second point mentioned at the beginning of this section highlighted the importance of simulation model validation and verification, which is pertinent to the generic E2E-SC simulation model like any other models. The challenge in achieving this is due to lack of standard process aimed at validation and verification (Carvalho et al., 2012). Therefore, a validation of the generic E2E-SC simulation model turns to be rather a complicated task and is further elaborated in the following sections.

Table 5.2-1 highlights validity and reliability elements of this research, offering specific examples for each aspect considered. The research selected a FMCG industry to validate the E2E-SC system elements. Highly experienced supply chain industry experts were purposively selected for the interviews.

Table 5.2-1 E2E-SC simulation model validity and reliability principles

Category	Description
Interview participants	Purposive sampling; SC director and SC capability mangers interviewed. Different operational areas and industry background.
Simulation model logic explained (content validation)	Conceptual framework used to support model creation (conceptual framework discussed in chapter 2). Validation of the framework and scientific model with industry and academic expert.
Simulation model codes and logic checks (internal validation of the model construction process)	Verification via structured walkthroughs to ensure correct details of a source code (tracing and debugging). Logic and design of the simulation model as well as codes used were examined. Model consistency was verified. Model development was well documented.
Simulation model applicability to business	Settings and subjects within the study clearly defined to enable generalizability.
Model results analysis	Interviews used to support simulation model development. Animation model developed to support model validation. Graphs recording model performance were analysed to ensure model validity.

All four selected participants had extensive knowledge relative to E2E-SC strategic, tactical and operational principles and a background in different supply chains such as automotive, FMCG, electronics, or food. Each of the participants had knowledge in FMCG as well as knowledge form other SC sectors. Each interview took between 56 minutes and 1 hour and 16 minutes. Interviews were not recorder due to confidentiality issues, but extensive notes were taken and then manually coded in the MS Excel document.

Conceptual model validation determined that the content, assumptions and elements of the framework are sufficiently accurate for the intended purpose and providing the answer to a question: *When modelling an E2E-SC using simulation, which are the main elements, processes and characteristics that should be considered?* The E2E-SC model requirements were gathered via SLR and this rigorous process was discussed and documented in Chapter 2. The logic of the

E2E-SC simulation model was discussed with the experts and results will be presented in the following sections.

Moreover, simulation model codes and logic of simulation modules sequence and connection between sub-models were reviewed. All aspects relative to the simulation model development process in Arena were documented, following a generic guideline to ensure clarity of the approach undertaken and to allow for easy access and reuse (Robinson, 2014).

Model applicability to businesses and other considerations relative to model validation such as analysing model results and testing will be discussed in the following section.

5.3. Generic simulation model validation elements

Often validation is associated with ensuring model's similarity in structure and behaviour to the real world (Rossetti, 2010). This approach seems quite simple and perhaps even naïve (Pidd, 2004) when viewed through the philosophical lenses showing multiple angles of knowledge creation. The relation between researcher, subject of inquiry and the way such inquiry ought to be investigated is influenced by the philosophical stance taken. This research argues that through mindful inquiry into systems' epistemic representation, one can learn from observing the system and/or changes made within it. This avows that validation and verification should be considered throughout the E2E-SC simulation model development process as well as during the process of making changes to the model.

Various authors acknowledged that validation and verification is not a stage in the process, but rather a continuous process throughout the model development

(Robinson, 2014). The first one is often referred to model accuracy, while the second term to transformation from conceptual model to simulation model. There are several key concepts to be accounted for when verifying the E2E-SC simulation model. One of them is to ensure that the conceptual model was accurately transformed into the simulation/computer model (Robinson, 2014). This aspect was highlighted in Chapter 4 in the Table 4.4.1-1 as part of the step by step guide to an E2E-SC simulation model development process. In a continuous manner, validation and verification were maintained during the lifecycle of this research and simulation model development with frequent reviews supported by academic expert (Pidd, 2004).

When it comes to validation and verification of a generic E2E-SC simulation model, the challenge is around the level of confidence that the model includes elements that can be used across different supply chains. This avows for a clear definition of a generic model. Robinson (2014) explained that a generic model is a simulation of a specific context that can be used across different organisations. This research efforts were directed to develop a generic modelling approach that can be used for any end to end supply chain (E2E-SC) or any of it members. This was to support a modeller or decision maker in understanding, which element should be considered when developing an E2E-SC model using simulation.

Recommendations from Banks, Carson, & Nelson (1996); Kelton, Sadowski, & Swets (2010); Kleijnen (1995); Pidd (2004) and Sargent (2013) were considered to address the objective relative to critical evaluation of the simulation model, leading to a twofold approach; (a) the E2E-SC model validation and verification by the researcher as a part of simulation model development process and (b) model validation through animation and evaluation of each sub-model. The E2E-SC model validation and verification elements are presented in Figure 5.3-1 below and are further discussed in the following sections of this chapter.

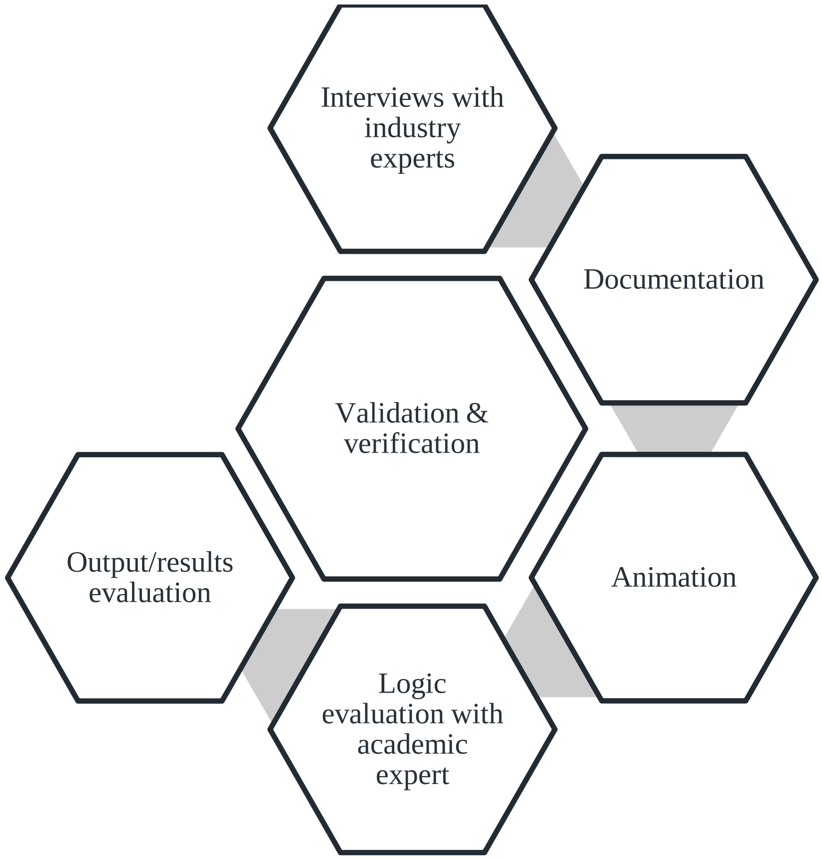


Figure 5.3-1 E2E-SC model validation and verification elements

Interviews were conducted with the FMCG industry experts to discuss generic pillars in the conceptual framework: structural, computational and systemic organisational, which were then used in developing the E2E-SC simulation model. The results obtained were discussed in the context of the research questions and were verified and validated against the intended purpose of the research. Simulation is a popular research methodology particularly for a study that intends to investigate complex systems and/or perform experimental or scenario analysis on a model instead of a real system (Kelton, Sadowski, & Swets, 2010; Stefanovic, Stefanovic, & Radenkovic, 2009; Pidd, 2004; Seila et al., 2003).

Therefore, a good documentation process that captures all steps undertaken can help in validation and verification of a simulation model (Robinson, 2014). A rigorous approach to modelling process was followed throughout this research allowing for continuous validation and verification of all steps to ensure model reliability.

Sargent (2013) acknowledged that any model should be created for a specific purpose (or application) and therefore its purpose should take a focal point in the validation process. The purpose of the research was to develop a generic E2E-SC system model, which was guided by the research questions as highlighted in Section 1.3.

The E2E-SC model was developed by the researcher to demonstrate that by following the guide provided in Chapter 4, in Table 4.4.1-1, a generic simulation model can be progressed. This research was not intended to address any specific problem in the supply chain, but rather to demonstrate the applicability of the generic elements gathered via SLR, which formed the conceptual framework. Consequently, instead of numerous sets of experimental conditions, which are usually used to evaluate model's intended applicability, this research focused on validation of the conceptual framework via interviews with the industry experts from one of the leading FMCG industry, that would wish not to be named for confidentiality purposes. Although model replicability is often considered in simulation studies, this was found more applicable to the conceptual E2E-SC system framework rather than simulation model. This was to ensure research findings credibility.

In the following section, a summary of findings from the interviews and discussion on the accuracy of the model's condition are presented. This is further supplemented by evaluation of model's input and output parameters. Firstly, model input and output variables are presented in answering the question on which generic elements should be considered when modelling E2E-SC using simulation. According to Sargent (2013) the model's variables of interest within the acceptable range between model variables and the corresponding system variables should be defined for the model to be valid. However, in the generic E2E-SC model, these were defined based on the conceptual framework and no real system to use for comparison existed. The variables selected for the study were generic with the random values and the range accuracy of each of the variables was evaluated based on the existing knowledge in the literature and supply chain expert opinions. These were documented and discussed in Sections 4.5 and 4.6.

Robinson (2014) acknowledged that validation of simulation models is often referred to drawing a comparison to a real system. This may prove difficult in a situation where there is no real system in existence to compare to. This is also a case in the current research, since a generic E2E-SC system model was developed, with the aim to provide an architecture for modelling end-to-end supply chain. The generic simulation model was developed to be used to model any similar E2E-SC system by simply changing the model data or by providing an option for extending the model to suit different needs of the business. Kelton et al. (2010) acknowledged that the task of changing the data input could be managed via external database. Similar method was adapted in the current research where the MS Excel database was created to facilitate compilation of information such as, product architecture (also known as bill of materials), supplier information, capacity related data, market and distribution logic information. Therefore, one way of using the model was to change the data input and analyse model output based on a given input.

