DOCTOR OF BUSINESS ADMINISTRATION

Selection of simulation tools for improving supply chain performance

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Aston University

SELECTION OF SIMULATION TOOLS FOR IMPROVING SUPPLY CHAIN PERFORMANCE

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Thesis Summary

Simulation is an effective method for improving supply chain performance. However, there is limited advice available to assist practitioners in selecting the most appropriate method for a given problem. Much of the advice that does exist relies on custom and practice rather than a rigorous conceptual or empirical analysis.

An analysis of the different modelling techniques applied in the supply chain domain was conducted, and the three main approaches to simulation used were identified; these are System Dynamics (SD), Discrete Event Simulation (DES) and Agent Based Modelling (ABM). This research has examined these approaches in two stages. Firstly, a first principles analysis was carried out in order to challenge the received wisdom about their strengths and weaknesses and a series of propositions were developed from this initial analysis. The second stage was to use the case study approach to test these propositions and to provide further empirical evidence to support their comparison.

The contributions of this research are both in terms of knowledge and practice. In terms of knowledge, this research is the first holistic cross paradigm comparison of the three main approaches in the supply chain domain. Case studies have involved building 'back to back' models of the same supply chain problem using SD and a discrete approach (either DES or ABM). This has led to contributions concerning the limitations of applying SD to operational problem types. SD has also been found to have risks when applied to strategic and policy problems. Discrete methods have been found to have potential for exploring strategic problem types. It has been found that discrete simulation methods can model material and information feedback successfully.

Further insights have been gained into the relationship between modelling purpose and modelling approach.

In terms of practice, the findings have been summarised in the form of a framework linking modelling purpose, problem characteristics and simulation approach.

Key words : Supply Chain, Simulation, Modelling, System Dynamics, Agent Based Modelling, Discrete Event Simulation

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Contents

List of Figures

List of Tables

Chapter 1 Introduction

1.1 Intrinsic motivation

In a career of over twenty years, this researcher has observed decisions being taken in supply chains in a variety of industry sectors and geographies. This was initially as a practitioner within industry and more recently, as a consultant advising clients. Sometimes these decisions were of an operational, tactical nature, at other times strategic and global. In some cases decisions were made after rigorous analysis and sometimes, seemingly with very little consideration of the important factors that should be taken into account. Being aware of the potential for analysis to support the decision making process, this researcher became intrigued as to which decision support tools existed to support the supply chain practitioner, and when they should be used. This was the initial motivation to embark on the research process. Having enrolled on the DBA at Aston Business School, in discussion with supervisors Dr. Doug Love and Dr. Pavel Albores in the Operations and Information Management Group (OIM), the idea of doing research into the use of simulation in the supply chain context was conceived.

1.2 The need for this research

Globalisation means that products and services may be created and sold anywhere in the world (Kanter, 1997). In order to compete in the modern, globalised context, firms have had to develop international manufacturing networks (Shi and Gregory, 1998). Supply chains are the means through which firms deliver their products and services from end to end, from raw materials to consumer and their effective management can provide businesses with enduring competitive advantage (Christopher, 2005). There are several examples of firms who have done this, for example Wall-Mart, Dell Computer and Seven-Eleven Japan (Chopra and Meindl, 2007). The increased complexity of supply chains is coupled with an increase in dynamics due to shorter product life cycles and consumer switching, in certain industries, due to increased competition (Meixell and Gargeya, 2005).

Simulation has been shown to be very effective at modelling the supply chain with its dynamic nature, complexity and variability (Biswas and Narahari, 2004). There are a number of reviews which have investigated the various ways simulation has been used in the supply chain including Akkermans and Dallaert (2005), Angerhofer and Angelides (2000), Terzi and Cavalieri (2004) and Min and Zhou (2002). Given that simulation is an effective approach for tackling supply chain problems, how does the practitioner, faced with a challenge decide which simulation approach to use? It appears that the choice of which simulation approach to use in a given situation owes much to the background of the modeller and the techniques they are more familiar with

(Morecroft and Robinson, 2005 ; Lane, 2000). In addition, custom and practice has led to the application of particular simulation approaches in certain situations. Supply chain practitioners are busy people, they need to know which of these modelling and simulation tools can be of use to them and when and how to apply them. Following a detailed review of practice and literature it became clear that unfortunately, there is little advice available to practitioners concerning the choice of modelling technique to use. Many modellers belong to a community of interest. There is little communication between these communities, so an independent comparison of methods is still lacking. Some work has been done to compare the different modelling approaches, but often the comparisons lack conceptual rigour and rely largely on custom and practice. Some reviews with a more practical bias include; a comparison of SD and DES (Sweetser, 1999) and a comparison of all three approaches (Borshchev and Fillipov, 2004 ; Lorenz, 2006). Several authors call for more research in this area. For example, at the 2010 OR Society Simulation Workshop (Siebers et al., 2010), there was agreement that more research needed to be done in developing a framework to assist practitioners in the selection of the appropriate simulation approach. Other authors have called for more 'back-to-back' modelling of problems using two different simulation methods to provide more insights (Van Der Zee and Van Der Vorst, 2005 ; Parunak, 1998 ; Ozgun and Barlas, 2009). There is, then, a need for research which reviews what simulation methods exist to model the supply chain, what are the relative strengths and weaknesses of these approaches and when and where they should be applied. This research needs to go beyond the accepted wisdom and examine these approaches critically in order to give more useful guidance to the practitioner community.

1.3 Aims and objectives

The overall aim of this work is to compare the strengths and weaknesses of different approaches to simulating the supply chain. The general objectives linked to this overall aim are:

1. Identify the main methods of simulation used in the supply chain domain.
2. Compare the strengths and weaknesses of the different approaches.
3. Make recommendations for supply chain professionals to select the approach best suited to their problem.

1.4 Thesis structure

The purpose of this section is to describe the overall structure of the thesis, explain the purpose of each chapter and how together the chapters contribute to the overall thesis. In addition, three conference outputs have been created as part of the research process, and these are also listed. The structure of the thesis is outlined in Figure 1.

Chapter 1 describes the intrinsic motivation behind this research, the need for this research, the overall aims and objectives and the structure of the thesis. The aim of this chapter is to explain why this topic was chosen for personal reasons and why it is an important area to research.

Chapter 2 presents a critical review of the literature in four main areas: supply chain challenges, modelling and simulation, literature comparing approaches and finally, hybrid modelling literature. The three main methods of simulation used in the supply chain domain are identified. The purpose of this chapter is point out the limitations of the current work done in this area which leads to the identification of the gap in the literature.

Chapter 3 provides a review of the research philosophy and a justification for the selection of the research methodology chosen. This chapter also provides a review of the research tools used as part of the methodology. Alternative research methodologies are considered and an explanation given as to why these alternatives were not chosen. The research questions are outlined, as well as a set of more refined propositions to be tested through case study analysis. A description of the case study protocol is given, together with methods that were used to ensure rigour and validity, due to the concerns sometimes expressed about case study research. The purpose of this chapter is to give confidence that the appropriate research methodology has been chosen.

Chapter 4 provides a theoretical analysis of the fundamental principles underpinning the three main simulation techniques by means of examining the historical foundations of the approaches and their origins. The purpose of this chapter is to provide a sound theoretical basis upon which to challenge the received wisdom identified in the literature review. This theoretical review also provides a sound foundation of theory with which to commence the case study review.

Chapter 5 provides a detailed report on each of the case studies. The report includes a comparison of the approaches used and an analysis of the findings of each case in relation to the propositions developed in Chapter 4. Each case description contains details of the simulation approach taken together with a review of the modelling process itself and the results obtained. The purpose of this chapter is to provide the detailed empirical evidence to support the findings and discussions in later chapters.

Chapter 6 provides a review of the findings of the cases. The chapter begins with cross case analysis of the propositions and then moves on to a review of these findings in relation to the enfolding literature. The chapter the considers the limitations of the research and the extent to which the findings can be generalised. The purpose of this chapter is to analyse the findings from the case studies and to move towards findings and conclusions.

Chapter 7 presents the key contributions of the research in relation to both practice and theory. Recommendations are then made for further research. The chapter concludes with a reflection on the overall research process, and lessons learned.

This chapter has set out the overall need for this research and the scope and structure of the thesis itself. In Chapter 2, a critical review of the relevant literature will be conducted.

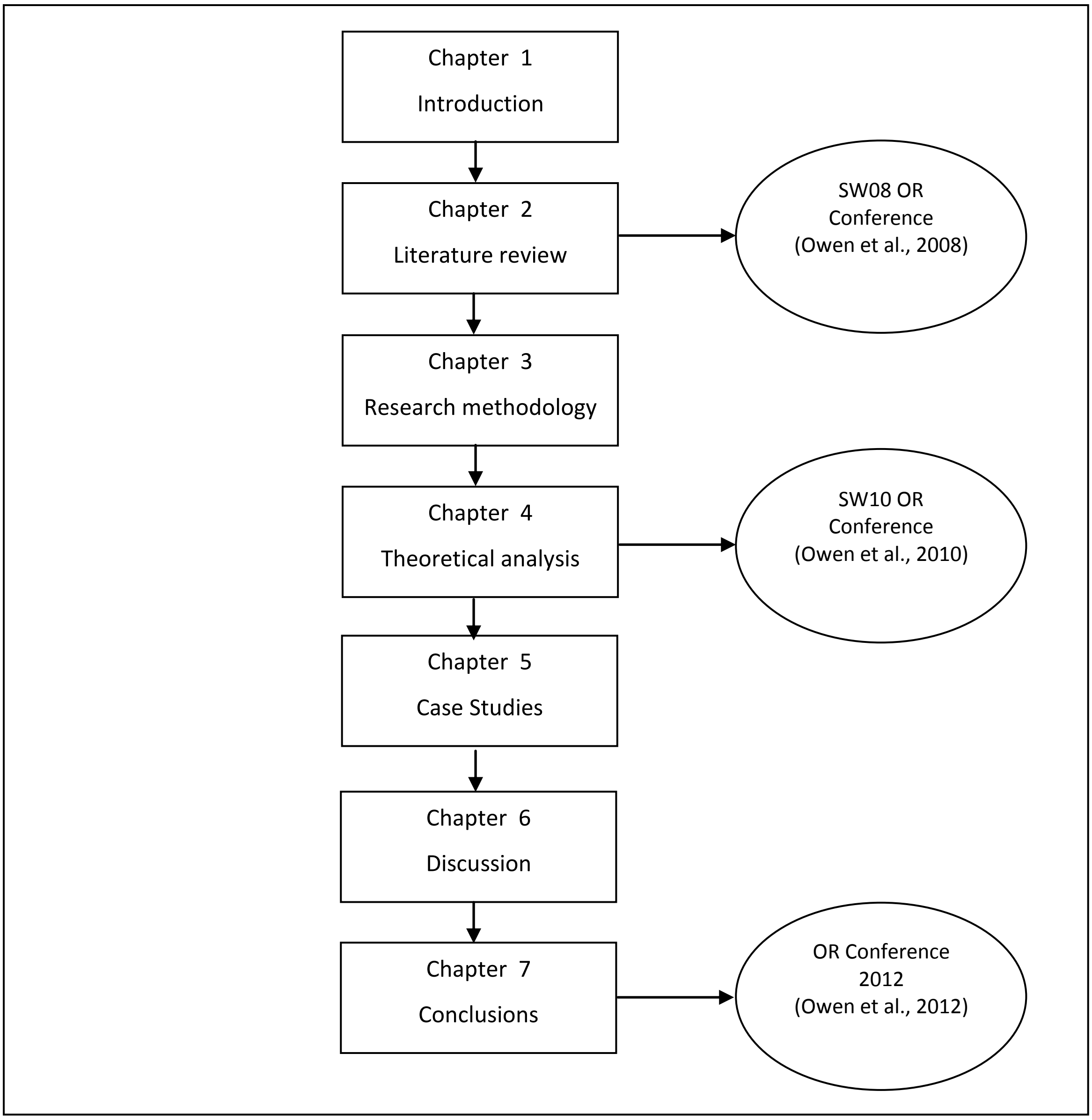


Figure 1 Thesis structure

Chapter 2 Literature review

In this chapter, a critical review of the relevant literature will be presented. This will lead up to the definition of the gap that exists in the current research and how this work will make a contribution.

2.1 Introduction

A literature review provides the foundation for the work that is to be undertaken. According to Lee and Lings (2008), "*The literature review is where you demonstrate that you understand that which has been done before, and can point to where the existing research is deficient in some way*." Thus as well as identifying and reviewing the literature, it is important to critique what is read, weighing up the strengths and weaknesses of the author's claims. Wallace and Wray (2006) describe what they call the Critical Literature Review as:

"*A reviewer's constructively critical account, developing an argument designed to convince a particular audience about what the published – and possibly also unpublished – literature (theory, research, practice or policy) indicates is and is not known about one or more questions that the reviewer has framed*."

This review will follow this approach, evaluating the literature in key areas, focused on addressing certain review questions related to the overarching research objective. The review of the literature has in fact taken place over a period of seven years. Initial areas of interest were investigated but over the period of the study, additional areas have come into view, found to be highly relevant and thus investigated. Thus the actual process of review has been both iterative and organic.

2.1.1 The scope of the review

The focal area, shown on Figure 2, concerns the application of simulation to supply chain management. As simulation sits within the wider modelling area, this was also in scope for the initial review. As will be shown in this review, the three main techniques of supply chain simulation are System Dynamics (SD), Discrete Event Simulation (DES) and Agent Based Modelling (ABM). The work concerns comparing the relative strengths and weaknesses of these three approaches, and thus there were two other areas of literature that were of interest, namely the comparison literature for these three techniques and also the literature concerning the combined application of these techniques to addressing supply chain problems i.e. the hybrid approach. These areas of focus are illustrated in Figure 3. The review then initially investigates how simulation is used to improve the performance of supply chains. In order to do this, a broader review of supply chain modelling is required to place simulation in context. The three main methods of supply chain simulation are then identified and reviewed, both in their individual capacities and in comparison with each other.

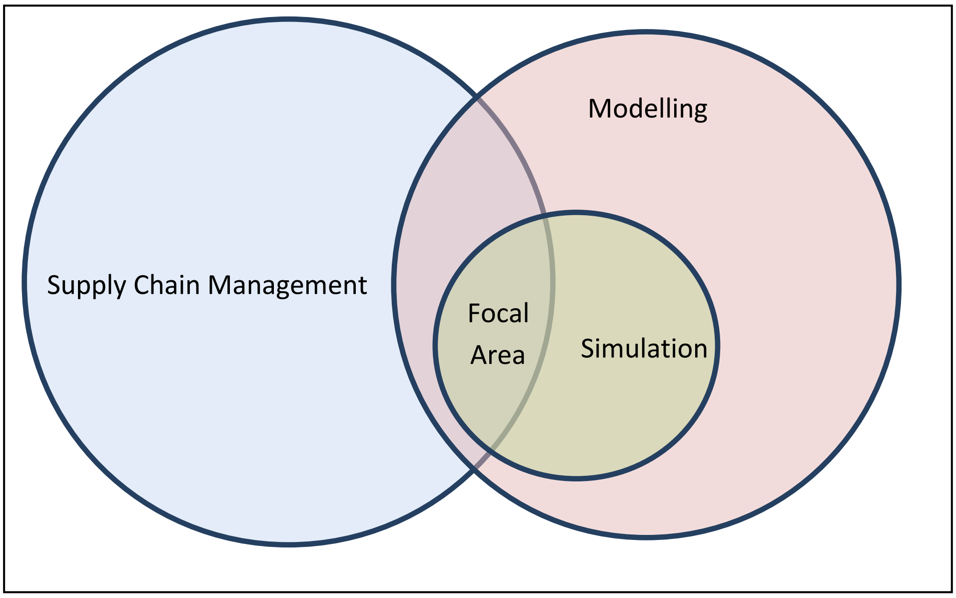


Figure 2 Scope of literature review

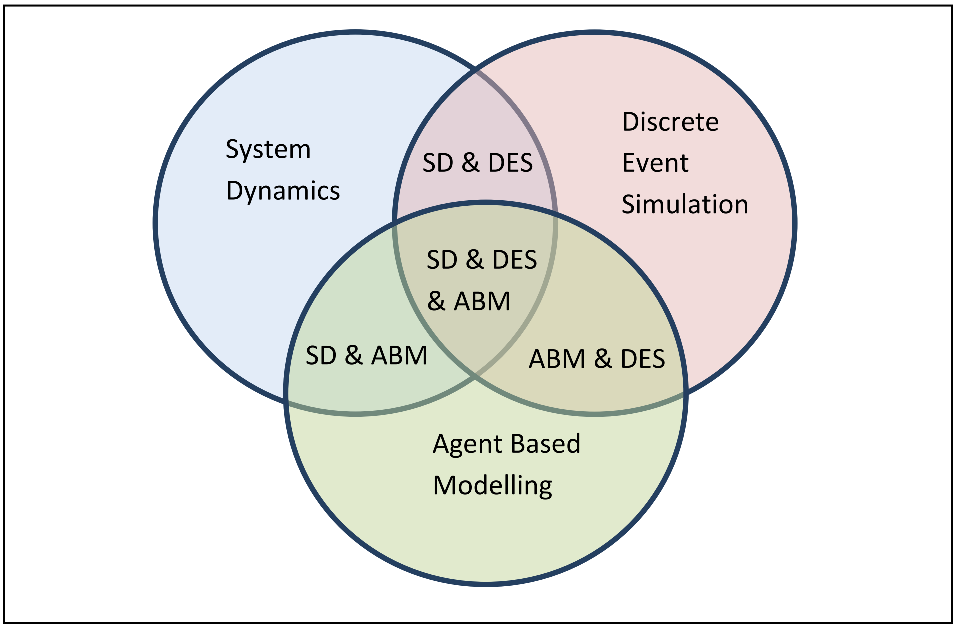


Figure 3 Comparison and hybrid literature

The literature review was conducted using the library services at Aston University. The e-library facility allows for keyword searches and includes several databases, including but not limited to ABI Inform, Business Source Premier (EBSCO), Emerald Full Text and Web of Knowledge. In addition, certain resources were also given more attention due to their particular relevance, for example, papers from the Winter Simulation Conference (http://informs-sim.org/) and particular journals such as System Dynamics Review and the Journal of the Operational Research Society. Key word searches were undertaken including different combinations of the following: supply chain, simulation, modelling, agent based modelling, system dynamics, discrete event simulation, hybrid and performance improvement.