As discussed in earlier section of the thesis, the generic E2E-SC simulation model development process was based on the ontological principles behind mindful inquiry into modelling E2E-SC and concepts summarised in the conceptual framework (Figure 2.6.1-1). Although, various textbooks call for the simulation model validation against a real system, this may also vary depending on how the world is viewed by the person who validates the model. Therefore, this research proposed the generic approach for developing the E2E-SC simulation model by combining ontological derivatives based on realism with the scent of empirical investigation to model the end-to-end supply chain from process and product perspective. Before discussing validation and verification facets of the simulation model developed in Arena, the next section evaluates the approach to E2E-SC model validation and summarises findings brought by the interviews with industry experts.

5.4. E2E-SC model validation and verification

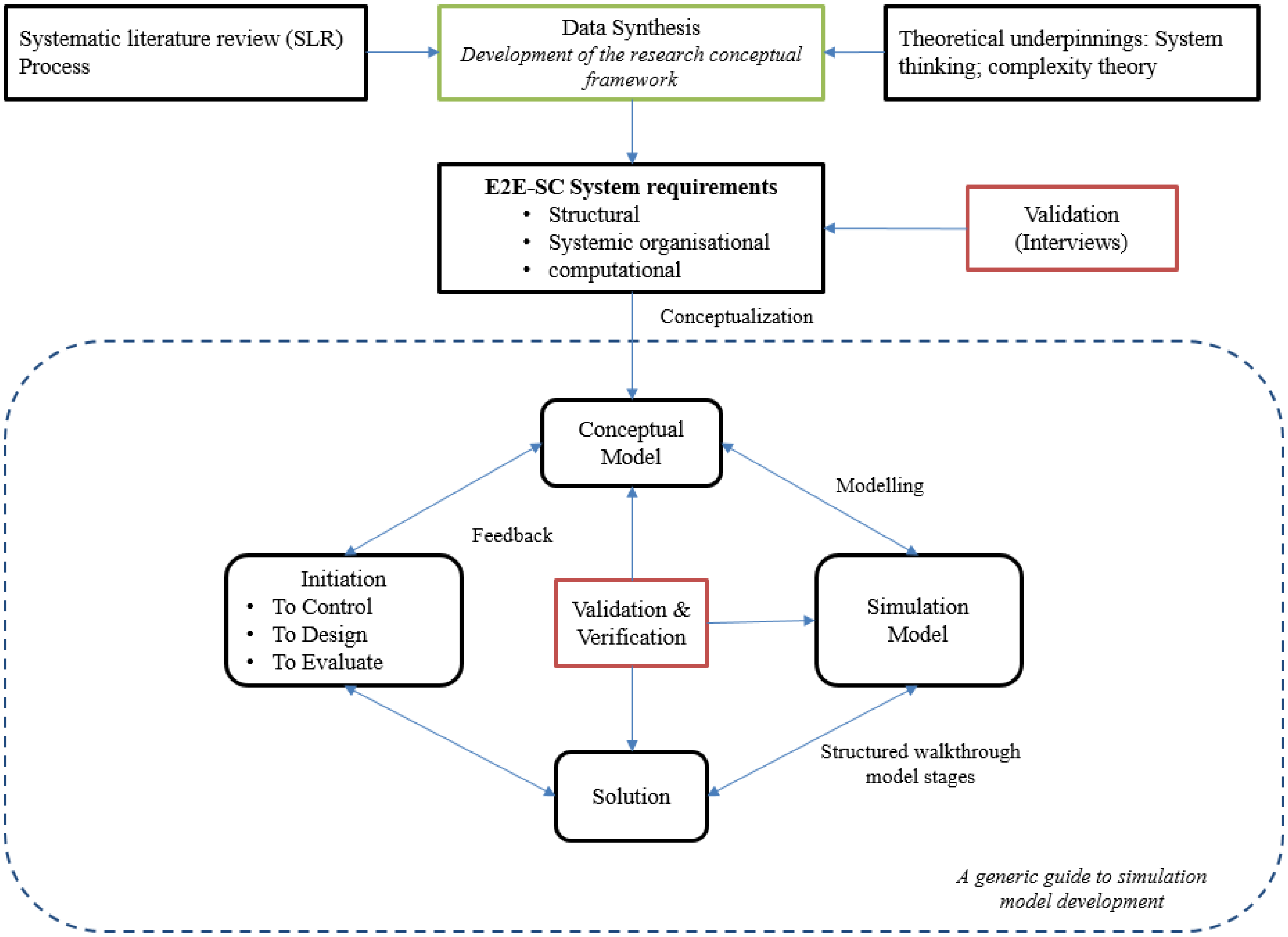
A generic E2E-SC system model developed in this research was resulting from the current altering levels of confluence between the two important ontological derivatives: (1) that regards the E2E-SC system as a physical construct, where the perception of the observer depicts the system description, and (2) that considers the E2E-SC system (organisation) as a perception of the ideal, heuristic and pragmatic model in nature designed with the aim to evaluate, improve, control or just model a phenomenon. Both aspects were inspired by the work of French philosopher Edgar Morin, who appreciated the importance of system structural elements as well as the benefits of knowledge creation when evaluating system organisation. These structural and systemic organisational elements formed two pillars in the conceptual framework (Figure 2.6.1-1) of which elements where gathered through data synthesis in the process of systematic literature review. The third pillar included computational elements that were identified in various studies as linking structure and organisation of the E2E-SC systems. The computational pillar referred to a process of mathematical calculation (Oxford dictionary) as well as the use of computer science (Oliveira et al., 2016). The elements that formed this pillar were also collected during the SLR.

The approach adopted to achieve this is presented in the flow diagram in Figure 5.4-1 below. The planning stage of the research included initial review of the literature, identification of the research aims, objectives and research questions as well as defined the need for SLR. A full discussion of the applicability and relevance of SLR approach was presented in chapter two, Section 2.4.1. The SLR approach resulted in selection of 228 studies for examination. The literature synthesis continued the work initiated by Shafer and Smunt (2004), and 11 thematic categories were also present in the current research: SCM, inventory management, production planning and inventory control, manufacturing, capacity planning, forecasting, purchasing, resource allocation and SC process design. Additionally, further 22 categories were found.

All papers were categorised, and a further distinction of specific categories was applied based on analytical and theoretical ideas developed and continuously validated with supervisory team throughout the research. These categories were further refined, reduced in numbers and ultimately classified under three pillars within the conceptual framework (Pope, Ziebland, & Mays, 2000). Through analysis of thematic categories, the conceptual framework consisting of structural, computational and systemic organisational pillars was constructed and these elements were validated through interviews with the industry experts. This section aims to present the process of data storage as well as data format, discuss interview specification and analysis, provide general remarks on modelling based on the interviews output to conclude with interview findings and evaluation of the conceptual framework.

Figure 5.4-1 Data synthesis, method and validation

Source: Further developed from Mitroff (1974)



The generic E2E-SC model guideline presented in Figure 4.3.1-2 in Chapter 4 was developed as a next step in the conceptual research framework further reinforced by system thinking and complexity theoretical underpinnings. Validation of the simulation model development approach is presented in Sections 5.5 and model verification is Section 5.6.

5.4.1. Data format and storage

A summary of interviews was documented in the Microsoft word file and each participant had a defined file name, which was stored on the secure memory stick, password protected. The main points noted during the interviews were codes in the MS Excel document and then extracted to supplementary MS Excel document, which was used to synthesise literature into three pillars.

5.4.2. Interviews specifications

The data collection for validation process included interviews with SC experts from the Company A. The interviews were conducted via Skype with the researcher present in the UK and participants in various locations globally, or in person in the company premises in the UK related to manufacturing stage of their E2E-SC (Table 5.4.2-1). Each interview commenced with greeting and other aspects relative to the interview process. Next, the researcher introduced the research topic and presented aims and objectives of the interview. The researcher shared the background of the research via e-mail in the form of a poster presentation with the interviewees before the interview. Likewise, a consent form was shared via the e-mail with the participant or in person in case of face-to-face interviews and signature was requested from the interviewees before commencing the interview. The data collection activities were conducted in the natural setting for the respondents, which were Skype and meetings room in one of the UK's business sites.

The researcher assumed the role of a moderator and asked a series of short questions to facilitate discussion (Berg and Lune 2012). Similarly, all ethical issues were addressed, and consent forms distributed a priori. The interviews activities specification is presented in table below. The interviews were conducted in Q3 2017 with senior managers and directors of the one of the top global FMCG supply chains, which took place when the conceptual framework was already created and the E2E-SC simulation model in Arena was in final development stage.

Table 5.4.2-1 Interviews activities specification

Activity	**Specification**
Data Collection techniques for validation	Interview
Date	June-August 2017
Location	Skype, UK
Number of participants	Four participants: SC director, SC Manager, 2x Long Term Capacity Planning Managers

5.4.3. Interviews analysis stages

This research required data for the simulation model validation and verification. Data can be classified as qualitative (interviews) and quantitative data relative to structural, computational and system organisational elements of the model. The qualitative data (interviews) were analysed following the data analysis approach proposed by Pope et al. (2000). Therefore, firstly the researcher became familiar (1) with the interview notes. After that, a recognition (2) of the thematic categories from the conceptual framework in the responses provided by the interviewees were acknowledged. These key thoughts provided by the interviewees regarding a specific category from the framework were noted and analysed. This was possible by linking the data with the aims and objectives of the research. Also, respondents provided an array of issues/views based on their individual experiences.

Based on the responses the data were coded and indexed (3) in accordance with the themes specified in the conceptual framework. Lastly, by evaluating the responses given and correlation between them, an explanation of the findings was drawn. This stage of the data analysis was influenced by the research objective and conceptual framework employed.

5.4.3.1. Structural elements evaluation

In Table 5.4.3.1-1 presents interviewees' feedback on the structural pillar of the conceptual framework. A general comment about the conceptual framework was that each of the elements were indeed applicable to E2E-SC system. All participants strongly agreed that products and level/layers were important but did not comment any further on these two points. The Table 5.4.3.1-1 provides a summary of interviews responses with a general comment 'relevant' if no further comment or example was given by the respondent. Likewise, a critical evaluation of the implications that each of the elements adds to modelling of the E2E-SC is provided.