2.2 Supply Chain Management

2.2.1 Introduction

The purpose of this section is to review the literature in relation to the supply chain domain and thereby describe its scope and its characteristics. This will lead to an appreciation of the range and complexity of the challenges that modelling this area presents. The section will conclude with a summary of the challenges presented by this domain to the modeller.

The globalisation of markets and of production (Levitt, 1983) has influenced the structure of supply chains since products that can be produced all over the world can also be consumed globally too. Furthermore, the advent of mass customisation (Pine, 1993) where companies provide customers with bespoke products as of the craft production age, with the efficiency of Fordist mass production techniques has also influenced the structure of the supply chain. Delfman and Albers (2000) distinguish between the impact of internationalisation, which increases the geographic spread of activities, and globalisation, which increases the requirement for businesses to integrate and coordinate activities across many locations and functions.

2.2.2 Definition of a supply chain

There are a number of definitions for a supply chain in the literature. A simple definition is from Harrison (2005) who defines a supply chain as *" …a set of value-adding activities that connects a firm's suppliers to the firm's customers".* Christopher (2005) introduces the concepts of value and cost when he defines supply chain management as *"The management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole".*

Chopra and Meindl (2007) extends this concept to include a more comprehensive description of the various parties involved: *"A supply chain consists of all parties involved, directly or indirectly, in fulfilling a customer request. The supply chain includes not only the manufacturer and suppliers, but also transporters, warehouses, retailers and even customers themselves".* Beamon (1998) introduces the notion of integration between these different parties towards the achievement of certain goals: *"A supply chain may be defined as an integrated process wherein a number of* *various business entities (i.e. suppliers, manufacturers, distributors and retailers) work together in an effort to : 1) acquire raw materials, 2) convert those raw materials into specified final products, and 3) deliver these final products to retailers".* Van Der Zee and Van Der Vorst (2005) also refer to concepts of integration and value adding activities: *"Supply Chain Management is the integrated planning, coordination and control of all logistic business processes and activities in the supply chain to deliver superior consumer value at less cost to the supply chain as a whole while satisfying requirements of other stakeholders in the supply chain (e.g. the government or NGOs)".* In a more comprehensive definition Min and Zhou (2002) introduce ideas of synchronisation, transformation, value-adding and facilitation: *"A supply chain is referred to as an integrated system which synchronises a series of inter-related business processes in order to : 1) acquire raw materials and parts; 2) transform these raw materials an parts into finished products ; 3) add value to these products; 4) distribute and promote these products to either retailers or customers; 5) facilitate information exchange among various business entities (e.g. suppliers, manufacturers, third party logistics providers, and retailers)".* Thus the supply chain involves the integration, coordination and synchronisation of activities between different business entities. It also requires the transmission of both material and information between those business entities.

An interesting approach to defining the supply chain is the Supply Chain Operations Reference Model (SCOR, 2013) which is a consensus model developed by practitioners. The SCOR model has been developed by the global members of the Supply Chain Council and attempts to capture the key characteristics of a supply chain for any industry. The model includes all the business processes, best practices and measures of performance for a given supply chain. The model defines the scope of the supply chain as extending from the focal firm's customer's customer to its supplier's supplier. SCOR identifies four levels of detail for processes, of which three are considered to be generic, and the fourth and most detailed is specific to the industry concerned. At level one, the business processes are defined as plan, source, make, deliver and return. At level two, examples are make-to-stock, make-to-order and engineer-to-order. SCOR identifies five core supply chain performance attributes: reliability, responsiveness, agility, costs, and asset management. These performance attributes are umbrella firm goals. Actual performance in the supply chain is measured in SCOR with performance metrics. These metrics are linked to the higher level performance attributes, but exist at the appropriate level of the model. The SCOR model can be used to describe the characteristics of a given supply chain, and can be used to benchmark performance and identify opportunities for improvement based on best practices. As a tool for modelling and simulation, SCOR has been used as a modelling template in combination with discrete event simulation software Arena to model supply chains (Persson and Araldi, 2009).

2.2.3 Scope of supply chain management

The definitions in the previous section provide some insights as to what activities and business processes are included within the scope of supply chain management (SCM). In terms of the business processes that should be included in scope, Lambert et al. (1998) suggest that SCM builds upon the field of logistics, and as such includes all logistics processes and activities, but extends into a number of other areas, namely:

- Customer relationship management
- Customer service management
- Demand management
- Order fulfilment
- Manufacturing flow management
- Procurement
- Product development and commercialisation
- Returns

In terms of the key issues that should be considered as part of the supply chain management domain, Simchi-Levi et al. (2003) suggest:

- Distribution network configuration
- Inventory control
- Supply contracts
- Distribution strategies
- Supply chain integration and strategic partnering
- Outsourcing and procurement strategies
- Product design
- Information technology and decision support systems
- Customer value

Chopra and Meindl (2007) suggest that all supply chain processes can be classified into three macro processes, namely:

1. Customer relationship management (CRM) : processes that focus on the interface between the firm and its customers (market, price, sell, call centre and order management);
2. Internal supply chain management (ISCM) : processes that are internal to the firm (strategic planning, demand planning, supply planning, fulfilment and field service);

3. Supplier relationship management (SRM) : processes that focus on the interface between the firm and its suppliers (source, negotiate, buy. design collaboration, supply collaboration).

2.2.4 Supply chain design

The definition and scope of the supply chain have been explored in the previous sections. Supply chain design involves matching the characteristics of the supply chain to its competitive environment. Chopra and Meindl (2007) describe the alignment between the competitive goals of a firm and its supply chain strategy as 'strategic fit'. They suggest that the supply chain design problem involves decisions regarding the number and location of production facilities, the amount of capacity at each facility, the assignment of each market region to one or more locations, and supplier selection for sub-assemblies, components and materials. Meixell and Gargeya (2005) suggest that in a global context these decisions are extended to include international location decisions and also the consideration of a number of specialised globalisation factors. These decisions may be decentralised and made by local managers, or centralised so that the decisions are coordinated across the different regions. Similarly, Baud-Lavigne et al. (2012) suggest that the supply chain design problem involves consideration of manufacturing (cost structure, workforce, capacity etc) and logistics across many sites. There are a number of key factors which influence supply chain strategy and structure, these will be identified and developed in the following sections.

2.2.4.1 Type of product

The type of products supplied by a firm will influence the nature of the supply chain used to produce and deliver them to the customer. Fisher (1997) suggested that functional products require an efficient supply chain, whereas innovative products need a responsive supply chain. An example given of a functional product is Campbell's soup, whereas an example of an innovative product is fashion skiwear. Fisher (1997) describes the differences between a functional and a responsive supply chain in terms of a number of factors including manufacturing focus; inventory strategy; lead-time focus, approach to choosing suppliers and product-design strategy. Lamming et al. (2000) extended this idea proposing an initial classification of supply networks based on two key dimensions, namely, innovative and unique products versus functional products and higher or lower product complexity. Thus it is proposed that the type of supply network will depend on the relative uniqueness of the product, but also its complexity.

Product architecture also impacts supply chain design. According to Nepal et al. (2012), product architecture concerns a number of factors, including product modularity; architecture consists of :

product size and shape; interfaces; component complexity; number of components; product platforms and component commonality. Baud-Lavigne et al. (2012) explore the link between product standardisation and supply chain design and suggest that firms should consider product design and supply chain design in parallel, rather than sequentially as has been the case in the past. In particular, product modularisation has a significant impact on supply chain design since it facilitates outsourcing and the development of so called mega-suppliers and integrators (Nepal et al., 2012 ; Salvador et al., 2004).

Another key factor which will influence supply chain structure is value density, the ratio of the value of an item to its physical size. Cooper (1993) points out that products such as cement , with relatively low value density, will have localised logistics systems, where the location of production will be close to the location of consumption. Products with high value density, such as precious stones, may be produced in a location and then shipped all over the world across large distances. According to Cooper (1993), price is another factor, since products that can command a higher price may allow for more costly logistics structures, whereas low priced products may drive firms to seek economies of scale and produce in fewer locations. The type of logistics network adopted will be the result of balancing these factors.

A further consideration is the degree of postponement that is possible. Postponement is delaying the customised aspect of the product as late as possible and as close as possible to the point of consumption. Product modularity is linked to postponement since it allows the variety to be built into the product at a later stage. According to Cooper (1993), the three factors which govern the approach to postponement are (1) brand: Is it global? (2) formulation: Is it common to all markets or different between countries/customers? (3) peripherals: Are labels, packaging and instruction manuals common to all markets? Cooper (1993) identifies four possible logistics strategies that firms may adopt, namely:

1. The unicentric strategy : the product is manufactured in one location across the world
2. The bundled manufacturing strategy, where certain elements of product formulation vary across the world, and thus may affect the location of production,
3. Deferred assembly, the assembly takes place closer to the market place, due to variations in local preferences,
4. Deferred packaging, the peripherals vary according to the local market requirements.

Perishable products present a unique set of challenges, and since their value declines rapidly at certain stages of their lifecycle, they cannot be treated like other product types. Thron et al. (2007) suggest that handling perishable products is more complex and risky than other product types due to their fragility and limited lifespan. Blackburn and Scudder (2009) suggest that the deterioration in value of fresh produce over time means that most conventional supply chain strategies do not apply. They examine the supply chains for two particular products, melons and sweetcorn. They demonstrate that the value of these products declines rapidly between harvest and chilling and then again from the end of the 'cold chain' to the point of purchase. Whilst the product is chilled within the 'cold chain' the decline in value is much slower. They show that the supply chain strategy must be different depending on which phase of the supply chain the product is in i.e. it should be responsive whilst the product value is declining rapidly and efficient whilst the product is in the 'cold chain'. This shows that the perishability of the product must be considered as a factor in supply chain design.

2.2.4.2 Demand

The nature of customer demand provides challenges to firms in their desire to satisfy that and profit from doing so. Demand may vary in terms of its volume and variety. Volumes may fluctuate within a short timescale or seasonally, this is the concept of demand volatility. Additionally, variety of demand may vary from one type of product to many different products or variations of a product. A number of authors have argued that the design of the supply chain must be related to the nature of the demand placed on it. For example, Christopher (2005) proposes that the supply chain strategy should be either lean, agile or some hybrid of the two depending on demand (predictable or unpredictable) and supply (long leadtime or short). In a similar way, Simchi-Levi et al. (2003) suggest a combination of demand uncertainty and economies of scale. These authors emphasise the importance of the boundary between the push and pull strategies, referred to as the 'push-pull boundary' (Simchi-Levi et al., 2003) or the 'decoupling point' (Christopher, 2005).

Towill and Christopher (2002) argue that the design of the supply chain, whether it should be lean, agile or a hybrid of the two, should be related to the market strategy of the firm. However, they suggest that few firms formalise supply chain strategy in this way, and that often marketing and operations are not integrated. The point at which the customer demand enters the supply chain is variously called the 'demand penetration point' (Christopher, 2005), the 'order penetration point' or the 'customer order decoupling point' (CODP) (Olhager, 2012). This point is significant for supply chain design since for activities upstream of this point the firm must forecast demand, and for activities downstream from this point they can be driven by actual demand (see Figure 4). Olhager (2012) suggest that activities downstream of the CODP add more value than those upstream of this point.

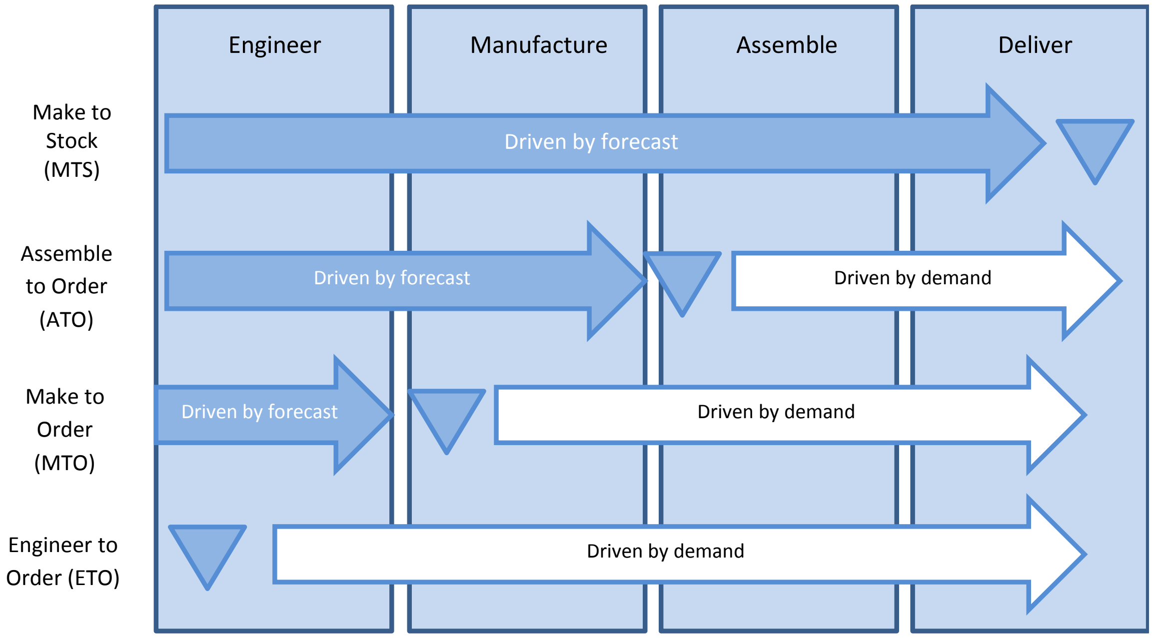


Figure 4 Demand and Customer Order Delivery Points

2.2.4.3 Environmental considerations

Recent developments in environmental awareness and legislation are placing new demands on businesses and their supply chains. Increasingly, businesses are required to manage the environmental impact of their products in use and at the end of life. An example of this is the European Union "Waste Electric and Electronic Equipment" (WEEE) Directive which focuses on the management of products at the end of their life in the electronics industry. New legislation places greater responsibility on manufacturers to take back their products at the end of life in order to re-use, refurbish, recycle or remanufacture them (Toffel, 2004). These trends have led to firms developing reverse logistics processes in order to manage the flow of these products. These reverse processes have also become known as closed loop supply chains (CLSC) (Lehr et al., 2013). This reframes the concept of the supply chain, since with CLSCs there may be additional complexity due to new companies being involved and a higher number of material flows. In addition, the customer is now acting as the supplier of the process.

As well as reverse logistics, there is the increased use of recycled materials in the manufacturing process. This also has implications on the supply chain structure and strategy and may involve many new companies which are not currently in the supply chain as found in research in the corrugated cardboard industry (Field and Sroufe, 2007). As well as managing reverse logistics, firms must also comply with legislation regarding the disposal of waste which is produced by their operations and supply chain. In the case of certain industries, for example construction, this can be an extensive challenge due to the amount of waste produced. In the UK construction industry, for example, waste must be classified and dealt with according to whether it is low risk or hazardous (Environment-Agency, 2011). A UK Government report in 2008 found that the construction industry was delivering over 25 million tonnes per annum of waste to landfill in England (UK-Government, 2008). The design of a modern supply chain must take account of these issues.

2.2.4.4 Distribution channels

In some industry sectors the number of distribution channels for the product to reach the consumer is limited, for example Aerospace and other large capital products. In other sectors, such as retail, due mainly to the internet, there are many different channels. In retail, single channel distribution would be for example, if the product was just available in store or alternatively on the internet on line. Multiple channel retail distribution is when the product is available both in store and on line (Müller-Lankenau et al., 2005). A more recent development in retail is the 'omni-channel' concept. The idea here is that consumers may be able to order a product through a multiplicity of points including from a smart phone, a computer at work or at home or in person at the store. In terms of locating and distributing that product, firms may have to check stock at various retail outlets, at regional warehouses or potentially further upstream in the supply chain. In terms of delivery, the product may be delivered to the consumer at home, or may be collected in store at a variety of destinations. The coordination of all these different locations and sources of information is presenting new challenges to the firms in the retail supply chain (Napolitano, 2013).

2.2.4.5 Industry

The nature of the industry itself may influence the characteristics of the supply chain. Fine (2000) describes how supply chain structure tends to oscillate between vertically integrated structures with one dominant company (IBM in the 1970's) to a more horizontal / modular structure with highly competitive niches (i.e. telecoms in the 1970's). The speed with which the structure changes relates to the 'clockspeed' of the industry. Fine (2000) argues that to thrive in such a competitive environment, firms must develop 'three dimensional' concurrent engineering capability i.e. the ability to simultaneously develop product, process and supply chain.

Based on an in depth empirical study, Harland et al. (2001) proposed a taxonomy for supply network classification across two dimensions, namely: supply network dynamics and focal firm supply chain influence. Supply network dynamics is a combination of operations process dynamics (process variety and volume) and market dynamics (frequency of new product launches). Focal firm supply network influence depends on whether a focal firm considers that there are suppliers or customers which are too large or powerful for them to influence.

Empirical work by Srai and Gregory (2008) showed that supply network configurations vary significantly from firm to firm. They found that the key elements of supply network configuration are: tier structure, shape and location (including key information/material flows); principal unit operations and their internal manufacturing processes; roles and relationships between key network partners; and product structure, complexity and composition.

2.2.4.6 Characteristics of supply chains

Supply chain strategy and structure will vary depending on product, demand and industry as has been described. A number of authors have identified the key characteristics of supply chains and how they vary in response to these factors. In terms of defining the key characteristics of the supply chain, Lambert et al. (1998) suggest a supply chain framework consisting of three elements i.e. the structure of the supply chain, the supply chain business processes and the supply chain management components. According to Lambert et al. (1998):

"The supply chain structure is the network of members and the links between members of the supply chain. Business processes are the activities that produce a specific output of value to the customer. The management components are the managerial variables by which the business processes are integrated and managed across the supply chain."

In terms of supply chain structure, they propose three structural aspects i.e. 1) the members of the supply chain, 2) the structural dimensions of the network, and 3) the different types of process links across the supply chain. The members of the supply chain are those companies which a firm interacts with between point of origin to point of consumption. The structural dimensions of the supply chain concern firstly, the vertical structure, the horizontal structure and the position of the company within the horizontal structure. In terms of vertical structure, a supply chain can be narrow with few firms in a particular tier, or broad, with many companies. In terms of horizontal structure, a supply chain may be narrow with few tiers or broad with many tiers. The degree of vertical integration will vary by industry. In certain industries, for example automotive, there is a degree of outsourcing and suppliers may take responsibility for significant product modules. These characteristics are illustrated in Figure 5. A particular firm may be located close to the point of consumption, close to the point of origin, or somewhere between. Process links concern the business process linkages between different member companies in the supply chain. These links are how companies manage and integrate the activities between different firms. The links are of four kinds: managed process links; not managed business process links;

monitored process links or non-member process links. Finally, supply chain management concepts are of two main kinds; physical and technical management components and managerial and behavioural components. In a similar vein, Stonebraker and Liao (2004) describe the two key characteristics of supply chains as being the number of stages and the form of integration i.e. the degree of ownership and control. They identify four types of configuration, namely independent integrator, collaborative integrator, controlling integrator and full integrator.

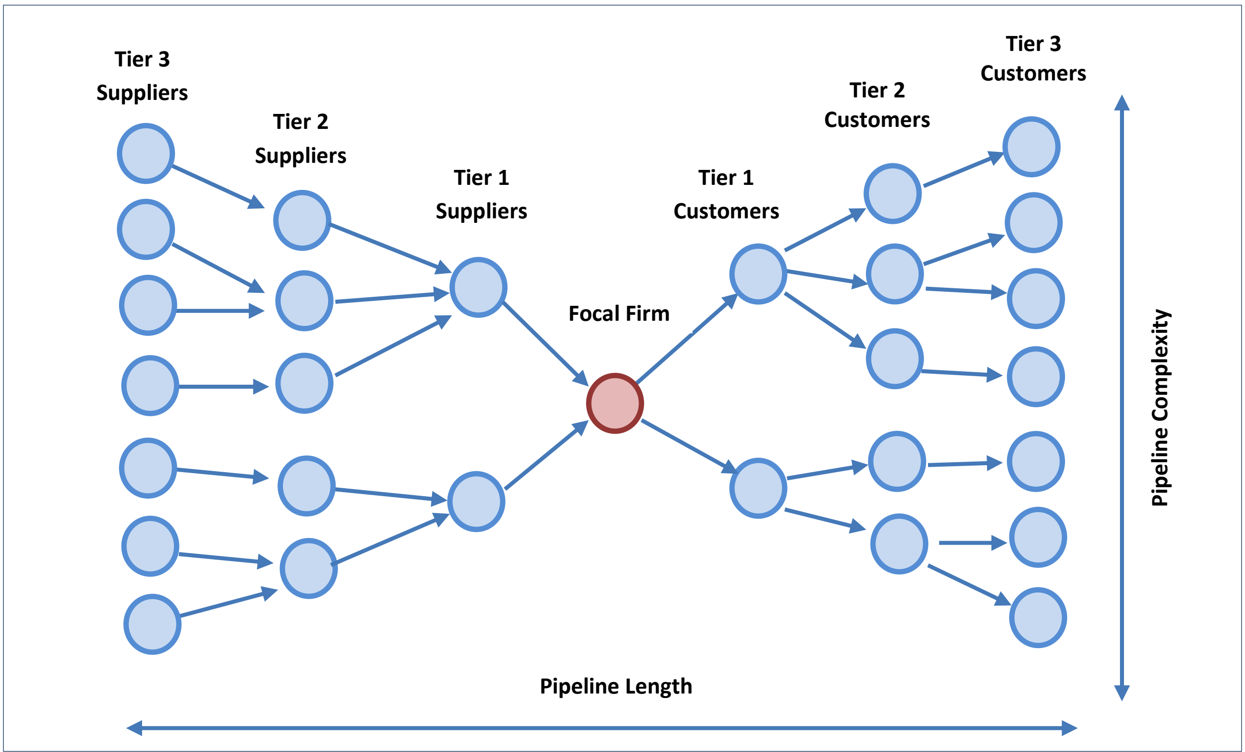


Figure 5 Supply Chain Characteristics

2.2.5 Implications for modelling and simulation

The previous sections have demonstrated the complexity of the supply chain domain. Traditionally, modelling in the supply chain would have mainly consisted of solving logistical problems involving material and information flows and inventory and scheduling challenges. However, increasingly, modelling the supply chain requires the ability to not only represent material and information flows, but also other key decision making activities and business processes. As mentioned in the previous section, the concepts in relation to SCM are not only physical and technical, but also managerial and behavioural (Stonebraker and Liao, 2004). Thus modelling and simulation must extend from technical problem solving to the ability to model behavioural and management issues such as decision making. Another key feature of supply chains is the variety in terms of their size and complexity. In terms of their structure, horizontally, supply chains may be long or short; vertically, they may be narrow or broad. The chains may be relatively simple, consisting of a small number of firms linked in a fairly linear fashion.

Alternatively, they may be complex, involving many firms linked together across a web or network including many echelons. The products supplied may be simple or complex, functional or innovative. Demand may be stable or dynamic, structures that supply these products may be lean or agile. The supply chain itself consists of various stages, the focal firm may have control and ownership of other stages, or may itself be controlled by other firms. Linkages between entities in the supply chain are used for various purposes including the transfer of information and material.

Different sectors may exhibit different characteristics in relation to the length of the supply pipeline, and its complexity i.e. the number of different suppliers at each stage. Some examples of how different sectors could map to these criteria are shown below in Figure 6.

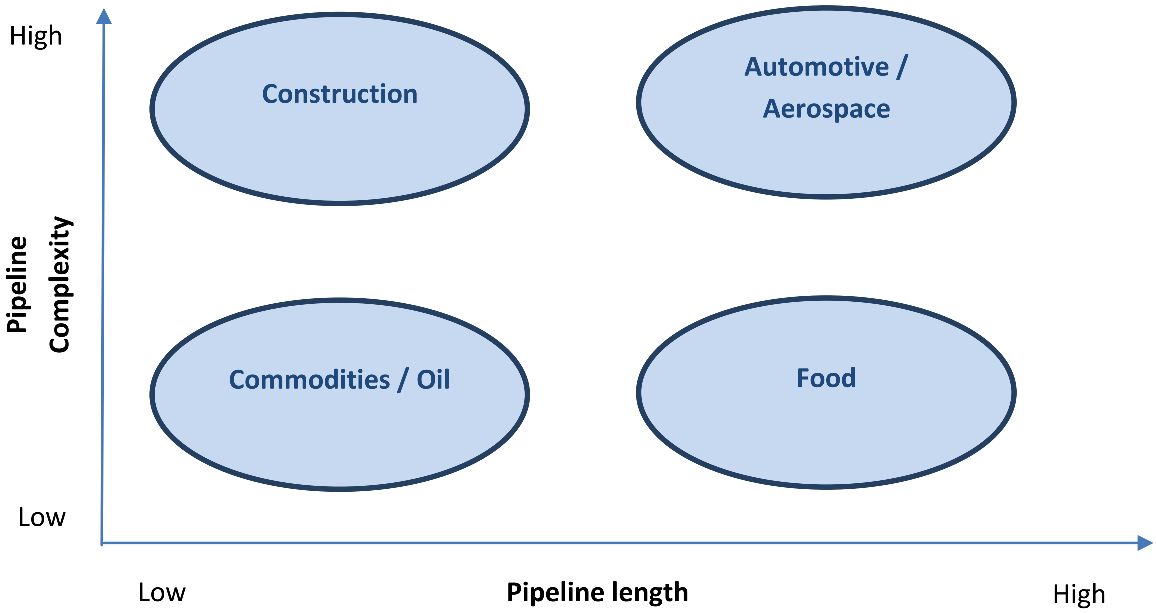


Figure 6 Sectors and Supply Chain Complexity

Any attempt to model the supply chain must attempt to model these various aspects and characteristics. Many models of supply chains can tend to oversimplify and can often be two echelon systems, real supply chains are more complex. Also, modelling must take account of key performance measures which can be qualitative or quantitative. In addition to the supply chain characteristics which need to be modelled, the nature of the decisions themselves vary between strategic, tactical and operational (Chopra and Meindl, 2007 ; Simchi-Levi et al., 2003).

Table 1 summarises the different supply chain challenges in relation to these three levels as well as the functional and business process scope as identified in section 2.2.3.

	Procurement	Network Configuration	Logistics	Internal Operations
Strategic (several years)	- Make versus buy - Strategic sourcing	- Location and capacities of plant and warehousing - Design of the distribution network - Postponement	- Transportation strategy - Where to hold inventory - Distribution strategy - Information strategy	- Production strategy - Process choice
Planning (3mths to one year)	- Supply contracts - Pricing and volume decisions	- Medium term location decisions for production or warehousing	- Medium term inventory policy - Reorder levels	- Master production schedule
Operational (daily / weekly)	- Placing purchase orders / call offs	-	- Daily or weekly inventory decisions - Kanban triggers - Shipping - Goods receipt	- Order fulfilment - Delivery - Batch sizes

Table 1 Supply chain decisions in relation to three levels: strategic, planning and operational

(Chopra and Meindl, 2007 ; Simchi-Levi et al., 2003)

2.2.6 Summary

This section has described the supply chain domain and demonstrated that it presents a particular set of challenges to the manager and indeed any scholar who aspires to studying and perhaps modelling this domain. The next section will explore the literature in relation to the modelling and simulation of this area.

2.3 Supply chain modelling and simulation

This section will introduce the concepts of modelling and simulation and describe how they are used to tackle the main problem types in the supply chain domain. Modelling and simulation are key tools in the systems analysis and operational research fields. The following review questions were used to guide this part of the review:

1. Why model the supply chain?
2. What is modelling?

3. What is simulation?
4. Why choose simulation to improve supply chain performance?

2.3.1 Modelling the supply chain

As has been described in the previous section, the supply chain presents a number of particular challenges. The performance of the supply chain has become ever more important for the overall competitiveness of firms and can become the focal point for performance improvement (Slone, 2004 ; Harrison, 2005). The success of the firm may depend on the ability to coordinate complex business relationships (Min and Zhou, 2002). The supply chain is becoming ever more complex due to the impact of globalisation and the numerous locations and control points that occur due to activities spanning the globe (Meixell and Gargeya, 2005). Further factors driving this increase in complexity include the large scale nature, the hierarchical structure of decisions, the randomness of inputs and the dynamic nature of interactions. In this context, the need for modelling to assist managers in making the right decisions is ever increasing (Biswas and Narahari, 2004). Harrison (2005) suggests that the first step in a supply chain design process is to decide which modelling approach to use. More generally, modelling provides a method for developing better understanding of the behaviour of complex systems (Pidd, 2003).

2.3.2 Modelling

According to Pidd (2003), models are 'tools for thinking' in that they allow the consequences of decisions to be evaluated before action is taken. The purpose and methods of modelling vary in the different communities of SD, ABM and DES. In SD there has been a long tradition of modelling as a way of learning about systems (Senge, 1990 ; Sterman, 2000 ; Morecroft, 2007). SD is used to surface the different mental models individuals have about the system they operate within. These models can then be used to test the effect of different policies on the behaviour of the system. The process of modelling itself helps the individuals and managers to better understand how the complex system operates. In the original work on SD, Forrester (1961) describes the purpose of a model as: *"A mathematical model of an industrial enterprise should aid in understanding that enterprise. It should be a useful guide to judgement and intuitive decisions. It should help establish desirable policies."* From a DES perspective, the purpose of modelling perhaps has a more problem solving bias. This definition by Pidd (2003) encapsulates this well: *"A model is 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."* From an ABM perspective, the purpose of modelling links to the underlying behaviour of agents in the system. North and Macal (2007) describe a number of reasons why an organisation might model a decision making process:

- *No one can understand how all the various parts of the system interact and add up to the whole*
- *No one can imagine all the possibilities that the real system could exhibit*
- *No one can foresee the full effects of events with limited mental models*
- *No one can foresee novel events outside their mental model*s

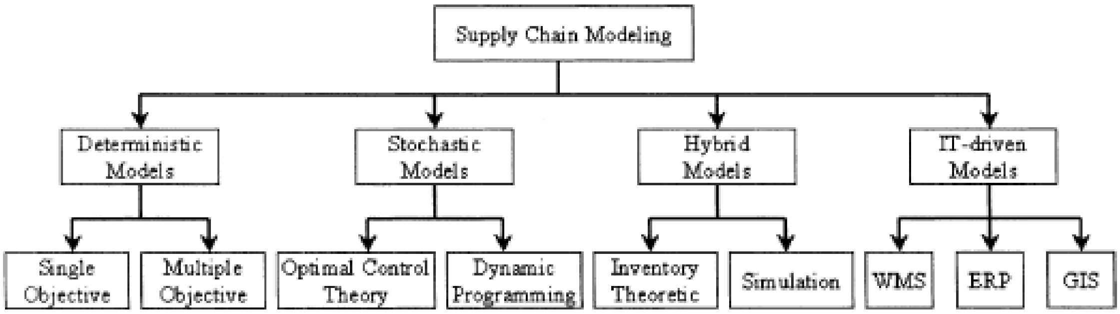
Although the different communities have a slightly different perspective and emphasis, they all agree that the model serves as a representation of complex reality that enables a better understanding of the behaviour of a complex system. It provides a vehicle for managers and teams to test different policies and decisions to see how these affect the behaviour of the system.

2.3.3 Simulation

Kelton et al. (2007) defines simulation as *"… the process of designing and creating a computerised model of a real or proposed system for the purposes of conducting numerical experiments to give us a better understanding of the behaviour of that system for a given set of conditions".* Pidd (2004a) defines simulation as: *"…experimentation on a computer-based model of some system. The model is used as a vehicle for experimentation, often in a 'trial and error' way to demonstrate the likely effects of various policies".*

SD practitioners consider that the surfacing of mental models is a necessary but not sufficient step in understanding complex systems. Sterman (2000) states that: "*Simulation becomes the main, and perhaps the only, way you can discover for yourself how complex systems work".* So having built up mental models of how the system operates, the simulation of that system to see how it behaves in response to different inputs and variables furthers that understanding in a key way. Another SD practitioner, Morecroft (2007) states *"Simulations offer a way to experience dynamic complexity and to develop an intuition for the causes and areas of puzzling dynamics in business and society".* As in modelling, the emphasis in the SD community is on simulation as learning and discovery. In the DES community, there are similar explanations for the rationale for simulation, with perhaps slightly more bias towards problem solving. North and Macal (2007) do not distinguish between modelling and simulation, but use the terms together. Simulation is effectively the use of the model to perform various experiments in order to learn more about the behaviour of that system in response to various inputs and situations.

There are a range of approaches to modelling the supply chain. Beamon (1998) proposes four categories of supply chain models i.e. deterministic analytical, stochastic analytical, economic models and simulation models. In the section on simulation, all the examples given are based on system dynamics, which is strange given that this is only one approach to simulation. Min and Zhou (2002) extend this modelling taxonomy as shown in Figure 7.



(Reprinted from Computers and Industrial Engineering, Vol. 43. Issue 1-2, by Min, H. and Zhou, G. "Supply chain modelling: past, present and future" pages 231-249, Copyright (2002), with permission from Elsevier).