Table 5.4.3.1-1 Interviewees responses on structural pillar of the conceptual framework

Structural pillar	Participant 1	Participant 2	Participant 3	Participant 4
Products	*relevant*	*Relevant*	*relevant*	*relevant*
Processes/policy	i.e. FG stockholding, inventory management Complex policies on managing components (constraint)	Understand your supply chain A methods to control a SC Supplier agreements	Considering more policies/processes increases modelling complexity (constraint)	Mapping the E2E-SC and key processes
Services	Service performance	Quality in one respect versus speed and lead time on the other side	Any model may be a good fit for product but may not be a good fit for a service	*relevant*
Echelons/nodes	*relevant*	*Relevant*	Understanding your industry, this will vary depending on the supply chain type the capacity ramp up of the new node - capacity constraint	*relevant*
Levels/layers	*relevant*	*Relevant*	*relevant*	*relevant*
Interconnections/ linkages	Long term partnership	Advent of much information allows for wider access	I.e. emergency back-up option	Key critical participants
Flows	*relevant*	*Relevant*	Important to logistics planning Vital to know exact flow pattern, i.e. to understand demand picks	*relevant*
Deterministic parameters	*relevant*	'defined' parameters	Strategic supplier- partner to win	*relevant*
Performance measures	Service performance Low level of recorded KPIs Specific KPIs for key participants	Accuracy and same across each point in the SC Simple triangle	I.e. utilisation of your assets, order fulfilment. Scenarios comparison	Depending on the SC type, aligned across business
Objectives	Level of control over SC Conflicting objectives	Clear upfront	*relevant*	Will depend on stakeholder involved
Boundaries	*relevant*	Push/pull boundary	Operational capacity	*relevant*
Constraints	Capacity utilisation	*Relevant*	I.e. policy, capacity	Capacity

Participant number 1 stressed on the importance of control and level of control in the E2E-SC system. He observed that the Company A had the most control of its E2E-SC except for retailers and markets nodes. Lack of control was particularly concerning and a suggestion was made that modelling of an upstream side of the E2E-SC would allow to understand the system behaviour better as there was a lot of the dynamic born there, although gaining a full control was unlikely.

Processes and policy structural elements were believed to be very important to the E2E-SC system. It was acknowledged that inventory management, as a driver of the free cash flow through any business, right from supplier through to the retailer, can only be optimised if the E2E-SC is fully understood. Notwithstanding a huge importance of inventory, it was noted that decisions on the right policies cannot be made in isolation. Therefore, as affirmed by Participant number 2, a decision on the right amount of stock needed in the E2E-SC should be based on a full understanding of all lead times, drivers of the responsiveness, the forecast accuracy and all other elements relative to the E2E-SC. The pressure on inventory has driven decision makers to try and understand much broader scope of the SC than it was done years ago. Technological advancements enabled to reach further, providing system capability to understand downstream and upstream SC better. However, it was acknowledged that data overload may prove challenging during E2E-SC model creation process.

It was also noted that complex processes and/or policies can be regarded as a constraint. Participant number 1 provided an example relative to the FMCG industry, whereby the high volatility of demand for FG and low flexibility on the packaging materials drove SC difficulties. On the other hand, Interviewee number 2 acknowledged that processes and policies can be used to control the E2E-SC for instance by setting a partnership agreement with suppliers. Another point was added by the Participant number 3, who regarded modelling of multiple processes and policies as constraint. The example provided by the Participant number 3, suggested that government policies may often affect cross regional sourcing or setting an emergency supply lines.

In discussing the service element, the Participant number 2 explained that most of industries segment themselves and can be classified within one of the four quadrants in the matrix, where on one side is low or high cost and on the other side is low or high service level. The participant number 2 also acknowledged that service level is associated with matching the product with the right supply chain design and the customer expectations in terms of lead time, product quality and service provided will vary accordingly. Therefore, when talking about service it is about quality in one respect versus speed and lead time on the other side. Another point was raised by the Participant number 3, who contended that a model could be a good fit for a product may not necessarily fit for a service.

In terms of echelons and nodes, these were considered relevant for the E2E-SC model. It was affirmed that understanding of the industry is vital when it comes to this element as this will vary depending on the supply chain type. An example was given, that adding a new node to the model may require the capacity ramp up before reaching a full capacity availability. Also, it was noted that there are some gaps and quite complex policies on managing the materials/subcomponents. An example was provided by the Participant number 1, who referred to the annual booking of capacity for a given number of materials/sub-components based on some decisions and setting the right flexibility boundaries based on the volatile demand for the FGs. The challenge was seen in getting the balance right in matching the cost and the service. The gap was noticed in lack of tools and techniques to model these quite complex policies and their impact on the E2E-SC.

This led to a discussion on performance measures. The Participant number 1 observed a low number of historic key performance indicators recorded by the Company A. Lack of historic data on the service performance, such as for example inventory ‘Days on Hands’ in the E2E-SC system, make it difficult to compare or evaluate various policies or FG performances. This combined with a mismatch between a high level of the demand fluctuation or volatility on one side and the relatively complex portfolio on the other side, creates further challenges and issues to managing E2E-SC. Moreover, the E2E-SC complexity was observed, when considering the overall category of products demand fluctuation, multiplied by the inner mix volatility as businesses were never sure how many FG they were going to sell in each region. This had an impact on the materials/sub-components and agreed flexibility boundaries on the top of the booked capacity, hence increasing the volatility in the entire system. It was affirmed by all participants that use of modelling would help in enlarging the understanding of processes, policies and evaluating SC performance, predominantly due to the observed existence of constraints, for example on materials/sub-components capacity utilisation, which had a direct impact on the format level and confronted with the high demand volatility drove the E2E-SC difficulties. Similarly, it was noted that some policies may not be good for all participants in the E2E-SC resulting in sub-optimising one part over another, which seemed to be only possible to correct via escalation and high level/ stakeholders review.

Participant number 2, affirmed that service, cost and inventory fall within a triangle of most pragmatic and clear performance measures for any company that's floating on the stock exchange. The trade-offs were identified in the triangle as follows: an aggressive policy on the service affected the cost and increased inventory levels, but a reduction in inventory level lowered down the associated cost, yet affecting transportation and logistics cost requiring, for instance; express delivery, and achieving a lower overall service level. It was assumed that similar approach may be widely used in FMCG but found the very simple way of balancing these three key fundamental drivers, which were perceived as linking to shareholder return, in a way that everyone in the business fully understands. This was found equally applicable to innovations supply chain, where considerations were given to very high quality or very high cost products. This led to a vital point that accuracy, simplicity and alignment of key performance measures across each node in the E2E-SC should be considered when modelling the supply chain.

Interconnections/linkages very important for the E2E-SC, and main emphasis were given long term partnership. Two participants acknowledged that by optimising the total performance within these long-term partnerships can bring savings, which can be then somehow commercially shared.

Modelling the end-to-end supply chain, whether using simulation or other techniques, was apprehended as a quite distant activity, driven by the complexities observed in these systems as captured in the conceptual framework. A general framework/guide to modelling the E2E-SC system was considered as incredibly relevant and needed to support decision makers and to better understand the E2E-SC behaviour. Participant number two recognised that technological advancements allow for wider access to information and the possibility to model more elements, however not yet full E2E-SC system.

Flows and boundaries were considered vital to logistics planning, where the exact flow pattern of goods and materials deemed important to ensure efficient and effective operations and where the demand volatility impact could be clearly observed. Setting boundaries was perceived by one participant as an ability to get the information within the E2E-SC. It was observed that the ability to reach upstream and downstream supply chain members increased due to the existence of various systems and computer programmes providing access to more information, which was understood to widen the boundaries. Another point relative to flows and boundaries was around location of push/pull boundary in the E2E-SC, which was perceived as central aspect while setting up the E2E-SC.

It was highlighted that simulation was not an answer to a problem, but rather a way to obtain multiple scenarios, which would require further evaluation and review. Consequently, participants affirmed that objectives needed to be clearly identified upfront before commencing the E2E-SC model development process to define whether simulation was the right approach. An example was described for inventory optimisation whereby multiple scenarios could be defined considering lead time variable, which could be modelled using simulation. However, simulation was not considered the best approach for better understanding of where to position all inventory in the E2E-SC. Therefore, application of OR/MS techniques i.e. application of inventory modelling could address some of the objectives, whereas uncertain variables could be modelled using simulation.

5.4.3.2. Computational elements evaluation

This section of the thesis is dedicated to discussing the computational pillar of the conceptual framework and presents the interviews comments in Figure

5.4.3.2-1. The computational element of the E2E-SC was viewed as a most difficult to comment on due to varying level of exposure to computational techniques.

One of the participant referred to a sensitivity of the model and the quality of the data input, which seemed not always clear or simple. Particularly important appeared to be a better understanding on how E2E-SC models react to sensitive parameters. The use of a graphical model representation was perceived as supplemental to recognise which input parameters affect model sensitivity. The assumption was made that the outcome of the model run may change depending on the input parameters and their sensitivity, but to ensure rigorous approach all assumptions needed to be made. It was also noted that aggregation of the data would allow to understand similarities in processes, constraints and characteristics so as to focus on these when modelling an E2E-SC system.

Table 5.4.3.2-1 Interviewees responses on computational pillar of the conceptual framework

	Participant 1	**Participant 2**	**Participant 3**	**Participant 4**
OR/MS mathematical techniques	Methods to evaluate model sensitivity	Computational output of the model	*relevant*	Inventory management policies
Modelling Assumptions/ Approximations	Clarity in assumptions; inner mix volatility	*relevant*	Aggregation	Clear definition required to allow reuse
Input/output limitations	quality of input	*relevant*	*relevant*	Lack of data

5.4.3.3. Systemic organisational elements evaluation

The systemic organisational pillar of the conceptual framework is discussed below based on the supply chain experts' comments as captured in Table 5.4.3.3-1. Decision impact was perceived as a big shift in the company priorities. For instance, a decision not to place a new line into operations in one of the manufacturing plants that Company A owns had a direct impact on the capacity availability, inventory levels and risks associated with potentially low service level. It was acknowledged that business consciously was taking more service risks with an attempt to streamline operations and avoid capital expenditure. There was more uncertainly by definition observed in the E2E-SC, but business agreed to deal with those choices relative to E2E-SC consciously and sometimes this required to take more risk on service and sometimes more risk on cost.