Figure 7 Supply chain taxonomy (Min and Zhou, 2002)

They place simulation in the hybrid modelling area and describe hybrid modelling as a mixture of deterministic and stochastic approaches. Their definition of these terms is given as "*Deterministic models assume that all the model parameters are known and fixed with certainty, whereas stochastic models take into account the uncertain and random parameters*" (Min and Zhou, 2002). In the section on simulation, they mention just two applications, the first being a system dynamics application and the second a fuzzy logic model implemented using the programming language C++. It is perhaps surprising that they do not mention discrete event simulations, despite it being a significant application area. Biswas and Narahari (2004) propose three categories of supply chain modelling, namely optimisation models, analytical performance models and simulation and information models. Optimisation models are deterministic and are used to develop optimal solutions to problems such as inventory control and site location questions. Analytical performance models are used in dynamic and stochastic situations, examples of these are Markov chains and Petri Nets. The authors propose that simulation is used for the following reason: "*To obtain very accurate and detailed models, one has to represent many realistic features, which is possible in simulation models*" (Biswas and Narahari, 2004).

Harrison (2005) introduces and additional category to those already identified in his classification framework for supply chain modelling i.e. heuristics. He identifies three main approaches; optimisation, simulation and heuristics. Heuristics is described as "*intelligent rules that often lead to good, but not necessarily the best, supply chain design solutions*" (Harrison, 2005).

2.3.4 Simulation of supply chains

Given the wide range of modelling options available, why would a practitioner choose simulation as opposed to any other approach? Several authors agree that analytical techniques have limits modelling the complexity of the supply chain, and that sometimes the problems cannot be solved using optimisation. Van Der Zee and Van Der Vorst (2005) suggest in relation to supply chains "*their complexity obstructs analytic evaluation*". In the context of supply chain forecasting, Ingalls (1998) argues that the degree of variation in the forecast will influence whether optimisation can be used. Optimisation may also have significant weaknesses when business objectives change over time. They argue that simulation will be a better choice in situations of uncertainty. In relation to heuristics, Harrison (2005) points out that the quality of the solution is unknown. These are some of the weaknesses of other approaches to modelling, but simulation is also seen to have a number of particular strengths as an approach. Simulation is highly flexible and can allow more detailed and complex aspects of the system to be modelled (Harrison, 2005). Simulation is very powerful for evaluating different decisions and strategies using 'what-if' analysis (Terzi and Cavalieri, 2004 ; Min and Zhou, 2002). Simulation can be used to represent many realistic features of the supply chain (Biswas and Narahari, 2004). Electronic supply chain (e-supply chain) aspects can be modelled using simulation (Tang et al., 2004 ; Albores-Barajas, 2007) and also business processes (Ball et al., 2004).

2.3.5 Limitations to current modelling approaches

Some authors argue that current approaches to supply chain modelling are inadequate. For example, Min and Zhou (2002) suggest that the broader context of the supply chain will require capabilities beyond the traditional 'hard' analytical approaches. Future models will need to be able to model 'soft' issues such as relationship management. Terzi and Cavalieri (2004) argue that models will need to be developed to be parallel and distributed in order to cope with the realities of geographically dispersed and complex supply chains. Although the majority of models use a local paradigm, this approach will not be sufficient in the future, they argue.

2.4 Comparison of the main simulation methods

The previous sections have described why and how simulation is used in the supply chain domain. In this section, the relative strengths and weaknesses of the three main simulation approaches are explored in more detail.

2.4.1 Introduction

In the following section, the main simulation methods are identified and reviewed. The main purpose of the review will be to answer the following review questions:

1. What are the main simulation approaches in the supply chain domain?
2. What are the relative strengths and weaknesses of these approaches?
3. Is there any guidance as to when to choose a particular approach?

The literature comparing the techniques is limited, but it does point the way towards the current view of the approaches. The final part of this section will present a summary of the claims made on behalf of the techniques in the literature.

2.4.2 The three main simulation methods

Having established that simulation is a valuable approach for modelling the supply chain, the term simulation needs to be clarified. Different authors use different definitions and focus on particular approaches or paradigms. In order to achieve this clarification, a literature search was conducted. The search string “supply chain” AND “simulation” was entered in EBSCO Business Source Premier Search engine, all databases were selected. A total of 517 hits were returned, this reduced to 439 when the option “Scholarly (Peer Reviewed) Journals” was selected. A random sample of 100 papers were reviewed and classified. In order to classify the papers a taxonomy was required. As a starting point, the Association for Computing Machinery (ACM) Special Interest Group (SIG) on SImulation and Modelling (SIM) has a high level classification for simulation approaches, and this was used to classify the papers (http://www.acm-sigsim-mskr.org). A review of other associations, professional groups and textbooks was performed but no more comprehensive taxonomy was discovered. The different types of simulation recognised by ACMSIGSIM are Discrete, Continuous, Monte Carlo, System Dynamics, Gaming, Agent, Artificial Intelligence, Virtual Reality, Distributed, Web based, Live and In the Loop.

The sampling method used was as follows. A list of 100 random numbers between 1 and 437 were selected and this number was used to select a paper from the list. Each paper was classified against the approaches listed above. If a method was found which was not on the list then the method was added to the taxonomy. A paper could be classified against more than one method, for example a paper could include both discrete simulation and gaming. If the method could not be identified then the method was classified as ‘not clear’. If the paper was not available or was clearly not about supply chain or simulation then it was rejected and an additional random number was selected for a different paper. Using this approach the results in Figure 8 were obtained. A number of additional methods were added during this classification, namely XML, Spreadsheet, Mathematical Modelling, Java, Bespoke Software, Matlab, Genetic Algorithm, Petri Net and Not Clear. On reflection, it was considered that methods such as Spreadsheet, Bespoke Software, XML, Java and Genetic Algorithm were not true simulation methods like the others and were rather programming or analytical methods and so were reclassified as one of the prime methods or ‘not clear’. Methods with no hits have also been removed. The second version of the classification is shown in Figure 9. The top six methods then are Discrete, Mathematical

Modelling, System Dynamics, Agent, Not Clear and Monte Carlo. Mathematical modelling is inherently different from other methods because it involves modelling the system by developing mathematical equations, which the authors hypothesise represent the system under consideration. Pidd (2004a) suggests that mathematical modelling is different in kind because it attempts to analytically identify an optimal solution to the problem under study. He argues that most mathematical models cannot deal with dynamic or transient effects. This means that mathematical modelling is not simulation in the same sense as the methods identified here. For this reason, mathematical modelling is discounted for the purposes of further study and comparison.

Monte Carlo simulation is a method for performing numerical integrations of functions that are impossible with direct analytical approaches. It is used in a fairly narrow set of circumstances and applications, for example Jahangirian et al. (2010) describe its use as limited to static problems and that it has played a trivial role in manufacturing and business domains. For this reason, Monte Carlo simulation is also discounted from further review. Gaming is an approach used in particular to explore the impact of human behaviour on the performance of the supply chain. A good example of this is the Beer Game, an interactive simulation developed at MIT to illustrate the Bullwhip Effect (http://beergame.mit.edu/guide.htm). Gaming is often used in a training or education context to demonstrate to participants certain principles of supply chain performance. Because of its relatively niche and specialised focus, Gaming is not considered as one of the main methods of simulation for further review. The remaining methods, i.e. distributed, petri net, continuous and web based were cited two or fewer times and so again are not considered as the main methods in use. The main methods, therefore, of supply chain simulation for further consideration are Discrete Event Simulation (DES), System Dynamics (SD) and Agent Based Modelling (ABM).

2.4.3 System Dynamics

This section will review System Dynamics in relation to its application in the supply chain domain, but also provide an overview of the approach and how it is applied to modelling systems.

2.4.3.1 System Dynamics in the Supply Chain

The origins of System Dynamics date back to 1958 and Jay Forrester (Forrester, 1958) who applied the principles of control engineering to the solution of management problems and developed a new approach. This caused some controversy at the time and the approach was criticised for lacking supportive evidence for its validity, among other things (Ansoff and Slevin, 1968 ; Forrester, 1961). The book 'World Dynamics' (Forrester, 1971) which led to the influential 'Limits to Growth' (Meadows et al., 2005) drew heavy criticism at the time. One example of this is Nordhaus (1973) who criticises the model for using non-standard formulations for classic quantities and relationships.

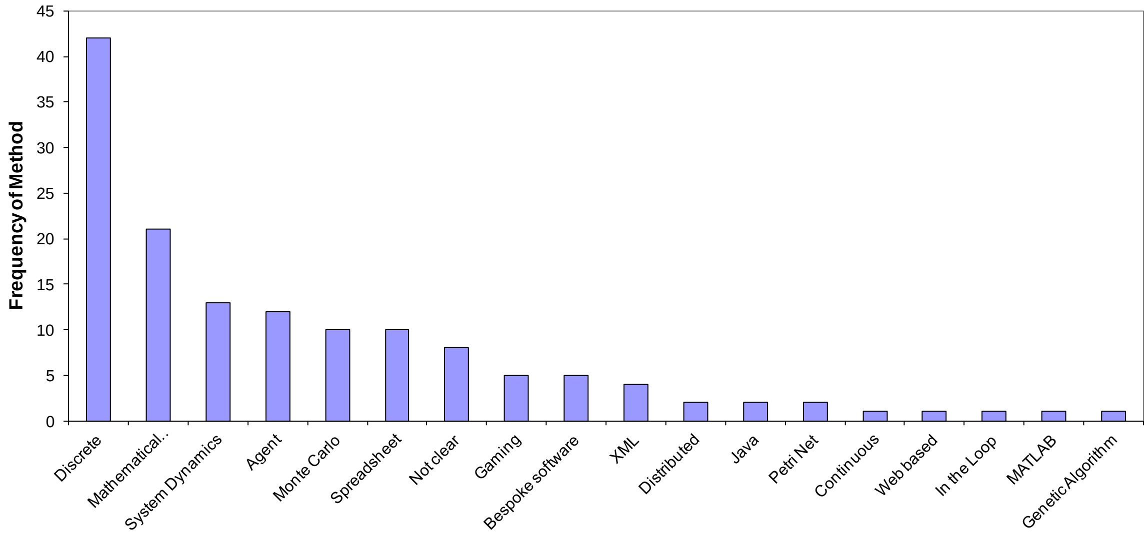


Figure 8 Classification of papers by simulation method

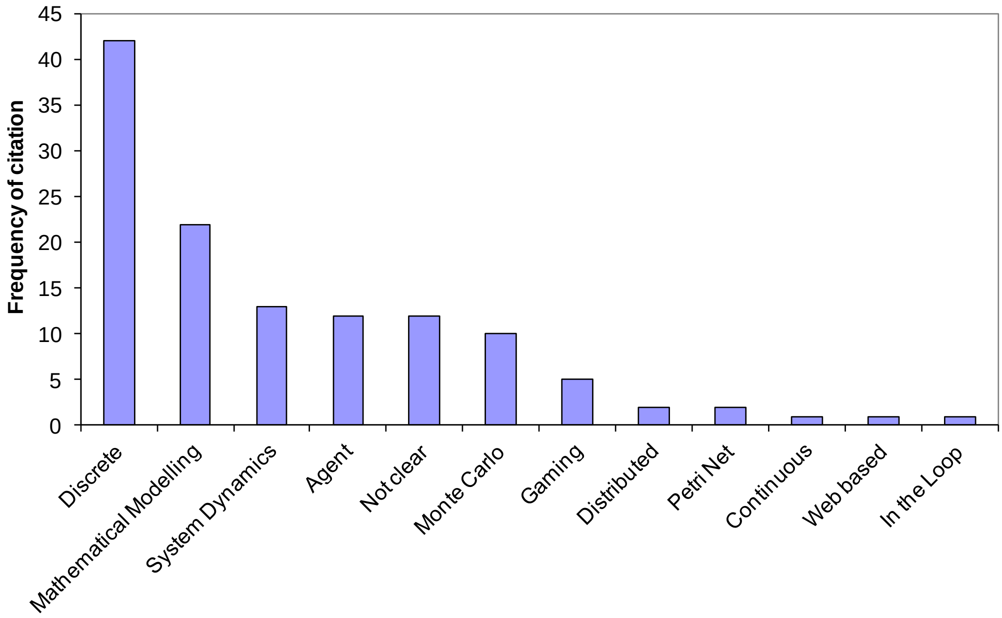


Figure 9 Classification of papers by simulation method following reclassification

He shows how some of the relationships in the model lead to nonsensical results. He also criticises the model for the fact that none of the equations and relationships have any empirical backing, nor do any of the results. These are different criticisms to this proposition, but this does illustrate the danger of taking a top down approach to developing the SD model.

Since then there has been a rich tradition of applying the System Dynamics approach to a range of supply chain problems including supply chain re-engineering (Berry, 1994 ; Towill, 1996b), demand amplification (Ge et al., 2004 ; Sterman, 2000 ; Towill and Del Vecchio, 1994); information sharing (Ovalle and Marquez, 2003a) and facility allocation (Vos and Akkermans, 1996). Towill (1996a) reports that system dynamics can be used to model supply chains and achieve significant performance improvement and that the approach is holistic and can accommodate the real world. A detailed summary of the work done in this field is given by Angerhofer and Angelides (2000). More recently, Akkermans and Dallaert (2005) suggest that system dynamics 'has never been so relevant for the field of Supply Chain Management (SCM) than today'. They propose that the field of SCM can learn from SD and vice versa. They also propose more cross learning between SD and other approaches. The papers from the literature search which cited System Dynamics as an approach dealt with a wide range of supply chain themes:

- Impact of demand amplification on transport cost (Potter and Lalwani, 2008)
- Reverse supply chain (Kumar and Yamaoka, 2007)
- Impact of batching on bullwhip (Potter and Disney, 2006)
- Efficient blood supply (Rytila and Spens, 2006)
- Quality perception (Wankhade and Dabade, 2006)
- E-collaboration (Crespo Marquez et al., 2004)
- Performance metrics (Kleijnen and Smits, 2003)
- Using a CONWIP (Constant Work in Progress) system (Ovalle and Marquez, 2003b)
- Agility (Helo, 2000)
- Supply chain dynamics (Riddalls et al., 2000)
- Cycle time compression (Mason-Jones and Towill, 1999)
- Supply chain redesign (Berry and Naim, 1996)
- Demand amplification (Towill and Del Vecchio, 1994)

2.4.3.2 System Dynamics – the approach

The purpose of this section is to give an overview of the key features of the SD approach, for a detailed description, refer to Sterman (2000). Sterman (2000) describes five stages in the SD approach (Figure 10). Many simulation approaches involve steps or phases with similar descriptors. This section will focus on the key characteristics which give SD its unique character.

The development of a dynamic hypothesis requires the modeller, in conjunction with the client, to identify the key variables, and their interactions, which causes the underlying behaviour of the system. The interrelationship between the variables is described in SD as a 'causal loop diagram'. The best way to explain a causal loop diagram is by way of an example (see Figure 11).

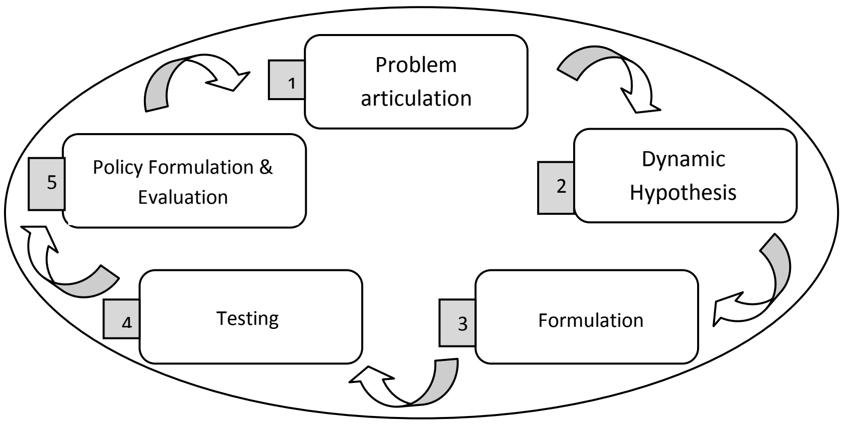


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Figure 10 The SD approach

Individual relationships between variables are shown using arrows. The sign at the end of the arrow denotes whether this relationship tends to increase or decrease the affected variable. So in this example, population increases due to birth rate and decreases due to the death rate. If both arrows in the loop increase the variable, this is known as a reinforcing loop (symbol R). If one arrow increases and one arrow decreases the quantity, this is known as a balancing loop (symbol B).

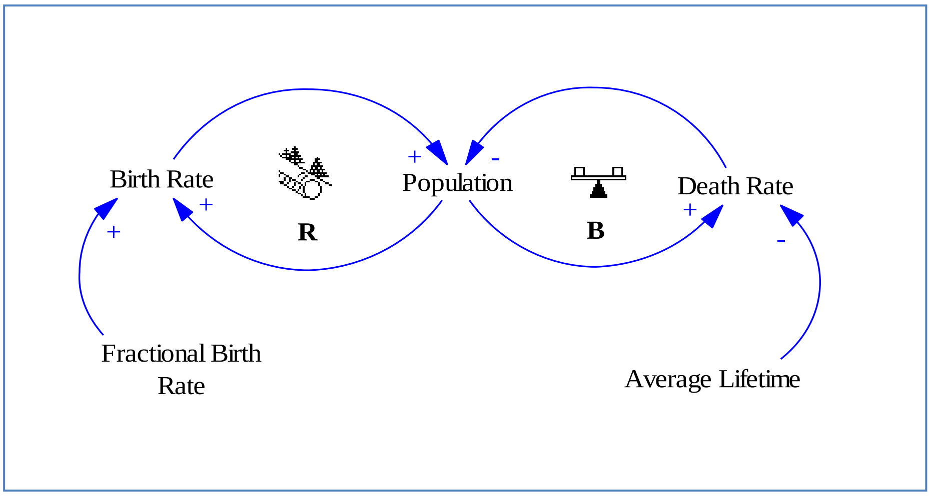


Figure 11 Causal loop diagram

The causal loop diagram is the basic building block of the SD diagram. Initial mapping of the system will involve developing linked causal loop diagrams with the client to describe a dynamic hypothesis of the system behaviour.