Table 5.4.3.3-1 Interviewees responses on systemic organisational pillar of the conceptual framework

	Participant 1	**Participant 2**	**Participant 3**	**Participant 4**
Interactions	*relevant*	*Relevant*	*relevant*	*relevant*
Interdependencies, relationships	Relationships between stakeholders, policy influenced, lack of supporting tool to highlight benefit of E2E-SC optimisation	*Relevant*	*relevant*	Focus on key business partners
Velocity, density	May be a given variable	*Relevant*	It may be relative to speed on line or speed to market	Speed to market
Learning	Leadership guidance on when to take a risk	Software learning, artificial intelligence	A feedback mechanism Software learning opportunity	Lack of E2E-SC models and experts in the field
Evolution in time	*relevant*	*Relevant*	*relevant*	*relevant*
Decision impact, uncertainty, dynamics	cost vs service sub-optimise the one part taking more risks	*Relevant*	clarity on the assumption	*relevant*
Structural variance	*relevant*	*Relevant*	*relevant*	Can be captured in assumptions
Innovations	*relevant*	*Relevant*	*relevant*	Can be considered for scenario analysis

One of the participants implied that innovations, was an element that was missing in the framework. Depending on how strategic the innovation was and how much trust the business had in the success of such innovation, the efforts to get the product on the market would impact the E2E-SC. This was identified as one of the areas where modelling of the E2E-SC would really contribute. For instance, mapping how much safety stock was required to ensure good E2E-SC responsiveness. The business was using a mapping tool to gather parameters that could be used for modelling the E2E-SC, but there were no models available to use. Therefore, a generic guide to E2E-SC model development was found beneficial in making conscious decisions about the future E2E-SC and to support decision maker on when to take risk and when not.

A complex SC requires more conscious decisions. An example was provided of a very long E2E-SC for one of the products launched by the Company A. The product was made within a three-layered SC. Some of its sub components were produced in China, with 13 weeks lead time, before they are shipped via sea and encounter another 12 weeks transport lead time to be finally assembled at 3rd party located in Europe, so the final product can be sent to the multiple countries/ market in the EU. Such new product would be characterised by high level of uncertainty in demand. This was an example where spreadsheet modelling was used to support decision maker and various scenarios were created. However, static methods do not allow to account for E2E-SC performance ever time when subjected to the high volatility of demand and the use of a simulation techniques would be useful.

In terms of learning, the leadership guidance was found important to understand the risk, and when to take risk. Some participants referred to software learning and the impact of artificial intelligence on developing a more sophisticated self-learning E2E-SC model. An acknowledgement was made that this seemed a good approach in principle, but lack of qualified and trained experts in the modelling field seemed important for the models use, reuse and alterations.

5.4.4. General remarks on modelling

There were few remarks made by all interviewees regarding the research topic selected, aims and objectives. All participants acknowledged that modelling the E2E-SC system is challenging and this area is not fully exploited by the business. Likewise, they affirmed that businesses are continuously tackling day to day issues and challenges, hence often there is no resources and time to focus on modelling. Another important point flagged during interviews was that there is a scarce number of skilled supply chain experts in the field of modelling, hence an employee with such skills may move roles leaving business with models that cannot be used or changes as no other skilled person in this area is available.

During the evaluation of the conceptual framework, each element of the framework was discussed in the light if its applicability to modelling E2E-SC. Considering decreasing time to market and challenges associated with bringing innovation, incorporating sustainability, as well as other societal changes, the complexity confronted by both managers and researchers may increase significantly. This was noted by Interviewees number 1 and 3 as potential implications to modelling.

The number of resources available was noted as a factor affecting the detail of the model specifications, the model boundaries and techniques used. Some small models may be used to establish a feasibility of the idea, and a complex model developed in the execution stage. Moreover, a trade-off between the complexity of the E2E-SC model and the accuracy of the outcome was pointed as a concern.

5.4.5. Validation of simulation models

Validation of simulation models requires a logical evaluation of the model and sub-model steps. Often in the case of specific problem evaluation a sensitivity analysis is used; however, this was not considered in this research as the aim was to create a generic model and not to provide a solution to a problem. One approach often used to account for uncertainty of data input is to use statistical distributions, which is proposed in this research however evaluation of statistical distribution would be useful in a specific case example.

Moreover, developing complex system models can return a wide range of errors creating various debugging issues difficult to track and correct, where the challenge is not only in verifying the model, but also in validating the procedural or algorithmic representation on the modelled system (Seila et al. 2003). The approach to overcome these is to review steps undertaken to create each of the sub-models to ensure internal model and data validity. Chapter 4 clarifies the use of algorithms, simulation models/modules in developing and E2E-SC model, which as noted by Hussein and Drake (2011) adds validity and value to the research.

Chapter 4 provided a step by step guide to an E2E-SC model development in Arena software. Each step and each of Arena's sub-models were described and challenges relative to inclusion of more elements from the conceptual framework acknowledged.

5.4.6. Simulation model verification

The Arena simulation model was verified via build in software debug system, that allows for identification of errors in the run button and 'Review errors' tab. This allows for identification of errors relative to the logical structure of the model and values assigned to operands in each of Arena modules. As suggested by Robinson (2014) multiple elements of the model should be checked during model development such as flows in the model, elements of the model, logic of the model, distribution sampling used, timings in the model. Structured walkthrough the model was performed with the simulation academic professional continuously during the model development process.

5.5. Chapter summary

This chapter validated the conceptual framework and verified and validated the E2E-SC model developed using computer simulation. To ensure research reliability and validity, interviews with industry experts were conducted and the summary of findings were presented. Each of the elements of the conceptual framework was critically evaluated in the light of potential implication to the E2E-SC simulation model development to arrive to the conclusion. Suggestions for improvement were presented.

A simulation of the E2E-SC system can be a powerful alternative approach to scientific research. This approach allows to study problems or to devise new solutions or to design new E2E-SC systems, which may be difficult or impossible by using any other scientific techniques (Harrison, 1999). The E2E-SC inherit complex system attributes, spanning across structural, computational and systemic organisational elements, which are often difficult to access and model for the researchers.

Simulation methodology is an approach that can be used to support a decision maker/researcher in developing theory and/or in guiding empirical work. It can serve as a vehicle to inquire into complex E2E-SC systems and to explore their behaviour. It can examine decisions impacts, subject to various assumptions, input and output limitations and produce an array of solutions and test the validity of these solutions.

Research that uses simulation has problems and limitations. Simulation models are often developed based on assumptions and validation against real system may not be possible due to lack of such system existence. Moreover, the interpretation of modelling requirements may vary depending on the decision maker and his/her perception of the system. Therefore, to overcome this issue a good documentation of the model development process can allow for model replicability and understanding of assumptions taken.

Chapter 6

Conclusion

6.1 Introduction

This research focused on the end-to-end supply chain (E2E-SC), which can be defined as a network of business entities with different set of objectives and constraints yet working together in order to deliver goods and services to the end customer in the most efficient and effective way (Swaminathan et al. 1998). E2E-SC involves an end-to-end process that starts from product and service design, through control and planning of various activities in the chain i.e. sourcing, producing, distributing or forecasting (Swaminathan and Tayur 2003). E2E-SC is complex and difficult to manage due to its systemic attributes often spanning several supply chain networks/systems reaching from supplier suppliers to customer customer's (Lin et al. 2000), where interests of multiple firms are considered.

This research advocated for modelling the end-to-end supply chain (E2E-SC) systems using simulation given that the knowledge on properties and attributes of these complex E2E-SC structures can be gained through modelling. Albeit the efforts in developing sophisticated and powerful modelling techniques are rather immense and accredited to many, still there appears to be lacking not only models that capture E2E-SC, but also a guide or a generic framework that provides the underlying principles for modelling E2E-SC systems. Therefore, this research contributed to literature by broadening the knowledge on modelling E2E-SCs and development of a conceptual framework, which provided generic requirements for modelling complex E2E-SC systems using simulation.

The chapter efforts are dedicated to highlight the key conclusions of this research. The findings of the research are related back to the aim and objectives and research question. The theoretical contribution and the practical relevance of the thesis is summarised. Lastly, the research limitations and lines of further inquiry are presented.

6.2 Research aim, objectives

The research questions as well as the aim and objectives of this thesis were proposed in section 1.3. The research questions were constructed based on the initial review of the literature and were reflected upon throughout the research journey helping in achieving the aim of this research.

The research questions (Section 1.3) helped to define the aim and objectives for this research. As a reminder, the aim of the research project was to develop a generic end-to-end supply chain (E2E-SC) system model using simulation and to define requirements for modelling an E2E-SC system when using simulation methodology. To achieve this, the following set of objectives were proposed:

• To develop a conceptual modelling framework for an E2E-SC system that cogitates on system thinking and complexity theory.

• To develop a computerized model using simulation that provides the architecture for combining various modelling techniques.

• To evaluate the implications to modelling when different elements from the proposed conceptual framework are included in the computerised/scientific model.

• To validate conceptual research framework and computerized/scientific model with industry experts.

In fulfilling the first objective, a rigorous systematic literature review (SLR) approach was adopted, which involved the evaluation/interpretation of the existing work surrounding the end-to-end supply chains and simulation within defined research boundaries. Figure 2.4.2-1 provided an overview of the SLR process, which was profoundly discussed in the Section 2.4. The review was underpinned by the system thinking, complexity theory and simulation methodology and led to the creation of the conceptual framework, which was presented in Figure 2.6.1-1.

This research argued that systemic attributes and complexity are inherent parts of an E2E-SC. The research identified that structural elements of an E2E-SC were relative to system components, which Serdarasan (2013) considered as static complexity and were viewed holistically during classification. The system organisations and computational pillar provided a set of elements that emphasise on the complex system properties and by modelling these using simulation a further contribution to knowledge can be gained. This objective was achieved by adopting a rigorous SLR, which was then validated by industry experts.

The second objective of the research was building further on the work of the Chapter 2, with the aim to develop a computerized model using simulation that can provide the architecture for combining various modelling techniques with simulation. This was achieved by specifying the methodological approach used, which was elaborated in chapter 3. As explained in chapter 3, the research adopted the explanatory approach, whereby all elements that constitute E2E-SC system were gathered via the SLR and the consequence of modelling these were examined using simulation.

Chapter 3 also discussed the role of modelling and models and referred this back to modelling complex E2E-SC systems using simulation. By examining the research philosophy, the researcher defined methodological approach, which impacted on the way the knowledge was developed and provided clarity to the research (Näslund, 2002). Moreover, the Chapter 3 discussed the philosophical underpinnings of the research, by elaborating on how mindful inquiry was required in the research on the E2E-SC systems.

In the light of the ontology based on realism, it became evident that a development of the E2E-SC system model was impossible due to difficulty in capturing all elements proposed in the conceptual framework. Moreover, when modelling the E2E-SC system, the reality is often non-existent hence the ambition may be to support the design of a new E2E-SC. To this extend a generic guide to the E2E-SC system model development process was proposed, which was introduced in Chapter 3 and the full description of the E2E-SC model development process was provided in Chapter 4. This furthered the body of knowledge by providing a set of structural, computational and systemic organisational similarities that exist in different supply chain systems. The simulation model considered all aspects from the conceptual framework and provided an architecture for further developments, ultimately fulfilling the second objective of the research.

The objective number three investigated the extent to which different elements from the proposed conceptual framework could be included in the simulation model and how these impacted on the modelling. These can be observed in Chapter 4, where the simulation model development process details were offered. Some insightful comments were also provided by industry experts during the validation stage, which were presented in Chapter 5. An E2E-SC can be viewed as an open system, in a sense that it operates under different conditions (policies) and consists of many components (processes, products, services), which may interact in different way depending on the input/output parameters (Cilliers, 2005).

Chapter 5 was dedicated to validating conceptual research framework and computerized/scientific model with industry experts. A summary of responses provided by industry experts gathered through semi-structured interviews were presented and discussed in Chapter 5 as well.

6.3 Research contribution

The overall research contribution is summarised in Figure 6.3-1. These include theoretical and practical contributions. Through the entire research process and while developing each of the chapters, there has been an ongoing purpose of contributing to the body of knowledge and the literature. Chapters 1 and 2 highlighted that preceding to this research, there has been not much investigation carried out on studying the generic requirement for modelling the E2E-SC system.

Based on the findings from SLR, underpinned by well-established theories relative to supply chains; system thinking philosophy and imposed by factors affecting complexity in modelling SC systems, a simplified framework of relations between various elements in a generic E2E-SC system model has been drawn (Figure 2.6.1-1)

Theoretical and Practical

- develops a conceptual framework that defines generic requirements for modelling an E2E-SC system
- contributes to the literature on system thinking and complexity theory
- broadens the knowledge on modelling an E2E-SC system using simulation
- provides an architecture/guideline for modelling an E2E-SC
- develops an example of the E2E-SC model in Arena
- develops a masterdata document to support the E2E-SC modelling

Figure 6.3-1 Research contribution

The conceptual framework contributed to knowledge by providing the key elements that constitute the E2E-SC. Consideration of each of these elements during the simulation model development allowed for better understanding and appreciation of the complexity observed in E2E-SC systems structure and organisation as well as an opportunity to learn more about these systems and their systemic attributes. Therefore, in order to broaden this understanding, the research engaged into discussion on the conceptualisation and use of the E2E-SC model to represent a part of reality or in case of new design to serve as vehicles to inquiry into subjects that help in better understanding of these systems (Pidd & Carvalho, 2006).

Chapter 2 showed that various issues and practical decisions relative to E2E-SC simulation modelling were influenced by the complex computational techniques and methods that were often spanning across multiple dimensions and disciplines such as mathematics, computer engineering, software design, biology, education and many others. Conclusively, the SLR underlined the following points on modelling the E2E-SC systems using simulation:

- Provided a summary of the most frequently researched themes relative to simulation modelling of the E2E-SC system, which were SCM, Inventory management, SC dynamics, Production Planning and Inventory control and performance measures. These themes were usually subjects within multi-disciplinary and cross-sectional studies, where multiple aspects, issues and processes were considered.
- Structural, computational and systemic organizational complexity factors observed in E2E-SC system models need to be considered during the modelling process.
- An advanced and extended version of existing modelling techniques were often used to facilitate E2E-SC simulation models' development.

- Aa observed shift in simulation modelling towards combined (hybrid) models that are the amalgamation of multiple modelling techniques and research methodologies.
- Simulation model outputs are often reinforced by artificial intelligence algorithms to aid the decision maker and offer a better understanding of the system behaviour and system evolution.
- E2E-SC system models are often hierarchical, where multiple decisions are made at various levels that have ultimate impact on the entire SC system performance.

Chapter 2 contributed to knowledge and understanding of the characteristics of E2E-SC systems as well as the requirements for simulation modelling. These were reinforced by Chapters 3 and 4, which discussed the methodological approach taken, the generic E2E-SC simulation guideline and developed an E2E-SC system model using simulation to underline its applicability and practicality.

This research further contributed to the body of knowledge by developing a generic model of an E2E-SC system in Arena simulation software, where the scientific representation of a system was used to gain knowledge and information about targeted system behaviour and changes resulting from interactions between elements within the framework. The challenge came from defining and understanding what should be regarded as a generic model needing clarity in assumptions and context of the subject of inquiry.

To support this challenge, a combined modelling approach was proposed linking simulation to master data document and OR/MS techniques. This was discussed in Section 4.5.1. The research emphasised on the benefits of using OR/MS techniques to define simulation model input parameters based on defined policy. A master data document was developed, that captured the key aspects of the conceptual framework and was used to support modelling the E2E-SC in

Arena. The MS Excel Master Data file captured such information as product specification and architecture, supply and market related information such, capacity utilisation information to ensure that key information and details were apprehended to support the E2E-SC model development process.

6.4 Practical relevance and impact of the research

Companies continuously search for ways to evaluate, control or improve their E2E-SC and seek to leverage modelling techniques such as simulation to support decision makers. Therefore, modelling is an important technique that can support businesses hence potential for high applicability of this research to industry.

Most of the simulation methods exist in isolation and appear to have focused on the particulars of the system to be modelled and/or a specific SC research agenda. The E2E-SC simulation model that combines simulation with knowledge on extended supply chain systems and computational complexity relative to modelling these E2E-SC system structures can benefit businesses in multiple ways. Firstly, it provides a guide on how to develop the E2E-SC system model, which can be used by the decision maker to evaluate multiple scenarios and provide a decision support tool.

Through the interviews with industry experts, it became evident that businesses lack expertise in modelling, and simulation is still not fully embedded into day to day operations. Having a defined E2E-SC system requirement and generic model would allow for future collaboration between businesses and academia in the common goal to contribute to the body of knowledge.

6.5 Research limitations

Throughout the research a rigorous approach was maintained, nevertheless, there are some limitations to this study that the reader needs to be aware of. One of the limitations is derived from the lack of a defined methodology for validation of generic simulation models. There are some recommendations provided by Robinson (2014), Sargent (2013), Kelton et al. (2010) or Pidd (2004), which refer to validation of a scientific simulation model against a real system. However, this may prove difficult if the research aims to design a new system using simulation, where no real system is in existence to allow for such comparison. The generic model presented in this research was a representation of an exemplary system, and therefore the tactic taken was to maintain a rigorous methodological approach supported by a good data documentation to overcome this limitation. There was no real system in place to compare to, however on the other hand the aim of the research was to develop a generic approach to model an E2E-SC system thus it deemed less of an important matter for this research to compare the developed simulation model against the real system, but to validate the generic conceptual framework against a real E2E-SC.

Likewise, modellers often would choose a familiar software to develop a simulation model, which may have some limitations in the way it was designed, thus constraining the method of representation and leading to revision to the conceptual model (Robinson, 2008). In this research Arena simulation software was used, which was chosen due to its applicability to model complex supply chain systems, as was discussed in Section 4.3.1. During simulation model development process, a continued learning took place and some adjustments were to ensure that model can capture all of the elements from the conceptual framework. It became apparent that the software has some limitations, for instance inventory review policies were maintained at materials and product level and in different nodes in the designed system, but there was no option to incorporate learning and model self-alteration to ensure that the optimal policy was in place for a given demand levels.

6.6 Lines of further inquiry

Apart from some limitations presented in Section 6.5, this research exhibited constraining factors relative to the research scope, time, finance or access to data (Potter, 2005). A further work in this area could be directed to address the limitations of this research, but there are also other options to contribute to the body of knowledge and literature in this area. Some points that could take this research further are summarised below:

- The E2E-SC simulation model can be used to study sensitivity of system control techniques when applied to an E2E-SC. This could involve evaluating to what extend the E2E-SC system can be controlled and how changing the remits of control given to a focal company or key participating organisations could impact on the E2E-SC system performance.
- The use of combined/hybrid approach whereby an artificial intelligence can be used to facilitate model learning and self-alterations of policies, processes and E2E-SC design. Some element of software learning principles could be included in the E2E-SC system models in support of development of intelligent and sophisticated model to evaluate to what extend a communication between computer programme and decision maker should exist within a given margin of errors.
- The use of simulation to support delivery of the E2E-SC innovations. This element can be further investigated in multiple ways, whereby innovative technologies, products, policies and other aspects could be incorporated into the E2E-SC system model to see their impact of the entire system performance. This would contribute

to the body of knowledge by examining the relation between system elements when subjected to innovative change and their impact on the network of key participating businesses. It would also provide further insights into challenges and implications to modelling when a significant change to a model structure is required.

- The E2E-SC simulation model used as a coaching tool to support decision maker in understanding the impact of various risks on the E2E-SC system performance.
- A further work could be directed to develop theoretical approaches that would allow for quick extraction of big data collected by businesses into an E2E-SC simulation model to run multiple scenarios and provide recommendations on constraints in the system.
- To incorporate elements of cognitive thinking of multiple decision makers in the E2E-SC model to understand the many ways that networks build by critical players affect the properties of the E2E-SC system.

While addressing model limitations and considerations brought in different stages of this research, there are several other options which would use this thesis as a starting point but add further to the body of literature. Hybrid modelling for supply chain. Applicability of hybrid modelling and discussion on challenges and issues with modelling an end-to-end supply chain.

6.7 Final remarks

This chapter has drawn a set of conclusive remarks to this thesis. The chapter discussed the research contribution to the body of knowledge by reflecting upon the initially set aim and objectives. It further highlighted the research contributions to the literature in the field of supply chain and simulation by emphasising on the importance of modelling an E2E-SC system using simulation. The study contributed to theory by developing a generic framework for modelling E2E-SC, which also showed to have a huge practical relevance.

Subsequently, the chapter presented research limitations and provided lines of further inquiry. Overall, the thesis has presented the conceptual framework highlighting key requirements of the E2E-SC system that were incorporated into a generic guide to the E2E-SC system model development process. The Arena simulation model was developed based on the guideline provided and validated with industry experts, highlighting huge practical relevance. The research opens door for a future work in this area and more contributions to theory and practise.