Causal loop diagrams are useful for describing the system behaviour, but they cannot investigate the stock and flow characteristics of the system. Stocks are accumulations and they describe the state of a system at a given time. Stocks are increased and decreased by flows. The rate of flows are controlled using valves. A typical example of a stock and flow diagram is shown in Figure 12.

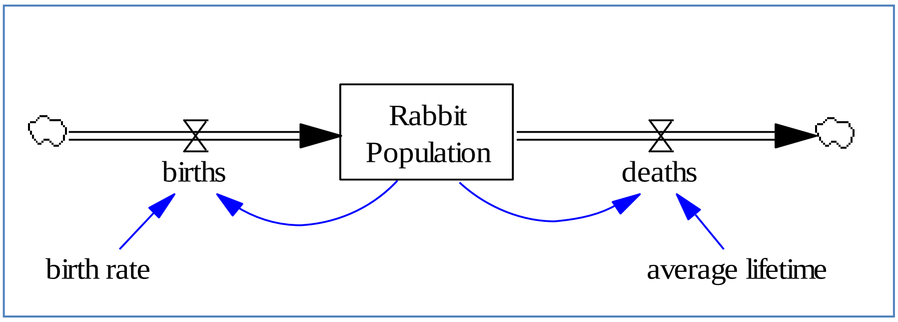


Figure 12 Stock and flow diagram

Fundamental to the SD view of the world are dynamic system behaviours driven by feedback and delays. Delays can be of various types, for example a pipeline delay, in which the order of items is preserved and a first order delay, where items are mixed. Examples of how these delays are calculated in SD are given below:

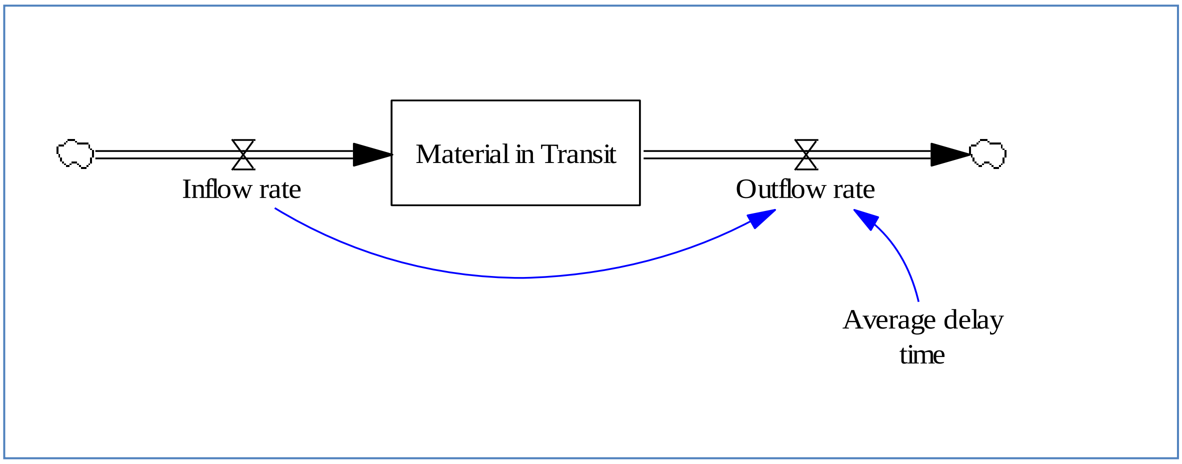


Figure 13 Pipeline delay

Figure 13 shows the diagram for a pipeline delay. With this type of delay, the outflow is simply the inflow delayed by the average delay time i.e.

$$\text{Outflow}(t) = \text{Inflow}(t - D)$$

If the sequence of the items is not preserved, then a first order delay may be used see (Figure 14). The formulation of a first order delay is:

$$\text{Outflow} = \text{Material in Transit} / \text{Average Delay Time}$$

This is an overview of the key features of the SD approach. SD involves working with clients to construct causal loop diagrams and stock and flow models that describe the key system behaviour. Then these models are used to study the behaviour of systems in response to various policy options.

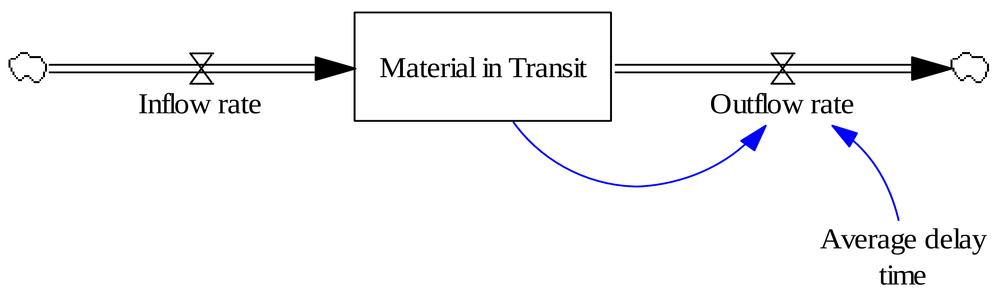


Figure 14 First order delay

2.4.4 Discrete Event Simulation

This section will review DES in the supply chain, and also give an overview of the approach.

2.4.4.1 Discrete Event Simulation in the supply chain

Discrete Event Simulation began in the 1950s with the development of early computers. Early advances in simulation methodology, such as the three-phase simulation approach (Tocher, 1963) also took place around this time. The real boom in the use of simulation coincided with the computer revolution in the 1980’s, the arrival of powerful micro-computers and PC’s. This enabled the development of software packages on which users could build useful models much more efficiently (Robinson, 2005). DES as a methodology differs from SD in a number of ways, the most fundamental being the treatment of time, which is continuous in SD and discrete in DES. Terzi and Cavalieri (2004) provide a comprehensive literature review of the application of DES to the supply chain context. They describe its application across a range of objectives including supply network design, strategic decision support and analysis of supply chain processes. They classify articles according to three criteria i.e. the scope and objectives of the application, the simulation paradigm and technology and the development stage. One key conclusion they reach is that the use of DES in this context can be divided into two approaches namely local simulation and parallel and distributed simulation (PDS). They suggest that distributed simulation offers a fruitful area of research because it allows firms in a network to retain their data integrity whilst still taking part in a simulation programme.

The methodology of DES in application is not as well defined as SD (Morecroft and Robinson, 2005 ; Robinson, 2005), although there are good descriptions of the overall approach (Law and Kelton, 2000 ; Pidd, 2004a). The papers from the literature search covered a wide range of supply chain themes (Table 2).

• Logistics (Ila et al., 2009) • Modular supply chain modelling (Chen and Chen, 2009) • CONWIP (Constant Work in Progress) versus Kanban (Pettersen and Segerstedt, 2009) • High volume semi-conductor manufacture (Huang et al., 2009) • Container terminal simulation (Legato and Mazza, 2001 ; Lee et al., 2003) • Coordinating bid prices (Harewood, 2008) • Cost effective blood supply (Katsaliaki, 2008 ; Katsaliaki and Brailsford, 2006) • Backordering policy (Thangam and Uthayakumar, 2008) • Supply chain optimisation (Hassini, 2008) • Information sharing (Choudhury et al., 2008) • Web service supply chain (Tewoldeberhan and Janssen, 2008)	• Balancing inventory and capacity (Jammernegg and Reiner, 2007) • Improving despatch bay performance (Potter et al., 2007) • Base stock model (Alok, 2006) • Integrated product and process (Röder and Tibken, 2006) • Distributed constraint satisfaction problem (Chan and Chan, 2006) • Supply chain simulation (Umeda and Zhang, 2006) • JIT (Just in Time) versus JIC (Just in Case) (Polat and Arditi, 2005) • Distributed modelling (Mertins et al., 2005) • Automotive supply chain (Turner and Williams, 2005) • Supplier selection (Ding et al., 2005) • Material flow (Manzini et al., 2005) • Coordination (Aslanertik, 2005) • Reducing construction lead times (Walsh et al., 2004)	• Retail clothing supply (Al-Zubaidi and Tyler, 2004) • Modelling returns (Choi et al., 2004) • Reducing cycle times (Ko et al., 2004) • Internet product fulfilment (Rabinovich and Evers, 2003) • Defining an inventory policy (Giannoccaro et al., 2003) • Performance metrics (Kleijnen and Smits, 2003) • Process management (Choi et al., 2003) • Modelling different levels of detail (Persson, 2002) • Theory of constraints (Gupta et al., 2002) • Supply chain dynamics (Riddalls et al., 2000) • Food supply chains (van der Vorst et al., 2000) • Logistics (Hameri and Paatela, 1995) • Modelling control elements (Van Der Zee and Van Der Vorst, 2005) • Optimisation (Shang et al., 2004)

Table 2 Supply chain problem types addressed by DES

2.4.4.2 Discrete Event Simulation – the approach

According to Pidd (2004a), there is no agreed terminology in DES, for the sake of this short introduction Pidd's definitions for common terms will be used. For illustration, consider a queue of shoppers being served in a supermarket as shown in Figure 15. Entities are the individual items in the system, they can be active or passive, for example in this case, the server is an active entity and the customer is passive. Resources are also the countable items in the system but are not modelled individually, in this case and example of a resource is the queue.

Entities arrive at the entrance of the shop, in DES a random arrival of individuals is often modelled as an exponential distribution. Entities leave the shop after being served. Entities may be organised into classes (for example, customers) and may have attributes, which are items of information belonging to that entity.

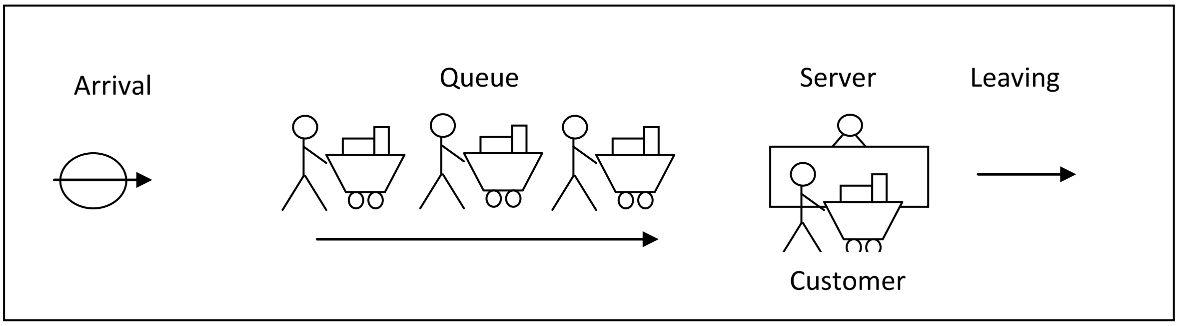


Figure 15 Supermarket queue with server

The development of a DES model may involve the construction of an activity cycle diagram (ACD). The ACD links the various types of entity together between active and passive states. ACD's can be derived for the various classes of entity and joined together to form the overall pattern of activity for the whole system.

There are four main world views in the discrete event simulation approach, these are: the three phase approach; the event-based world view; activity-scanning approach and the process-based approaches. These different world views concern the internal logic of the simulation. Pidd (2004a) suggests that of these the two serious contenders for consideration are the three phase approach and the process based approach. He maintains that for complex systems, the three phase approach may be superior to the process based approach since the executive maintains a more active control of each entity and potential deadlock is avoided.

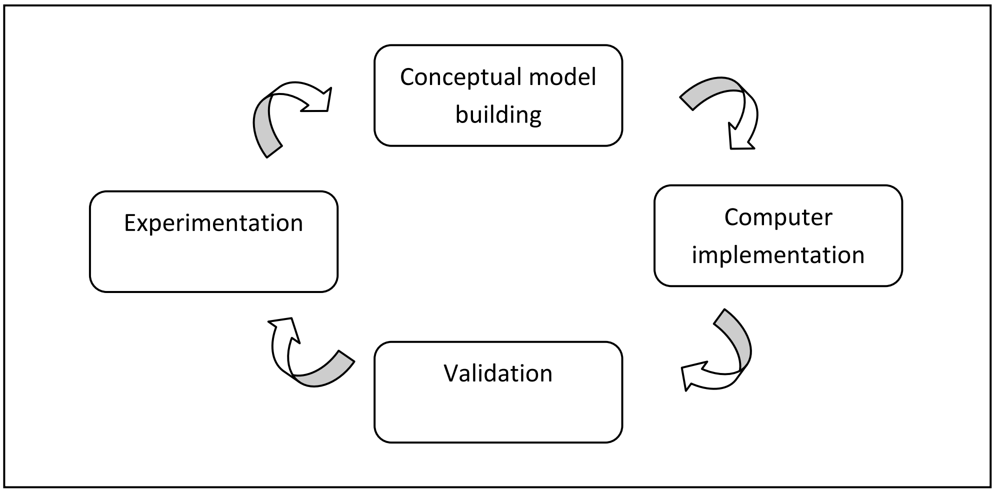
Treatment of random (stochastic) behaviour is a key characteristic of the DES approach. Random effects may influence arrival rates, the time taken for a process or activity, or other phenomena such as process or machine breakdowns. These characteristics can easily be built into the logic of the model. An overall approach to building a DES model is described in Figure 16.

2.4.5 Agent Based Modelling

This section will describe Agent Based Modelling in relation to the supply chain and also the ABM approach.

2.4.5.1 Agent Based Modelling in the supply chain

The use of agents in the design of simulation models has its origins in complexity science (Phelan, 2001) and game theory (Axelrod, 1997). Agent based modelling lacks a consistent set of definitions for key concepts such as what an agent actually is, as well as a philosophy of application (Borshchev and Fillipov, 2004 ; Schieritz and Milling, 2003). This may reflect the relative immaturity of this field when compared with SD and DES. A key feature of the agent based modelling approach is the concept of emergence. What this means is that a group of agents are defined which follow a set of rules. In their interaction, whilst following these rules the behaviour of the system emerges (Phelan, 2001). Another feature of this method is that the structure of the system, rather than being set in advance, is also a function of the interaction of the individual agents. Agent based modelling allows the modeller to give the individual agents rules for its interaction with other agents.



(Reprinted from Computer Simulation in Management Science, by Pidd , Copyright (2004), with permission from Wiley).

Figure 16 DES modelling approach (Pidd, 2004a)

This means that this approach can be used to model the behaviour of individual entities in systems. These features of agent based modelling are exciting interest among researchers and ABM is starting to be used to investigate the supply chain. Particular interest seems to be in areas where the behaviour of individual system entities in relation to each other is a significant feature, for example when studying the dynamics of supply chain competition (Akkermans, 2001 ; Allwood and Lee, 2005). The papers from the literature search which cited Agent Based Modelling as an approach dealt with a wide range of supply chain themes:

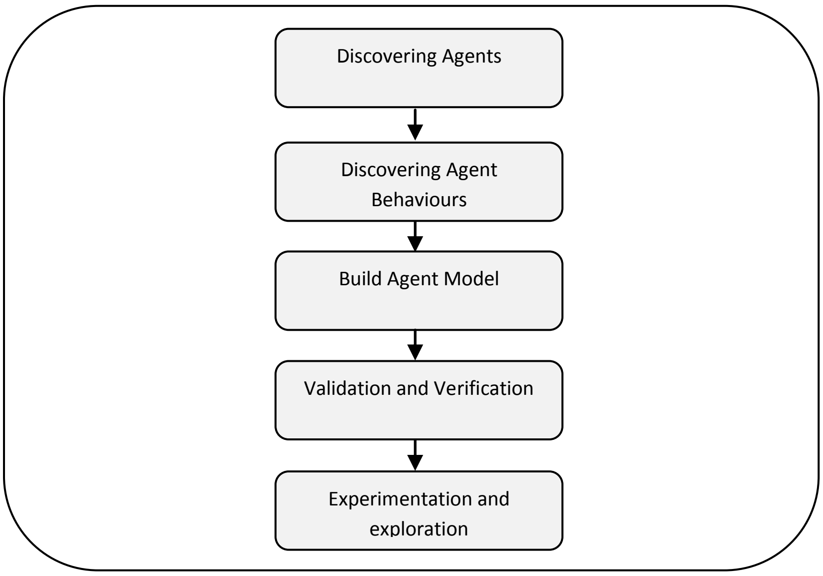
- Information sharing (Chan and Chan, 2008 ; Min and Bjonnsson, 2008)
- Human behaviour and trust (Tykhonov et al., 2008)
- Supply chain optimisation (Hassini, 2008)
- Distributed supply chain (de Santa-Eulalia et al., 2008)
- Collective customer collaboration (Elofson and Robinson, 2007)
- Cooperation (Albino et al., 2007)
- E-manufacturing optimisation (Zhang et al., 2006)
- Human behaviour on bullwhip effect (Nienhaus et al., 2006)
- Supply chain dynamics (Allwood and Lee, 2005)

- Modelling control elements (Van Der Zee and Van Der Vorst, 2005)
- Market dynamics (Kaihara, 2001)

2.4.5.2 Agent Based Modelling – the approach

Agent Based Modelling and Simulation is a younger discipline than System Dynamics and the methodology is not as fully developed. A description of the overall modelling approach is given by North and Macal (2007). The model building process can be summarised as consisting of the following five stages (Figure 17). The focus of ABM is the individual agent. In this section, key characteristics of the agent based approach will be described, focusing on those aspects of the approach which differ from the other two approaches.

Central to the agent based philosophy is the agent itself. The approach involves starting by identifying the decision makers in a system. As North and Macal (2007) state, "*agents are the decision making components in complex adaptive systems*". The use of the word 'component' is important, since this means agents are not just human beings, but can also be firms, households, countries i.e. anything that represents the decision making entity in the system. Thus deciding which agents to use as the building blocks for the model is a key aspect of the approach.



(Reprinted from Managing Business Complexity, by Michael North and Charles Macal, Copyright (2007), with permission from Oxford University Press).

Figure 17 The agent based modelling approach (North and Macal, 2007)

Having identified the agents in the system, the next step is to model their behaviour. In the case of human agents, it is important to understand the decision making processes they follow. North and Macal (2007) describe this process of surfacing the decision making process as "the knowledge engineering interview". This is a structured way of eliciting the decision process from interviewing an individual. These decision making processes must then be captured in the form of an agent state diagram. Agent state diagrams describe the various states that an agent can be in and the transition linkages between those states. The agent state diagram can be software independent and thus the building of the model can then take place in a variety of ways from raw coding, spreadsheets or more dedicated agent based software packages.

One key concept within ABM is emergence. Emergence is the phenomenon that the behaviour of the system emerges as a consequence of the lower level behaviour of the individual agents. The agents themselves may be following simple rules, but what emerges at a system level is a characteristic at a system level. An example of this might be the flocking of birds. The individual birds may be following a simple heuristic for direction of flight and proximity to other birds, but what emerges is a system known as a flock which itself has structure and behaviour. This notion of emergence can be seen as philosophically 'bottom up', rather than the 'top down' view of SD which believes that structure drives the dynamics of systems and that structure can be discovered top down. The ideas of emergence perhaps have their origins in system science (Bertalanffy, 1971).

2.4.6 Comparison literature

There is a small body of literature comparing these three main approaches. These comparisons are not limited to the supply chain domain, although some of them indeed do focus in that area. Given that ABM has more recently emerged, it is perhaps unsurprising that there is more literature comparing SD and DES than comparing either SD or DES with ABM. There are a few authors who compare SD and ABM, but very few who compare DES and ABM. The author has only found two articles comparing all three approaches. A recurring theme throughout the comparison literature is that modellers tend to use the approach with which they are most familiar rather than selecting the approach most suited to the problem itself. Modellers can be attached to a particular approach due to personal preference (Brailsford and Hilton, 2004) or familiarisation and early association (Lorenz, 2006 ; Morecroft and Robinson, 2005). There can be intellectual and institutional divisions due to each approach having its own academic community, adherents and conferences (Lane, 2000 ; Siebers et al., 2010 ; Sweetser, 1999). In the worst case, Lane (2000) describes the consequence of this as:

"Conferences not attended, references not cited, papers not read and – crucially – research problems are not illuminated using both sets of ideas."

Despite this, some authors have proposed a more respectful approach to dialogue, looking for areas of common ground but respecting the differences of the other approach; this approach is described by Lane (2000) as Mode 3 discourse. This more collaborative approach is also supported by Morecroft and Robinson (2005) who propose collaboration between the SD and DES communities and Van Der Zee and Van Der Vorst (2005) who call for multi-method and integrative approaches.

2.4.6.1 Comparing SD with DES

Lane (2000) provides a thorough comparison of SD and DES from a number of different perspectives. He describes three modes of discourse between the two approaches; Mode 1 he describes as focusing on the differences between the approaches, Mode 2 pretends they are both the same, and Mode 3 which focuses on building on the common ground whilst respectfully recognising the differences. He argues strongly for Mode 3 discourse. In terms of the domain of application he proposes a three dimensional model including separate parameters for organisational, dynamic and detail complexity. Detail complexity arises from the multiple variables and attributes; dynamic complexity is concerned with the interaction of variables resulting in non-linear behaviour; organisational complexity occurs due to multiple 'world views' and the competition between different interest groups. He positions SD and DES on this three dimensional matrix as shown in Figure 18.

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Figure 18 Mapping SD and DES against the complexity of the system being modelled (Lane, 2000)

A summary of the different attributes of the two techniques from his analysis is provided in Table 3. One key limitation of this study is that it mainly describes the characteristics of the current application of the two techniques. Thus it is not truly a comparison in the sense of comparing the two approaches when used to analyse the same problem. To illustrate his comparison he contrasts the use of both SD and DES to model the same problem domain i.e. Accident and Emergency departments in two hospitals. However they are two different projects and thus the comparison is limited in this respect. A second criticism of this comparison is that the author introduces many terms without providing a thorough definition of what those terms mean. Thus from a practitioner perspective, it would be very difficult to judge, for example, the relative complexity of a given system against the parameters shown in Figure 18.

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Table 3 Comparing SD and DES (Lane, 2000)

Brailsford and Hilton (2004) continue in the spirit of the Mode 3 discourse proposed by David Lane. They describe the application of the two techniques in the healthcare setting; SD is used to model cardiac surgery and DES is used to model the spread of AIDS. This is interesting because in this case both models have been built by academics in the same department thus they cannot necessarily be accused of being wedded to one of the approaches and thus are more likely to be objective in their comparison. The results of their comparison are shown in (Reproduced with permission of the author)

Table 4. This study still suffers from two potential weaknesses similar to the previous example. The terms used are still not precisely defined, for example, what does 'large' and 'small' mean what is a 'long' or a 'short' timescale? Again, the authors seem to be reporting what has been done rather than rigorously critiquing the approaches. For example, there is evidence that SD is used for policy making and DES is used for more tactical problems, but there is little justification or explanation as to why. There is limited exploration as to the use of SD to approach more detailed problem types. Some of the claims appear to be assertions not backed by sufficient evidence. Again the modelling is done separately; we do not know what would have happened or what the authors would have learned by applying the different techniques to the same problem. What if SD had been used to model the spread of AIDS next to the DES approach? Surely this would provide more insights into the relative strengths and weaknesses of the two approaches?

	System Dynamics	**Discrete Event Simulation**
Scope	Strategic	Operational, tactical
Importance of variability	Low	High
Importance of tracking individuals	Low	High
Number of entities	Large	Small
Control	Rates (flows)	Holding (queues)
Relative timescale	Long	Short
Purpose	Policy making: gaining understanding	Decisions: optimisation, prediction and comparison.

(Reproduced with permission of the author)

Table 4 Comparing SD and DES (Brailsford and Hilton, 2004)

Morecroft and Robinson (2005) provide a true Mode 3 comparison of the two techniques. They review previous comparisons and state *"A shortcoming of all of these comparisons is that they are written from the perspective of either a specialist in SD or DES. A comparison that brings together the world views of SD and DES modellers does not appear to exist."* Morecroft is an SD proponent and Robinson a DES proponent. They proceed to model the same problem i.e. a fishery problem and use the two techniques separately to draw insights as to the strengths and weaknesses of the techniques. The conclusions of their study is summarised in Table 5. However, there are some problems and limitations in this comparison. Although the same problem is modelled the approach used and the way the system is modelled is significantly different by the two practitioners. Now this could be justified by arguing that this is to do with the different modelling paradigms and the way the different techniques are used.

System Dynamics	Discrete Event Simulation
Representation	
System represented as stocks and flows	System represented as queues and activities (processes)
Feedback explicit	Feedback implicit
Many relationships are non-linear	Many relationships are linear
No randomness (subsumed into delays)	Randomness explicitly modelled
Growth/decay modelled as exponential or s-shaped	Growth/decay represented as random often with discrete steps e.g. a cut-off point
Standard recurring modelling structures exist e.g. asset stock adjustment process	Standard modelling structures generally do not exist
Interpretation	
Feedback and delays are vital to system performance	Feedback and delay are not emphasised
Randomness is not normally important to system performance	Randomness is a vital element of system performance
Structure leads to system behaviour	Randomness leads to system behaviour

(Reproduced with permission of the authors)

Table 5 Comparing SD and DES (Morecroft and Robinson, 2005)

However, because the modelling is conceptualised differently by the two modellers, it is difficult to perceive the precise points of departure between the two techniques. In other words, is the observed difference to do with the differences in the way the system has been modelled i.e. the approach to modelling rather than the inherent characteristics of the modelling approach? Two specific examples of this will be given to illustrate this point because this is an important argument in the context of what will follow. Firstly, at the very beginning of the modelling process the modellers must model the way that the fish in the sea are replenished. The system dynamics approach to modelling this includes a feedback function based on the volume of fish in the sea. Thus the regeneration rate depends on the number of fish already in the sea, based on a look up table. In the case of the DES model, the regeneration rate is modelled as a proportion of the fish in the sea multiplied by a factor with a random normal distribution. There appears to be no reason why the function describing the replenishment rate could not be the same for both models and represented by both models. Would this not be a more insightful comparison? Secondly, after the model is built in the steady state, the authors introduce some factors which will disturb the equilibrium of the model. For example, in the SD model the factor 'pressure to increase fleet size' is introduced to explore the impact of increasing the size of the fishing fleet in response to the size of the catch. This leads to the unintended consequences of a collapse in the fish population due to over fishing. On the other hand the DES modeller introduces a random element to the size of the catch. It is unclear why the authors did not choose to introduce the same factors and model them in both approaches. The authors argue that both approaches potentially illuminate the puzzling dynamics of fisheries, the SD model showing collapse which has been observed in the Pacific sardine catch, the DES showing oscillation in fish population observed in the North Sea herring catch. They argue that the DES model also leads to the collapse of the fish population, although this is shown as occurring after 5,000 years in the DES model as compared with 40 years in the SD model, this difference is not explained!

This comparison, then, still falls short of a true 'back-to-back' model of the same system in the same way. A thorough comparison requires that the same system and as far as possible the same factors and attributes be modelled in the different approaches. This will then serve to highlight when and where the differences occur.

Some authors explore the extent to which system dynamics can embody or model discrete characteristics or attributes. Ozgun and Barlas (2009) model a queuing system with two servers using both SD and DES. They demonstrate that in a simple queuing situation, SD can be used to develop approximate solutions to problems. However, this is a simple problem and even in this case they recognise that *"Clearly, a more thorough and comprehensive study is needed to arrive at more concrete conclusions on the potential role of continuous simulation in queuing systems."* This is an interesting and unusual piece of work exploring where the limits of usefulness of the techniques may lie. However, its limitations are the simplicity of the problem chosen. The limitations of SD in terms of modelling more discrete problem types needs further investigation. Coyle (1985) demonstrates how a SD model can incorporate a discrete event, such as a machine breakdown. He shows how such an event can be programmed into the code of the SD program using the appropriate logic. He argues that the inability for continuous models to incorporate discrete events is *"largely illusory".*

Other researchers (Tako and Robinson, 2008) used an approach to compare and contrast SD and DES. They were more focused on comparing the model building process and model use of the two techniques. They used a single case for their empirical work for both studies. There are two exercises, one with a group of experienced modellers and one with a group of MBA students. The exercise with the experienced modellers focuses on studying the model building process, and the exercise with the MBA students focuses on model use. They use VPA (Verbal Protocol Analysis) to analyse the process of modelling. The two exercises take 60-90 minutes. After considering a number of options, they choose a Case Study of the UK Prison Population. They admit "*The system presented in the current case is a rather simple view of the criminal justice system. Obviously, additional factors that affect the system performance and also more complex relationships can be identified such as the social effects on the number of crimes committed or the number of deaths in prison, etc. However, for the purposes of keeping the case and the associated models simple, these factors were left out of the conceptual model provided, focusing mainly on the key aspects of the problem."* (p. 87). They also admit that certain of their hypotheses cannot be tested because they only model one problem and thus is restricted to conclusions around that one problem type. Thus they identify two non-testable hypotheses: *Hypothesis 2.2: DES models problems at tactical/operational level, while SD at a strategic level. Hypothesis 2.9: DES models represent mainly material flows. Information flows can be incorporated but these are not obvious. In SD modelling both material and information flows are equally represented*. In terms of model use, and of interest in the context of my own research, they identify another hypothesis related to strategic thinking: *Hypothesis 3.5: SD models can aid strategic thinking to a higher extent.* They explore this hypothesis using the following questions: *"To what extent do you feel using the prison simulation model helped you think strategically about the prison population problem? and "In what other contexts might a similar model be used? Please name a few. Why is it relevant?"* In their results discussion they observe that there are no significant differences in the responses from the MBA students on these questions and thus reject hypothesis 3.5.

2.4.6.2 Comparing SD with ABM

In a similar vein to the comparison of SD and DES, the SD and ABM communities have traditionally not worked together and have developed separately (Van Der Zee and Van Der Vorst, 2005). Schieritz and Milling (2003) compare and contrast the two approaches by using a 'forest and trees' analogy to describe the difference in philosophy between ABM, which focuses on individual behaviour, and SD which focuses more on structure and feedback. A summary of their findings is in Table 5. They propose that perhaps a way forward is to integrate the methods to benefit from their complementary characteristics. The limitation of their study is that it is more a review of what has gone on than based on any real comparative modelling of real problems. Van Der Zee and Van Der Vorst (2005) point out that the two methods use different approaches. In an agent based model, the focus is on the agent. The agents' behaviours and relationships are defined, they then interact and the product of their interaction may be some system level property. This system level property comes about through a process called 'emergence', and this is linked to the wider field of complexity theory. In SD, on the other hand, the system is defined 'top down'. The unit of analysis is the feedback loop and the behaviour of the system is determined by the structure and feedback loops. They propose that further insights will be achieved through comparison models of the same problem, for example, developing an agent-based model of SD classics such as the Bull Whip effect.

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Table 6 Comparing SD and ABM (Schieritz and Milling, 2003)

In an interesting comparison, Parunak (1998) uses both ABM and SD to model an automotive supply chain. He proposes two key differences between ABM and SD, namely; the way critical relationships between entities are modelled and, the level at which they focus their attention. In terms of critical relationships, he describes SD as modelling those through equations. The equations lead to observables which are measurable characteristics of interest. On the other hand, ABM defines behaviours associated with individuals, when the individuals interact this leads to relationships. Thus in SD relationships are pre-defined, whereas in ABM the relationships are an outcome of the behaviour of the individuals. In terms of the level of interest, SD tends to focus on system level observables, whereas ABM focuses more on observables at the level of the individual. Interestingly, the author proposes a number of advantages for ABM over SD in their experience, which are:

- *ABMs are easier to construct*
- *ABMs make it easier to distinguish physical space from interaction space*
- *ABMs offer an additional level of validation*
- *ABMs support more direct experimentation*
- *ABMs are easier to translate back into practice*

He concludes by summarising where he thinks the two methods are most appropriate:

"ABM is most appropriate for domains characterised by a high degree of localisation and distribution and dominated by discrete decisions. EBM (Equation Based Modelling) is most naturally applied to systems that can be modelled centrally, and in which the dynamics are dominated by physical laws rather than information processing"(Parunak, 1998).

Along with Van Der Zee and Van Der Vorst (2005), he proposes that further valuable insights will be obtained through back-to-back modelling of simple systems where the causes of divergence of the two modelling approaches will be more easy to trace.

Rahmandad and Sterman (2008) compare and contrast ABM and SD in the study of disease propagation. They study the transmission of disease through a series of different network types which characterise the way that individuals may interact with each other. Heterogeneity of individual contact rates are dealt with differently by the two methods. For SD, this is achieved through developing different compartments to represent this. In ABM, properties can be associated with individuals. The authors report that for many cases SD provides an accurate and more efficient approach to modelling disease propagation. Where ABM has the advantage is where there are small populations of highly heterogeneous entities in particular cluster patterns. However, again it is not clear that the advantages of the accuracy of ABM override the practical limitations of model development. They also point out that where the boundary of the model is drawn may be more important than the level of detail shown within the model. These conclusions are interesting because they introduce the practical considerations of modelling. One method may indeed be more accurate or faithful to the system being modelled, but that additional accuracy will come at a price. It may be that the accuracy of the SD model is sufficient for the objective of the modeller and moreover this can be achieved potentially at lower cost and with a lower requirement for data.

2.4.6.3 Comparing DES with ABM

There is very little literature comparing DES and ABM. Siebers and Aickelin (2011) describe the modelling of a retail situation in which consumers are shopping in a department store. The authors claim that whilst DES is useful for modelling process type situations such as manufacturing it is more limited in the more service oriented environments. In particular, they point to the need to model shopper behaviours such as browsing, queuing, seeking and receiving help, buying and paying. They propose that DES can be used to model the workflow aspects of the system and ABM to model the proactive behavioural characteristics. They conclude that the extra effort of modelling shoppers as agents is worth it i.e. "*the extra work of adding proactivity to the simulation model is worth the effort, i.e. it does produce a significant improvement of the* *simulation output accuracy that justifies the extra costs for data collection and modelling*" (Siebers and Aickelin, 2011).