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Appendices

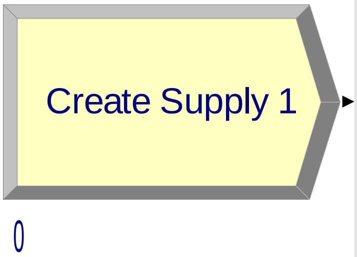
Appendix 1 Literature selection details- scoping study

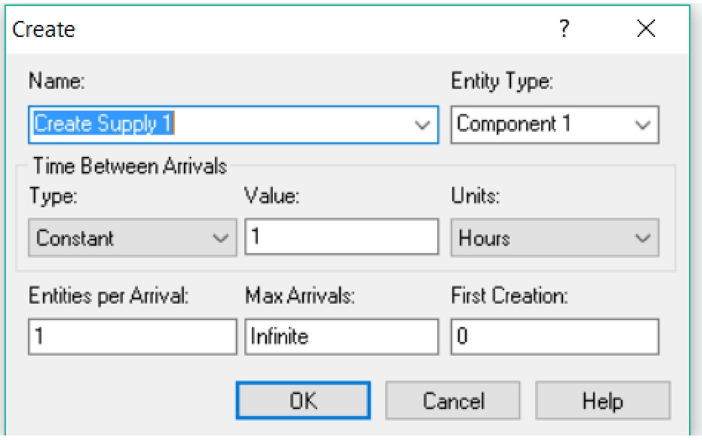
Journal Title	Abbr.	Research Domain	30.8.17 Scopus	30.8.17 Science Direct	30.8.17 EBSCO	Scoping study total
Computers and Industrial Engineering	CIE	IE/ENG	61	58		61
Computers and Operations Research	COR	OR/MS	20	18		20
Decision Sciences	DS	OR/MS	12	NA	9	12
European Journal of Operational Research	EJOR	OR/MS	77	76		77
Harvard Business review	HBR	GM	NA	NA	0	0
IEEE Transactions on Engineering Management	IEEE-TEM	IE/ENG	7			7
IIE Transactions	IIE	IE/ENG	12			12
Interfaces	INFCS	OR/MS	12			12
International Journal of Operations and Productions Management	IJOPM	OM	8			8
International Journal of Production Economics	IJPE	OM	148	144		148
International Journal of Production Research	IJPR	OM	170			170
Journal of Operations Management	JOM	OM	10			10
Journal of Operational Research Society	JORS	OR/MS	22			22
Management Science	MS	OR/MS	NA	NA	3	3
Naval Research Logistics	NRL	OR/MS	3	NA	0	3
Omega	OME	OR/MS	8	15		15
Operations Research	OR	OR/MS	8			8
Productions and Operations Management	POM	OM	16			16
Journal of Supply Chain Management	JSCM		1	NA	NA	1
Production and Inventory Management Journal	PIM		0	0	0	0
Supply Chain Management: An International	SCM:IJ	OR/MS	15			15
International Journal of Physical Distribution and Logistics Management	IJPDLM		23			23
Annals of Operations Research	AOR	OR	11			11
International Journal of Simulation and Process Modelling	IJSPM	SPM	44	NA	NA	44
Simulation Modelling Practice and Theory	SMPT	SSM	20	20		20
International Journal of Modelling and Simulation	IJMS	CS/ENG/M	6	NA	NA	6
International Journal of Simulation Modelling	IJSIMM	CS	22			22
		Total				746

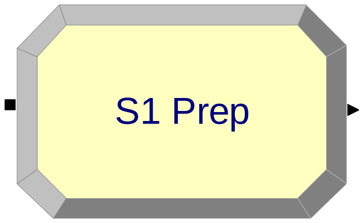
Appendix 2 Details of selected journals

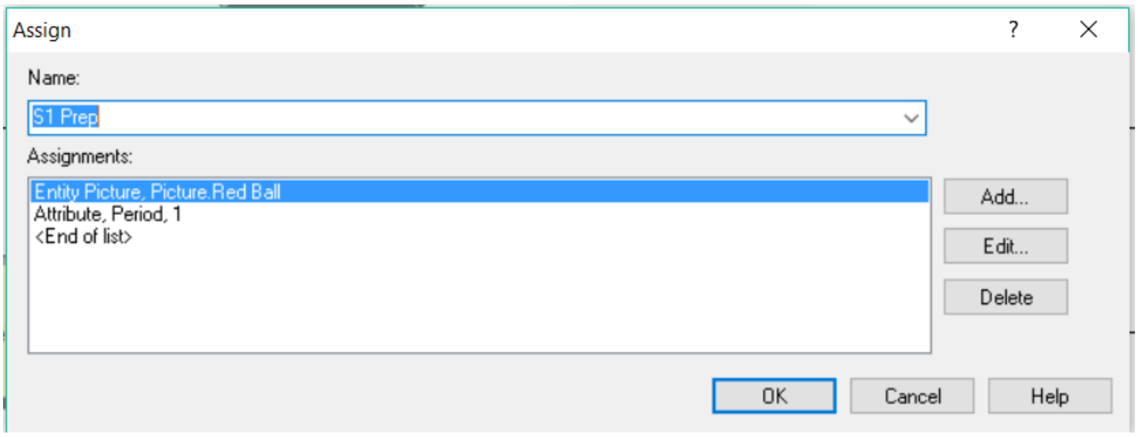
No.	Journal	ISSN	Publisher	coverage in Scopus
1	*Computers and Industrial Engineering*	0360-8352	Elsevier	from 1976
2	*Computers and Operations Research*	0305-0548	Elsevier	from 1974
3	*Decision Sciences*	1540-5915	John Wiley & Sons	from 1996
4	*European Journal of Operational Research*	0377-2217	Elsevier	from 1977
5	*Harvard Business review*	0017-8012	Harvard Business Publishing	1974, from 1978 to 1987, from 1989 to Present
6	*IEEE Transactions on Engineering Management*	0018-9391	Institute of Electrical and Electronics Engineers (IEEE)	from 1969
7	*IIE Transactions*	0740-817X	Taylor & Francis	from 1982 to 1991, from 1993 to Present
8	*Interfaces*	0092-**2102**	INFORMS	from 1983 to 1988, from 1996 to Present
9	*International Journal of Operations and Productions Management*	0144-3577	Emerald	1985, from 1995 to Present
10	*International Journal of Production Economics*	0925-5273	Elsevier	from 1991
11	*International Journal of Production Research*	0020-7543	Taylor & Francis	from 1970
12	*Journal of Operations Management*	0272-6963	Elsevier	from 1981 to 1991, from 1993 to Present
13	*Journal of Operational Research Society*	0160-5682	Palgrave Macmillian	from 1978
14	*Management Science*	1526-5501	INFORMS	
15	*Naval Research Logistics**	0894-069X	Wiley Online Library	from 1973 to 1978, from 1987 to Present
16	*Omega*	0305-0483	Elsevier	from 1973 to 2016
17	*Operations Research*	0011-7315	INFORMS	from 1996
18	*Productions and Operations Management*	1937-5956	Wiley Online Library	
19	*International Journal of Physical Distribution and Logistics Management*	0960-0035	Emerald	from 2000
20	*Annals of Operations Research*	0254-5330	Springer	from 1984
21	*International Journal of Simulation and Process Modelling*	1740-2131	INDERSCIENCE Publishers	from 2007
22	*Simulation Modelling Practice and Theory*	1569-190X	Elsevier	from 2002
23	*Simulation*	1741-3133	Sage Publications	from 1963
24	*Journal of Simulation*	1747-7778	Palgrave Macmillian	from 2006
25	*International Journal of Modelling and Simulation*	0228-6203	ACTA Publishing	from 1996 to 2014
26	*International Journal of Simulation Modelling*	1726-4529	DAAAM International	from 2005 to 2014
	Management Science	1526-5501	INFORMS	from 1969 to Present
27	Supply Chain Management	1359-8546	Emerald	from 1996 to Present

Appendix 3 Supply 1 sub-model details







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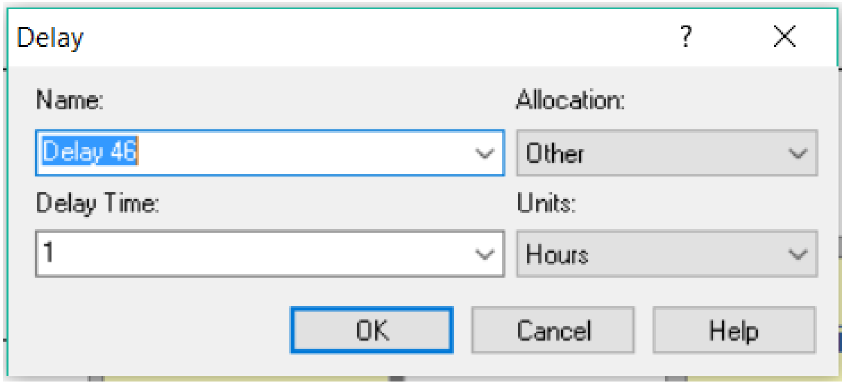
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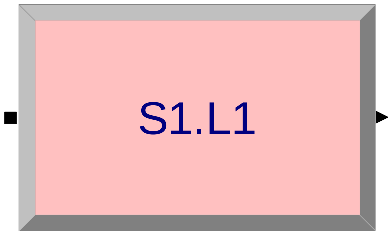
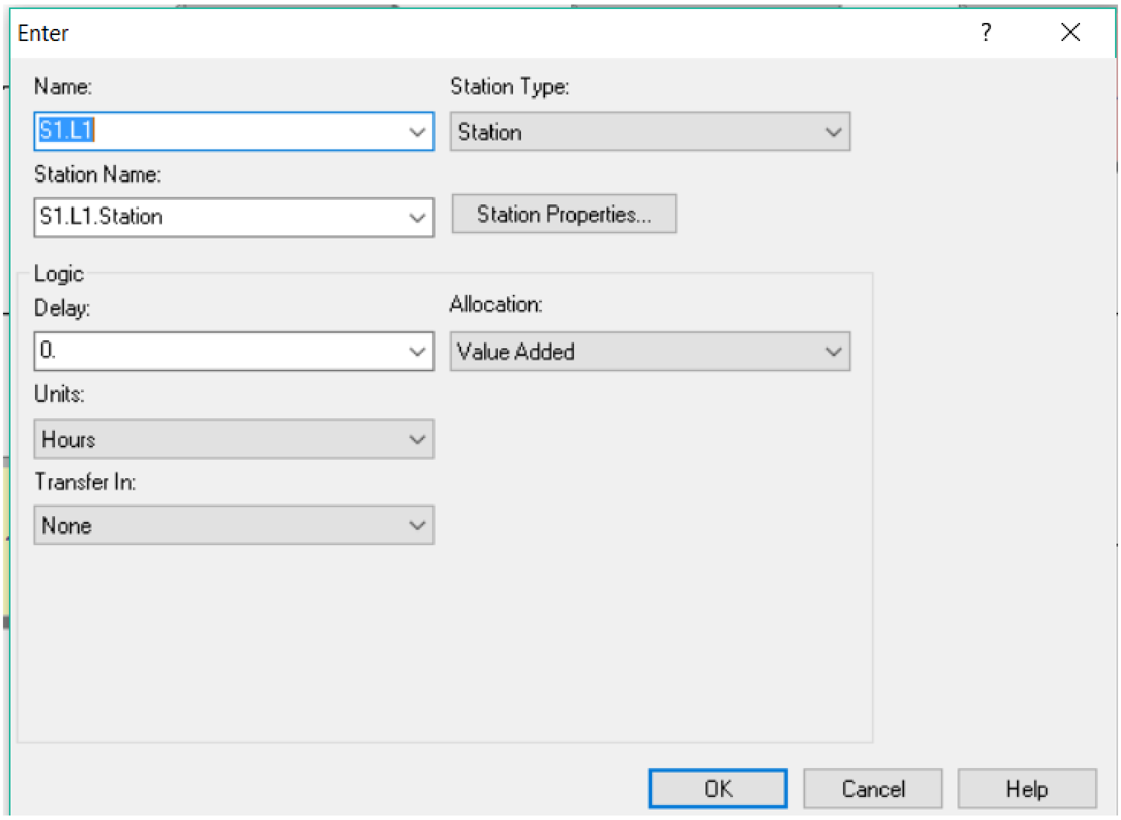
Name:
Delay 46
Allocation:
Other
Delay Time:
1
Units:
Hours
OK
Cancel
Help