At the 2010 Simulation Workshop of the UK Operational Research Society, which this author attended, a panel discussion on this topic was held with experts from both DES and ABM (Siebers et al., 2010). The discussion was wide ranging, including why there has not been much dialogue between the two groups in the past, differences in the approaches and ideas for the way forward. In summary the conclusions of this panel discussion were:

- Selection of modelling approach should be based on the needs of the problem being modelled
- People tend to use the approach they are most familiar with, then switch only if this turns out to be inadequate to the challenge
- OR is more concerned with problem solving than pure science, thus the overlap with ABM is more likely to be in this area
- One key reason for the lack of uptake of ABM is the lack of easy-to-use 'drag-and-drop' software packages as are available with DES
- Model development time may prevent the wider adoption of ABM
- The validation approach is more clearly established for DES than for ABM
- Perhaps a framework to assist modellers with the choice of approach would be useful, this should be the focus of further research
- There are no established frameworks or methodologies to guide researchers through the ABM process

Despite these concerns and limitations, there is clearly growing awareness of ABM amongst the DES community. There is recognition that perhaps some problems are not best represented or modelled using DES and that perhaps ABM offers an interesting area for collaboration.

2.4.6.4 Comparing SD, DES and ABM

Lorenz (2006) proposes a framework for the selection of the methodology most suited to a particular problem type. They suggest that the methodology chosen should best match the purpose i.e. "why are we modelling?" and the object i.e. "what are we modelling?" They review the comparison literature and identify the key characteristics of the three approaches. In terms of what they describe as 'purpose-oriented modelling' they propose, for example, that since feedback is a fundamental aspect of SD modelling, "if the feedback of a system (and it is argued that there is feedback everywhere) has only a minor effect on the problem to explain then of course the importance of this feedback should not be overstated by using System Dynamics methodology". However, this recommendation is problematic, since the authors do not explain how such a judgement is to be made. Later they state "the discussion of long-term strategic policies favors SD" although no evidence is provided to support this assertion other than reference to custom and practice. The overall conclusion of this paper is shown in

Figure 19. However, there are significant concerns about this framework because it appears to simply restate custom and practice rather than provide a rigorous, evidence based proposal. There are no models built to compare the approaches, for example. The risk is that the framework proposed simply reinforces the current received wisdom. An example of this concerns the level of problems addressed. The authors suggest that SD and ABM should be focused on strategic problems and DES on logistic and quantitative problems, but no justification is given other than reference to what others have traditionally done. Another concern of this framework is that terms are not adequately defined. So the authors propose criteria to be used to aid selection of an approach, but these criteria are not themselves rigorously defined. The authors do acknowledge the limitations in their findings when they state "..these criteria form a first step towards an orientation framework in multi-paradigm modelling. Further research is necessary .. in order to come closer to this declared goal."

In a more practical vein, Borshchev and Fillipov (2004) describe their multi-paradigm modelling software Anylogic (www.xjtek.com). This software allows users to build models incorporating all three of the modelling paradigms either separately or in a hybrid model. They provide suggest a framework to aid the selection of approach in Figure 20. Again, though from a practitioner viewpoint it is difficult to see how this diagram would assist in practice other than to give vague guidelines. The reasons for the position of the techniques are not explored or explained in any detail. Thus one must conclude that although potentially useful as a guide, this diagram does not provide adequate guidance for the practitioner.

2.4.6.5 Conclusions from comparison literature

The review questions which this review set out to answer were stated in section 2.3.1 i.e.

1. What are the main simulation approaches in the supply chain domain?
2. What are the relative strengths and weaknesses of these approaches?
3. Is there any guidance as to when to choose a particular approach?

Question 1 has been satisfactorily answered as SD, DES and ABM. In terms of questions 2 and 3 the review of the comparison literature has identified a number of issues and concerns which will now be outlined. Several of the comparisons introduce concepts and terms without providing an adequate definition of what the term means or how the term should be interpreted, the comparisons lack conceptual rigour. This means that the comparisons are of limited benefit to practitioners because it is very difficult or impossible to interpret the terms in order to apply them in a real world situation. Thus the comparisons as they stand fall well short of providing any guidance to practitioners as to which approach to use in a given situation.

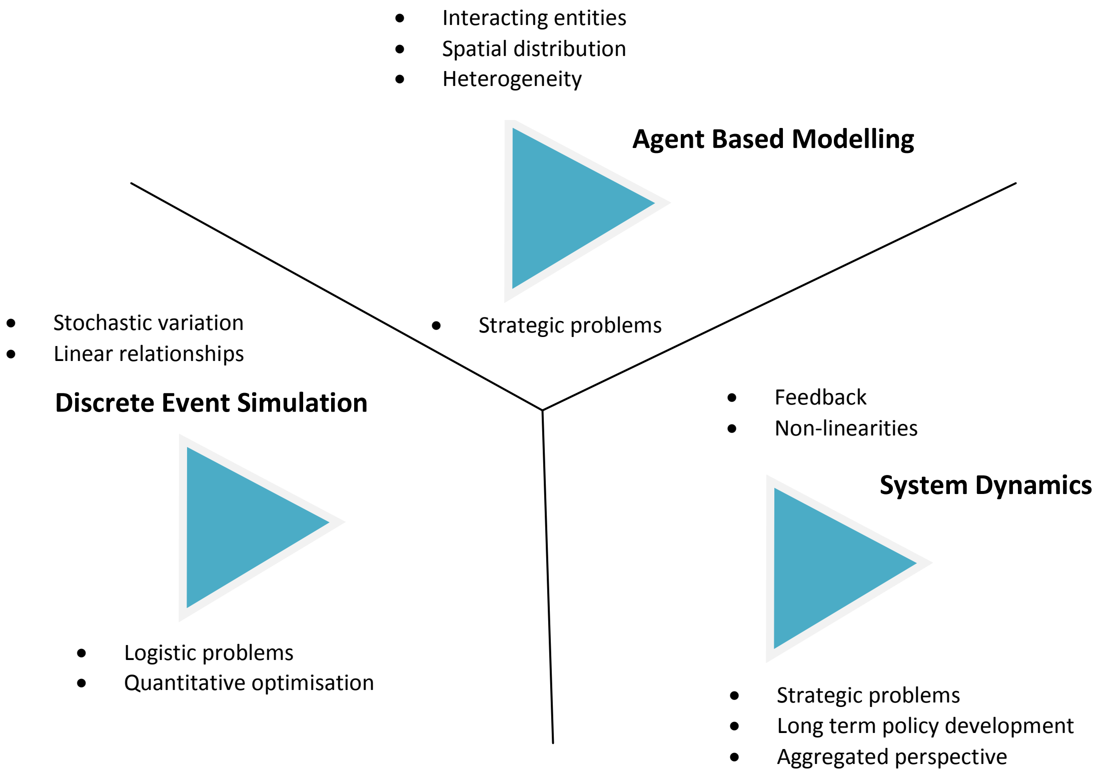

Figure 19 Comparing SD, DES and ABM (Lorenz, 2006) (reproduced with permission of the author)

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Figure 20 Application of SD, DES and ABM (Borshchev and Fillipov, 2004)

Many of the comparisons restate the received wisdom of previous practice. Given the lack of rigour in the terms and concepts used, these are repeated and built upon in later examples. Unfortunately, this means that, for example SD is recommended by Lorenz (2006) as being suitable for strategic problems with no supporting evidence other than that other authors have said this in the past. Thus the current comparison literature runs the risk of relying on custom and practice rather than any rigorous analysis or foundation.

Few of the comparisons are based on practical applications of the techniques to a real life situation. Even fewer are 'back-to-back' comparisons of modelling the same problem or system using a different approach. Even those that do, do not model the system in the same way but allow significant variation in the key concepts and parameters modelled (Morecroft and Robinson, 2005). This serves to confuse the comparison because we do not know whether the differences observed are to do with the inherent aspects of the modelling approach or to do with differences in way the problem has been modelled and conceptualised. Several authors, (Van Der Zee and Van Der Vorst, 2005 ; Parunak, 1998 ; Ozgun and Barlas, 2009) suggest that valuable insights would be obtained by back-to-back modelling of simple systems, and yet very few, if any such models have been built. This provides a real gap in the current research for a contribution to be made to understanding the true nature of some of these differences and providing useful guidance to practitioners as to how to choose which approach. Thus in relation to the review questions, it must be stated that the current understanding of the relative strengths and weaknesses is partial, since it lacks conceptual rigour and testing through application. The guidance to selecting the particular approach is incomplete and hard to follow in its current form. In order to focus the research, the received wisdom and key claims from the literature are summarised in the form of Table 7.

Aspect	**System Dynamics**	**Discrete Event Simulation**	**Agent Based Modelling**
Problem Level	Strategic and Policy	Tactical and Operational	Strategic, Tactical and Operational
Representation			
Model Elements	Stocks, flows and causal loop diagrams	Processes, entities, resources	Agents, state charts
Number and type of entities	Large, homogenous	Small, can be homogenous or heterogeneous	Any number, maximum level of heterogeneity

Feedback	Explicit, shown on causal loops, important	Hidden, not important	Function of the behaviour of the agent
Decisions	Modelled as causal loop diagrams	Hidden in the code processes and resources	Modelled in agent state charts
Space	Not modelled	Can be modelled	Often modelled and can be important
Behaviours such as proactivity, memory, adaptiveness	Not modelled	Not modelled	Modelled within Agent statechart
Randomness	No randomness (hidden in delays)	Explicitly modelled and important	Can be built into Agent behaviour
Interpretation	Structure determines dynamic behaviour	Randomness creates behaviour of entities in process	Relationships and system level behaviour emerges as consequence of entity behaviour
Purpose	Understanding	Problem solving	Exploration

Table 7 Summary of comparison literature

2.5 Combined approaches to modelling the supply chain: literature on hybrid models

The review of the comparison literature has shown that authors see differences in the relative strengths and weaknesses of the three approaches. It is perhaps unsurprising then that some researchers have been exploring the use of hybrid models so as to benefit, as they see it, from these differences. Most progress seems to have been reported in the area of combining SD and DES which are the more mature of the methods. Given the received wisdom that SD is more useful for modelling strategic problems and DES for detailed operational problems, several authors have developed hybrid models which use the techniques in that way. For example, two researchers in the Operations and Information Management Group (OIM) at Aston University, Peckett (1979) and Love (1980) investigated the spares provisioning operation at Compair Industrial Limited. Peckett (1979) developed a simulation model for the overall system. He identified the following criteria as requirements for the model:

1. *To consider several levels of a multi-echelon system, with independent policies at each level.*
2. *To deal with the dynamic interactions of the various levels, including the effects of and upon the manufacturing lead time.*

3. *To examine specific stock control policies applied to a range of components.*
4. *To examine specific production control policies as applied to a range of components.*
5. *To run for an appreciable period of simulated time (eight years minimum) without excessive computer capacity.*

He identifies that industrial dynamics (ID) is capable of meeting requirements 1,2 and 5 but that it cannot meet requirements 3 and 4 *"being incapable of operating at the detailed part level".* His solution to this is to build a composite model, where the details of the spares stock control system are modelled in more detail. In this case, both the ID model and the more detailed stock control model are written in ICL extended Fortran. The interface between the high level ID model and the more detailed stock control model required significant changes to the ID model for two reasons. Firstly the time increments of the models were originally different and needed to be made consistent. Secondly, the inputs and outputs between the two parts of the model required the use of consistent units of measure. Thus additional work was required to enable the two parts of the model to interface. The author comments on this later in the thesis where he states: *"The composite model developed by the author overcomes the above problem by operating at a semi detailed level only in those areas relevant to the case being studied. Although slightly more expensive in programming and execution requirements than a pure Industrial Dynamics model, the technique is considerably more economical than the more detailed simulation techniques which would otherwise be required."* This introduces the idea that the level of detail in the model should be that which is required and appropriate to the investigation. Of course, when this work was done around 1980, computer speeds were slower than they are now, and the resource requirements to model a system in detail, particularly writing in computer code, would have been more demanding than is the case today.

Love (1980) extended the research in the same company to build a model of the spares manufacturing area. He also concludes that ID is limited in its approach to the more detailed design aspects of systems concluding that *"the industrial dynamics literature can offer no guidance in the specification of the detail design features."* He identifies that although the ID model could indicate the desirability of certain operational characteristics such as short lead times and rapid capacity response, it could not be used to identify how these could be achieved in the company's operations. His approach to this challenge, rather than building a detailed model to interface to the ID model, was to build a separate discrete event model of the spares manufacturing system. The model is built using Extended Control and Simulation Language (ECSL). This model is then used to perform 'what-if' scenarios to determine the design characteristics of the manufacturing unit including plant and physical layout, manning levels and skill patterns. He suggests that the approach taken by Peckett (1979) is preferred where possible because it retains the dynamic interaction between system elements, but says *"is practicable only if the discrete model is very efficient."* Both authors then have concluded that ID did not permit them to investigate the phenomena of interest in sufficient detail. They use two different approaches to tackle this. Peckett (1979) creates a composite model, written in Fortran, which is a high level ID model, with a more detailed model of one area, namely the spares control function. On the other hand, Love (1980) builds a separate detailed model of the spares manufacturing facility in ECSL which is used to model key parameters within the ID model.

Venkateswaran and Son * (2005) develop a hybrid model of a manufacturing enterprise in which the enterprise level is modelled in SD whilst the shop floor is modelled in DES. The authors argue that *"The DES model captures the detailed operational procedures of the shop"* whilst *"SD presents a natural way to model the dynamics associated with the production rates in the system".* The two layers are integrated with the High Level Architecture's (HLA) RunTime Infrastructure (RTI). Rabelo et al. (2003) use a similar approach integrating an SD model for the enterprise system and a number of DES models for selected areas to model in more detail. The two models are integrated by using a communications facilitator database. Brailsford et al. (2010) propose that this combination of SD and DES represents the 'holy grail' of simulation modelling. They provide two examples from healthcare where SD and DES have been used together to model a system. They argue that true combination is still a long way off and may even not be possible. What is less clear in all these examples is why the SD/DES hybrid is seen to be superior to using one method i.e. either SD, DES or ABM. Brailsford et al. (2010) state *"Could we have done either of the case studies in either SD or DES alone? The answer is probably yes, but it would have been a tortuous process: a case of hammering in a screw."* However, they do not explain why this is the case. They do suggest that DES could probably have been used for the whole model, but at considerable cost to runtimes. SD on the other hand could probably not have been used to model the more detailed aspects of the systems, they argue.

What is less clear from these comparisons is whether a hybrid SD/DES model is better than a single solution i.e. a complete DES or ABM model. Whilst accepting that SD may have limitations at the more detailed end of the spectrum, the authors do not investigate whether it would be possible to develop full system models using DES or ABM. Hybrid models come at an additional cost to the modeller. Firstly, the modeller must be familiar and competent in two modelling approaches. Secondly, the modeller must build an interface to allow the two different models to exchange data. There is some evidence that certain authors are beginning to put forward an argument for a single approach. An example of this is an enterprise level simulation model known as the whole business simulator (WBS) developed by the Aston OIM Group. The purpose of the WBS was to allow a holistic model of a business to be developed in which decisions at all levels could be evaluated. In terms of the requirements of such a model, it was stated that: *"The modelling system must not constrain the range of decisions that can be tested by the user but should be able to cope with any level from strategic to operational".* (Barton et al., 2001). In his work on modelling the impact of design decisions, Barton (1997) had earlier rejected the use of a hybrid system dynamics and discrete event approach, suggesting that the choice was between SD with a shorter build and execution time and DES with a more valid model. He further suggested that as computer processing power continues to decrease over time, DES will be a better choice due to its improved validity. The details of the WBS are described in Love and Barton (1996) and Barton et al. (1992). The WBS attempted to represent the entire business including all aspects of order processing, MRP, factory scheduling and importantly, modelling of the financial flows in the business. A key characteristic of the WBS was to use an object oriented approach to constructing the model. This meant that different components of the model could be developed separately and treated as software objects which could exchange information through interfaces. In this way, different elements of the model could be created to cover design, production engineering, accounting and the factory, for example.

Gunal and Pidd (2005) propose that for the effective development of policy in healthcare, a whole hospital model is required to represent the full complexity of the system. They propose that DES is a good candidate for developing such a model. They also point out that SD may have difficulties at the more detailed level and thus tends to be restricted to being applied at the policy level. Some authors have attempted to combine SD and ABM approaches. Akkermans (2001) develops an agent based model of the supply chain using the SD approach. Interestingly, he models the individual suppliers' decision making processes in SD using a standard model from Sterman (2000). He investigates how different supply strategies (short term and long term) affect the development of relationships between customers and suppliers. He explains that the existence of this accepted model of the supply chain was one key reason for his selection of SD as an approach. This shows that sometimes the pragmatic issue of reliability and familiarity will influence the choice of the approach. Even though this was an agent based model, the author did not choose an approach from the agent stable i.e. tools such as NetLogo, Repast or SWARM (SWARM, 2012 ; Netlogo, 2012 ; Repast, 2012) since he was more confident in an SD representation of the process. This work appears to contradict some other conclusions since in this case SD is being used to model the more detailed aspects of the system. Schieritz and GroBler (2003) extend this idea of using SD to model the agent decision making. In their research they model the supply chain system using a DES software package EM-Plant ® (eM-Plant, 2012) and use SD to model the individual agent behaviours and decision making processes.