S1.L1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S1.L1
Station Type:
Station
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S1.L1.Station
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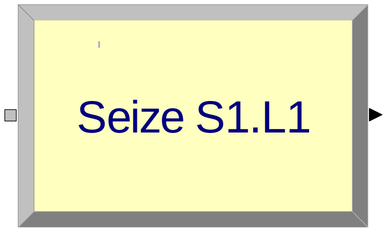
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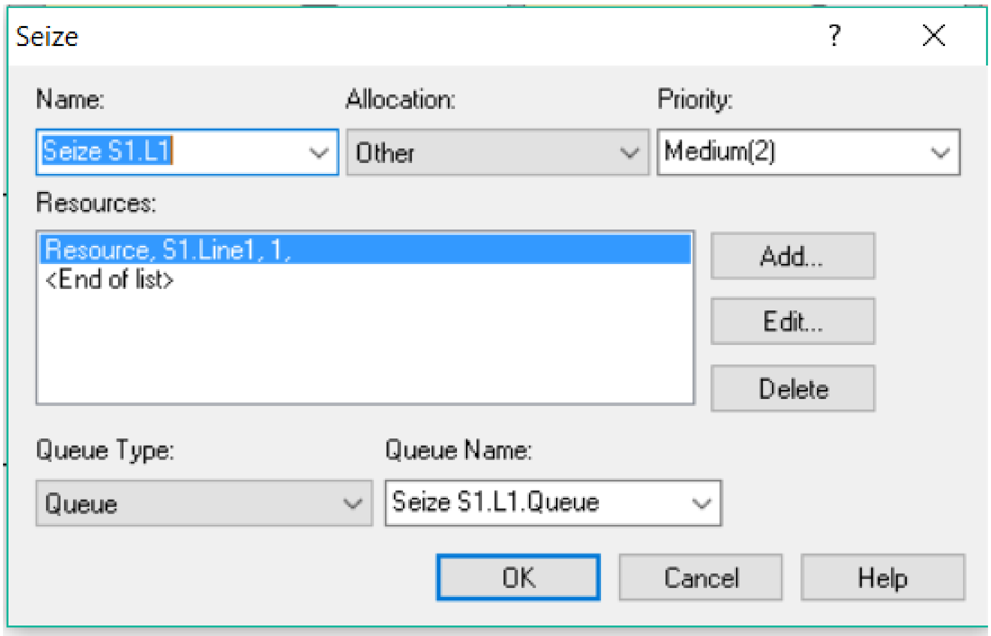
Seize
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Name:
Allocation:
Priority:
Seize S1.L1
Other
Medium(2)
Resources:
Resource, S1.Line1, 1,
<End of list>
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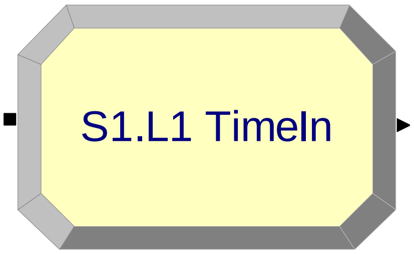
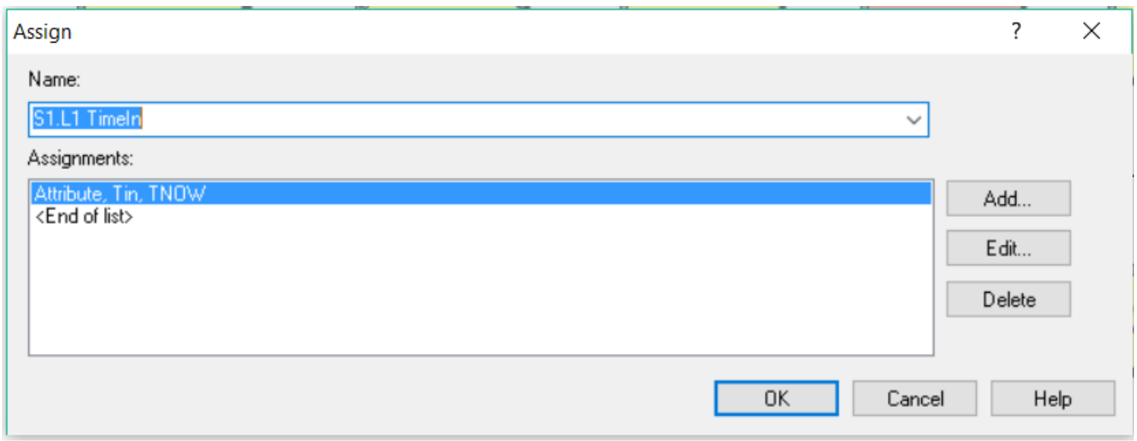
Edit...
Delete
Queue Type:
Queue Name:
Queue
Seize S1.L1.Queue
OK
Cancel
Help


S1.L1 TimeIn


Assign
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Name:
S1.L1 TimeIn
Assignments:
Attribute, Tin, TNOW
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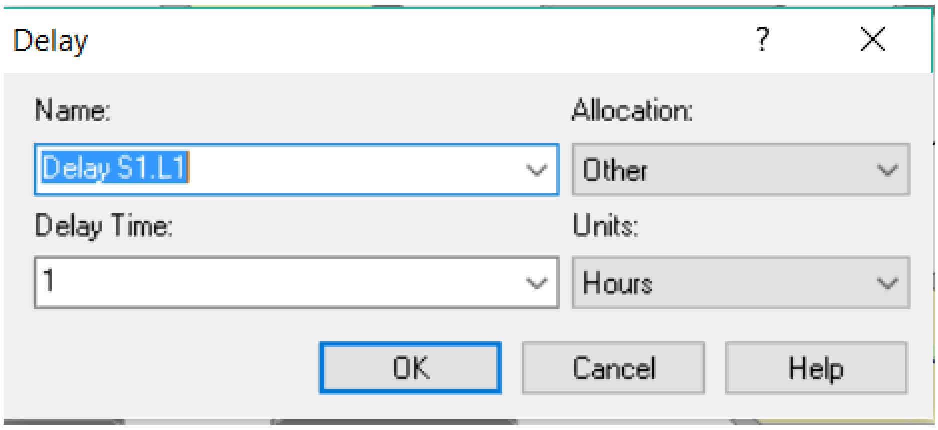
Add...
Edit...
Delete
OK
Cancel
Help


Delay S1.L1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Delay Time:
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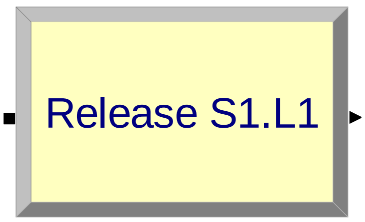
Hours
OK
Cancel
Help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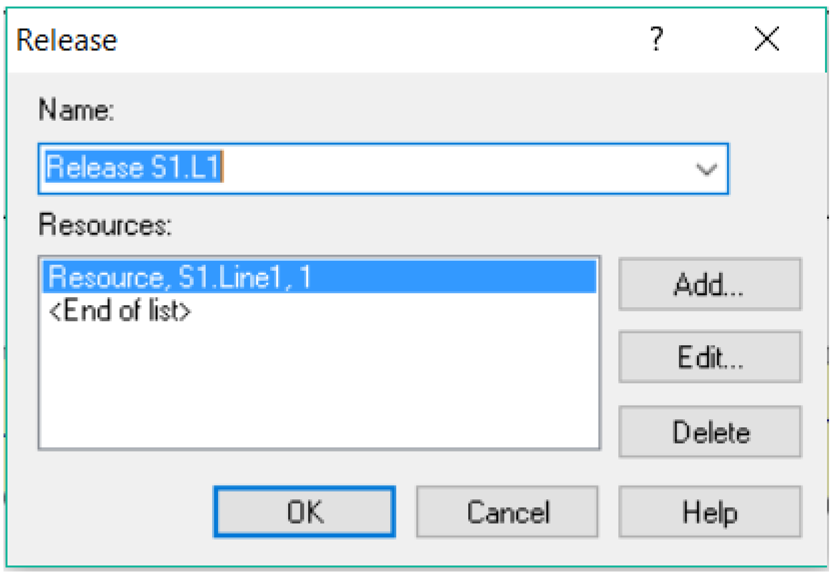
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Edit...
Delete
OK
Cancel
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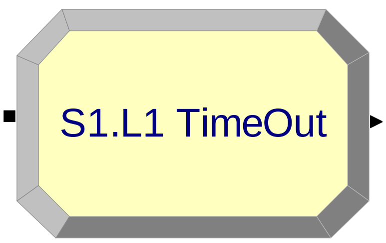
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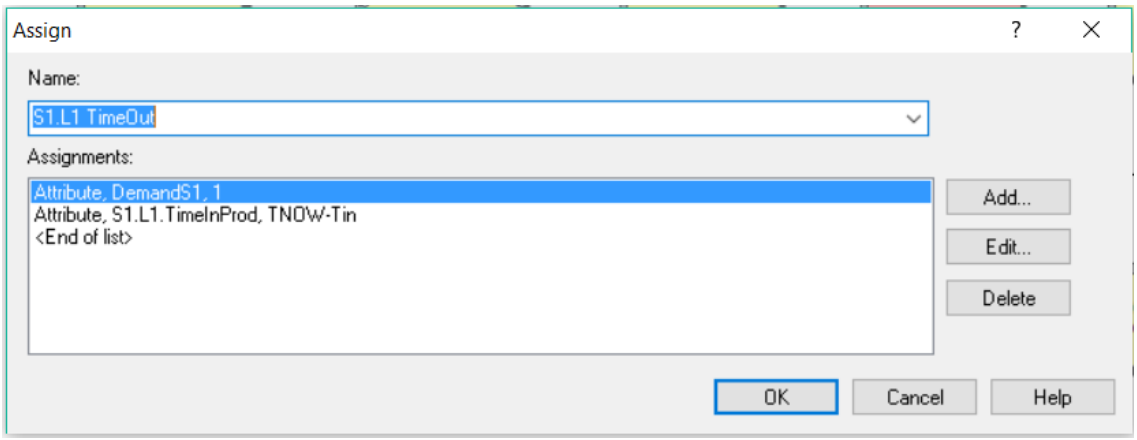
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S1.L1 TimeOut
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Attribute, S1.L1.TimeInProd, TNOW-Tin
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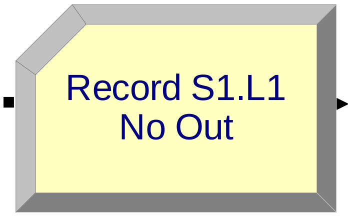
Edit...
Delete
OK
Cancel
Help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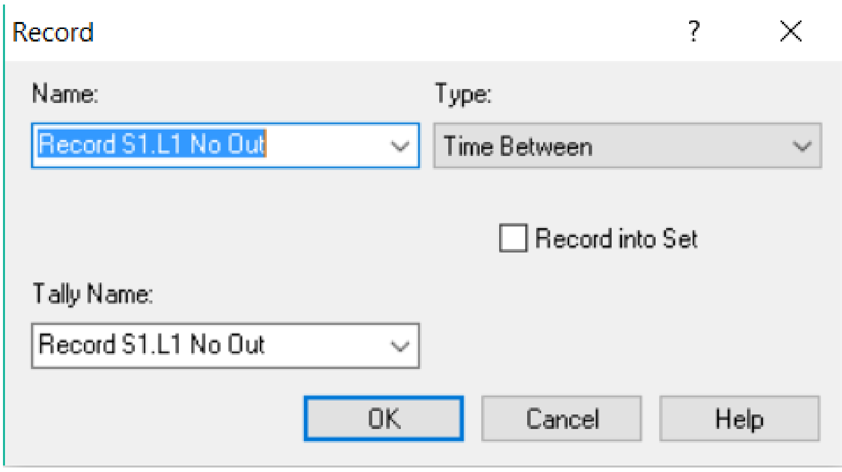
No Out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Name:
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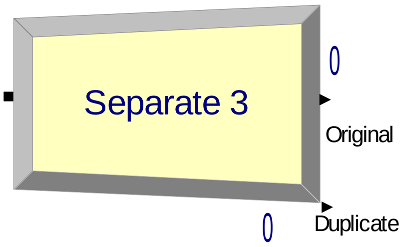
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Original
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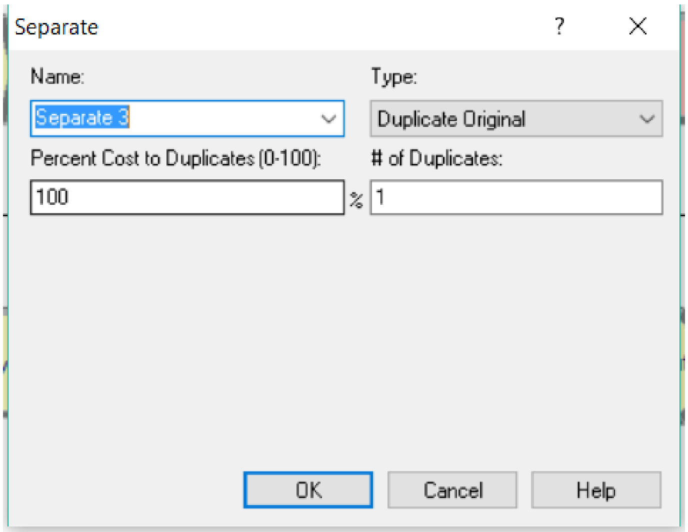
Duplicate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Name:
Separate 3
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Percent Cost to Duplicates (0-100):
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# of Duplicates:
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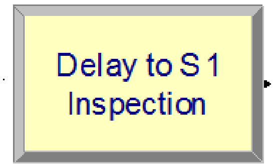
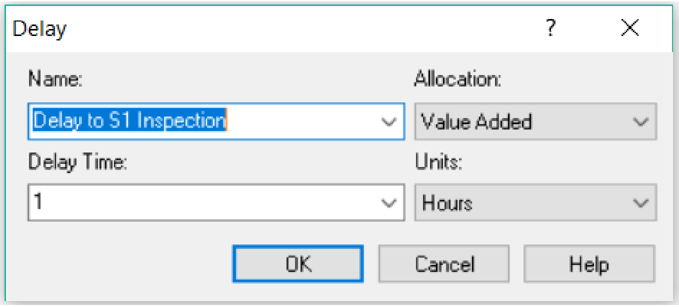
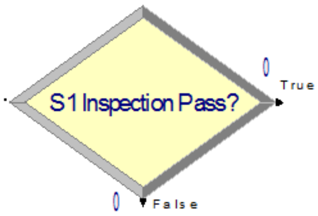
Cancel
Help

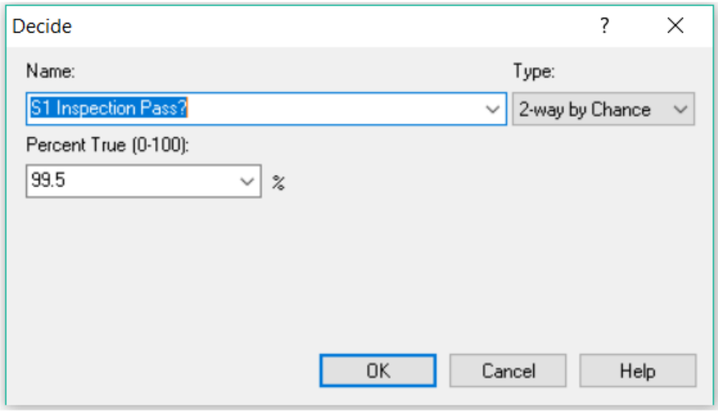
Appendix 4 Make sub-model details

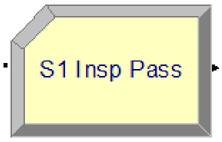
"Supply 1 Quality Check" Sub-model

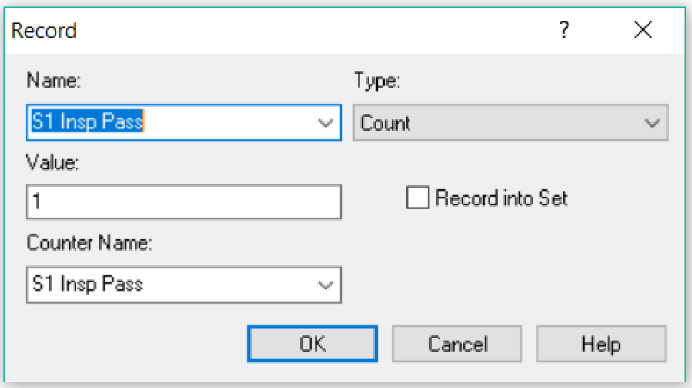









S1 Insp Pass


Record
Name:
S1 Insp Pass
Type:
Count
Value:
1
Record into Set
Counter Name:
S1 Insp Pass
OK
Cancel
Help

Appendix 5 Template Development in Arena

As mentioned above, Arena simulation software provides an architecture for template developments, where the modeller can develop a range of dedicated template panels like ‘Packaging’ or ‘Flow Process’. Each panel consists of set of constructs such as ‘Palletizer’ or ‘Storage’ found in ‘Packaging’ panel, which are also referred to as templates. In templates, all information relative to constructs are documented and defined using two SIMAN panels: Blocks and Elements. The template developers usually attach supportive template panels to Project Bar; alike modellers, who build Arena models using existing template panels such as Basic Process.

A new template panel can be developed in advanced version of the software, where modellers create a new ‘Template Window’, similar in layout to ‘Model Window’, with the difference observed in functionality of ‘Template Development Toolbar’ and the relative module definition windows. Simulation models are built in Arena by placing the existing generic or newly designed dedicated modules into the model window, as well as by providing relevant data for these modules, which should ultimately reproduce the flow of entities through these modules. The sequence of modules in the Arena’s model window reflects the real or hypothetical system design. The module itself provides user view and graphical representation (animation) of the underlying logic that entity follows while in the module. From the template developers’ perspective, such modules are products of computer programming efforts and are composed of SIMAN simulation language components (Kelton et al., 2010).

A new template development commences by defining a set of module definitions. This can be performed in the Template Window by adding new module definitions and specifying a new name for a module. Another option is to mark the module as a data module, which would allow to create a spreadsheet view like ‘Resource’ in ‘Basic

Process' template panel. Furthermore, the 'Name Operand' function can be populated, which is particularly useful for data module as it adds a restriction for unique value of the operand, hence in multiple module uses returning an error if same operand value are provided.

To develop a module definition, the following operations need to be performed:

- a dialog box needs to be designed,
- module instances need to be placed in the model window to define module logic that will form a template panel,
- defining switches to control turning on and off module options,
- adding the user view, and panel icon for graphical representation.

Simulation models are created by placing module instanced in the model window and modules are created by placing module instances in the module logic in the template window. To create a new template, panel a modeller is required to define a new template name and design/develop modules, which would ultimately be added to the 'Project Bar' under the newly developed name. The five described module elements can be defined in any order as often changes occur throughout the module development process.