2.5.1 Conclusions from the hybrid literature

The rationale for using hybrid approaches appears on the surface to be plausible. The different techniques have their strengths and weaknesses, therefore surely the best approach would be to use them in ways that make the best use of their strengths and avoid their weaknesses? However, there are some problems with this approach. There is some evidence of researchers being wedded to their own approach, for example Akkermans (2001) using SD to build an agent based model of the supply chain. Secondly, it is by no means clear that the strengths and weaknesses of the approaches have been identified in a rigorous manner and therefore the hybrid models may not be the best solution. Hybrid models involve additional costs to the model builder and thus it may be more efficient and effective to build the whole model using one of the three main approaches. The description of the SD/DES hybrid as the 'holy grail' of modelling by Brailsford et al. (2010) is somewhat presumptuous since it precludes that an agent based model is not a better solution. There is further work required to understand the true limits and capabilities of the different techniques before the full usefulness of hybrid modelling is to be understood.

2.6 Identification of the gap

The review of the literature has demonstrated that the comparison of the three main simulation approaches to date has been insufficient in a number of key ways. Firstly, comparisons lack conceptual rigour. What this means is that the concepts used to compare the approaches are themselves not sufficiently well defined. Examples of this are feedback, where SD is seen to be a more suitable approach for modelling. Authors do not explain how the degree of feedback in a particular problem or system can be determined, nor indeed why SD is a more suitable technique even if a high degree of feedback were deemed to be present. Another example is the level of the problem. SD is claimed to be more suitable for policy or strategic problems rather than operational problems. However these terms are not defined, nor are it clear why SD should be more suitable, nor conversely why discrete methods should be unsuitable.

There has not been an examination of the approaches from first principles to examine when and why they should be more or less suitable in solving different problem types. This is very important, since without this authors are often relying on received wisdom and custom and practice, rather than any rigorous comparison. A second key flaw in the current comparison literature is that the techniques have not been used to model the same problem in a 'back to back' manner. Even in the cases where authors have attempted to do this such as (Morecroft and Robinson, 2005) they have conceptualised and modelled the problem differently, thus making it impossible to truly compare the approaches. This lack of true comparative modelling serves to reinforce the transmission of received wisdom in the literature. Authors have suggested that more such comparative modelling of simple systems would provide more insights (Ozgun and Barlas, 2009).

A third and related problem concerns the hybrid literature. Hybrid modelling claims to provide a solution, building on the relative strengths and weaknesses of the techniques. Given the problems with the comparison literature, it cannot be assumed that a hybrid model is a better solution than a model built using a single approach. The hybrid model will quite possible be more costly to build due to the requirement on the modeller to learn two modelling approaches. The hybrid approach may be necessary, but a more precise definition of when it is likely to be useful is required. Although simulation is undoubtedly very useful and applicable in the supply chain domain, there is a lack of practical guidance for modellers as to which simulation approach they should choose to model a particular problem type. There is only one study which compares all three approaches and the authors concede that they have only started the process towards developing a framework to aid the selection of the appropriate technique. The need for such a framework was reinforced as a conclusion of a discussion on the relative merits of different simulation approaches at the OR Simulation Workshop in 2010 (Siebers et al., 2010).

2.6.1 The purpose of this research

In light of the aforementioned gap, the purpose of this research will be to provide a rigorous comparison of the three modelling approaches (SD, DES and ABM), supported with a theoretical analysis of the techniques from first principles. This will then be supported with a number of 'back to back' modelling case studies in the supply chain domain to provide empirical and practical exploration of these techniques when used to model the same problem. This will lead to more clarity of the relative strengths and weaknesses of the approaches and the development of a framework to guide practitioners in the selection of the most suitable approach given the problem they are facing. This will also provide more clarity on the limits of applicability of the techniques and when hybrid approaches are most likely to be useful.

The next chapter will set out the research questions that follow from this review, together with the overall philosophy, methodology, methods and techniques used in this research to address these research questions.

Chapter 3 Research methodology

This chapter will set out and justify the research philosophy and methods that have been employed in this work. Alternative approaches will also be reviewed and an explanation as to why these alternatives were not chosen will be provided.

3.1 Introduction

During the period of this research, which was approximately seven years, the author was employed as a management consultant in the field of operational improvement. There can be real benefits to being involved in the real life solving of problems for research purposes. Gummeson (2000) provides an interesting critique of what he calls 'traditional business research' in that it does not provide satisfactory access to the complexities of real world decision making. He argues that access to real data is critical to the ability to conduct meaningful research. This research has involved a mix of both a real world case and secondary 'academic' cases to provide the raw material for the analysis.

3.2 Research questions

The overarching research objective has been described in the introduction section. The literature review has shown that although some work has been done to compare or combine these approaches in various ways, more work needs to be done in order to draw useful conclusions and guidance for practitioners. In particular, the current analysis is not sufficiently rigorous and conceptual terms are not well defined. Secondly, little if any 'back-to-back' testing has been done where the practitioner builds the same model of a system using different techniques in order to compare and contrast their strengths and weaknesses. As a result of this, the following research questions have been identified in support of the research objective. These are:

1. What are the main methods of simulation used to improve supply chain performance?
2. What are the theoretical building blocks and assumptions that lie behind these techniques?
3. How does this illuminate the supply chain problem types for which certain techniques might be better suited than others?
4. What are the relative strengths and weaknesses of different techniques in simulating certain supply chain problem types?
5. What experiments can be done to test and compare alternative approaches?
6. How can these conclusions be used to generate recommendations for practitioners on how they should deploy these tools in achieving their supply chain objectives?

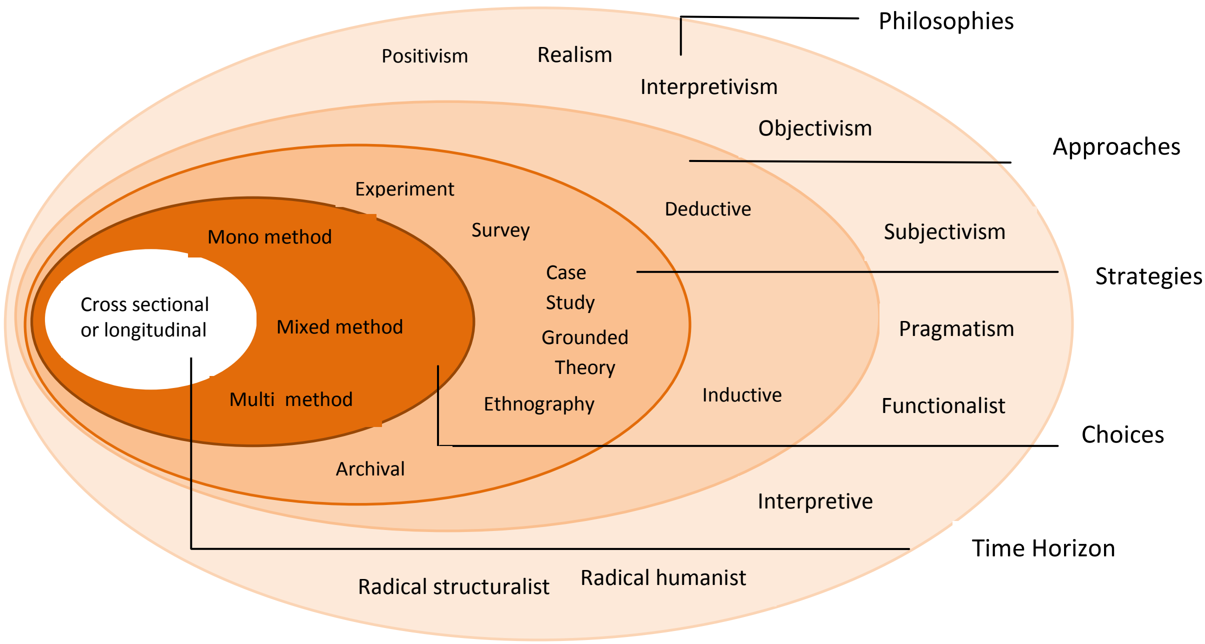
3.3 Research methodology

3.3.1 Requirements of a DBA versus a PhD

Before entering into a discussion on Research Philosophy, it is important to review the difference between the requirements of a DBA versus the traditional PhD. While the traditional PhD focuses on academic careers in teaching and research, the DBA is more practical and applied in nature, but commands equivalent status and rigour. The difference between the PhD and the DBA is neatly summarised in the AMBA, DBA Accreditation Criteria: "*The DBA is a Doctoral level, research-based qualification, designed to make a contribution to the enhancement of trans-disciplinary professional practice in management as well as contribution to knowledge via the application and development of theoretical frameworks, methods and techniques. It differs from a PhD, which focuses on the creation of new knowledge and theory within a relatively narrow discipline or field. A DBA therefore places more emphasis on the novel application of theory, rather than the creation and testing of theory*."

3.3.2 Research philosophy

Saunders et al. (2009) describe the choices relating to management research in the context of a model they call 'the research onion' see Figure 21 below. This is a useful model because it illustrates the layered aspect to these choices. They suggest that the choice of method is of secondary importance to the question of the research paradigm which is applied. They describe epistemology as "*what constitutes acceptable knowledge in a field of study*." They describe four philosophies of research namely positivism, realism, interpretivism and pragmatism. Positivism is closely linked to the scientific approach in which the researcher takes an objectivist, value free stance. The role of the researcher is as an observer of the system, reality is seen as observable and measurable. Positivism will more likely follow a deductive approach with hypothesis testing and experiments as the methods followed. Where data is collected it will be done in a scientific and objective manner. Realism relates to scientific enquiry, but realists believe that what is observed is experienced indirectly, i.e. through the senses. Thus there is not necessarily an objective reality. Healy and Perry (2000) describe realists as believing that "*there is a 'real' world to discover even though it is only imperfectly apprehensible*". Interpretivism is an approach which believes that rather than there being an objective reality, reality is socially constructed and that in order to understand what is going on the researcher must study the behaviour of social actors within the organisation. The interpretivist researcher must '*enter the world of our research subjects*' (Saunders et al., 2009).



(reproduced with permission from Research Methods for Business Students by Mark Saunders, Philip Lewis and Adrian Thornhill, Copyright 2007, Pearson Education Limited).

Figure 21 The research onion (Saunders et al., 2009)

Healy and Perry (2000) describe a similar paradigm which they call constructivism. In a similar way, the researcher is described as a '*passionate participant*' and in this approach reality is seen as being constructed by the interaction between the researcher and the subjects of her study. Finally, Saunders et al. (2009)describe pragmatism, where the priority is the research question, the researcher should adopt the philosophy most appropriate to the objective of the study and moreover that the choice of approach should not be seen as a competition between mutually exclusive stances. In relation to these different philosophies, this researcher has found that the positivist approach is unsuitable because certain aspects of the study are not purely objective, measurable phenomena. The modelling of complex systems inherently involves some degree of subjectivity and interaction with the system being modelled. In addition, some of the issues being explored are not of the 'hard' scientific kind but more soft behavioural issues such as the modelling of human decision making for example. On the other hand, the interpretivist and constructivist approaches were also found to be unsuitable because the researcher is trying to assist in developing objective decision making in at least two ways, firstly assisting supply chain professionals in choosing the most suitable modelling approach, and secondly in assisting them to model systems so as to make objective decisions about how to improve performance. The approach that seems to best fit the challenge of this research is the realism philosophy. In particular, as described by Beamon (1998), positivism deals with world one, objective and material things, constructivism deals with world two, socially constructed reality and realism with world three, i.e. abstract things which exist independently of any one person. In particular, and this informs the research method adopted by this researcher, realism can use the instrumental case as a vehicle to understand world three (Stake, 1995).

3.3.3 Research strategy and approach

Having explained that this researcher has operated within the 'realism' philosophy, the next question is the choice of overall approach. Referring to the research onion again (Figure 21), there are a spectrum of approaches from deductive to inductive. This researcher has broadly followed a hypothetico-deductive approach as described by Lee and Lings (2008). This is a process of conducting research which starts with the general formulation of a research question (see Figure 22). This is followed by step 2, where there is a search for ideas about that question. This could be through a review of the existing literature, or by a review of prior experience in that area. This process leads to the development of some hypotheses which are testable. The hypotheses themselves are statements about what should be observable in the data, and should be derived from theory. In relation to this research, this search for ideas is a good description of the process the author went through in the literature review phase. This phase led to some clarity around what previous authors have claimed in terms of these approaches to simulation, but also the limitations and weaknesses of these claims. The claims have been summarised in Table 7.

Figure 22 The hypothetico-deductive approach (Lee and Lings, 2008)

Step 3 of this process is described as Conceptual Development. This means moving from the ideas phase to the development of key concepts and propositions which can be tested. In the context of this research, a key aspect of this step is to address to some extent the weaknesses in the previous analysis. What this means for this research is returning to first principles and examining each of the three simulation approaches from a theoretical basis to see what this would tell us about their relative strengths and weaknesses. In the context of this research, the author has performed a theoretical analysis as described in Chapter 4. This provides a start in the process of concept development in that ideas identified in the literature review are refined in the light of further analysis to provide more clarity and focus for the work.

Concept development provides some key concepts and may provide some key hypotheses to be tested. The next phase requires the researcher to determine how to measure these concepts, known as operationalising them. The determination of the measurement process will then inform the next phase which is the collection of appropriate data. The data is then analysed and interpreted to determine whether the hypotheses have been supported. This brings the researcher back to the theory and provides an opportunity to make a contribution through either a change to existing theory or perhaps the development of new theory. The details of how concept development, measurement, data collection and analysis and the key conclusions reached will be the subject of subsequent chapters.

In order to clarify the role of the various activities in the research, the following table maps the key phases with the activities undertaken in this research.

Phase of Research	**Research Activity**	**Outputs**
Research Question	Research aim. At this stage the goal of the research is high level.	
Search for ideas	Literature Review (Chapter 2).	Refined research questions.
Conceptual Development	Theoretical analysis (Chapter 4).	Refined propositions.
Determine measurement	Multiple case study design (Chapter 3). Case study protocol. Embedded units of analysis. (Chapter 5).	
Data collection	Case studies (Chapter 5).	
Analysis	Within case reports (Chapter 5).	Results and findings.
Interpretation	Cross case analysis. Controlled deduction. (Chapter 6).	Refined results and findings.

Table 8 Mapping research activities to phases

3.3.4 Method selection: case studies

The choice of research strategy is linked to the overall research philosophy as well as the research objective and questions. In this research the researcher is attempting to understand the comparative strengths and weaknesses of different modelling methods when applied to solving supply chain problems. In this case, a mechanism is needed where the same problem can be modelled using multiple techniques and then conclusions drawn. The strategy felt to be most suitable for this purpose is the case study. Stake (1995) describes the use of the case study "*we will have a research question, a puzzlement, a need for general understanding, and feel that we may get insight into the question by studying a particular case... The case study here is instrumental to accomplishing something other than understanding this particular teacher, and we may call our inquiry instrumental case study*."

In this research, the author needed to develop supply chain problems to investigate particular research questions. The best approach to this was to identify suitable case studies which served as good exemplars of this problem type so as to allow investigation and conclusions to be drawn. According to Gummeson (2000), a key advantage of the case study method is that it is holistic and the situation can be viewed from a number of different standpoints. In this research the author was concerned also with investigating the process of model building as well as the results of the model building. Thus the case study is used both to represent the problem type but also as the vehicle for learning and understanding. This is because the cases are used to explore certain questions and in a sense the modelling of each case study using multiple modelling methods itself represents a form of experiment. Thus the overall strategy is a mixture of experimentation and case study research. There may be concerns over the extent to which results can be generalised from case studies, however several authors have argued that case studies can make a significant contribution to management research for example Norman as cited in Gummeson (2000) states "*If you have a good description or analytic language by means of which you can really grasp the interaction between various parts of the system and the important characteristics of the system, the possibility to generalize also from very few cases, or even one single case, may be reasonably good*"; and also Harrison (2005) who state "*We would argue that a case study strategy can be a very worthwhile way of exploring existing theory*".

Eisenhardt (1989) proposes that the case study method can be particularly relevant in certain circumstances i.e. "*However, there are times when little is known about a phenomenon, current perspectives seem inadequate because they have little empirical substantiation, or they conflict with each other or common sense*". This is a good description of the current situation in this area where current perspectives do appear to be challenged from first principles and also are not backed up with practical comparison modelling as has been explained. Yin (2003) suggests that the case study method is particularly useful for investigating explanatory 'how' and 'why' questions. He also suggests that the method should not require control over behavioural events and should be focused on contemporary events. Again there appears to be a good fit with the objectives of this research since it is aiming to explore and understand the use of certain techniques in practice. Merriam (2009) considers the defining characteristic of the case study approach to be delimiting the object of study and the case being a "bounded system". This notion of studying a number of cases or "bounded systems" which exhibit the characteristics of interest for the study corresponds to the objectives of the research.

3.3.4.1 Challenges of the case study method

The case study method provides the potential for a rich and holistic empirical enquiry. However, traditionally the method has been criticised in a number of ways. Firstly, the case method has been seen as a less rigorous form of research with problems of reliability and validity (Merriam, 2009 ; Yin, 2003). The method is seen as being more vulnerable to the performance of the individual case study researcher, their integrity and ethical standards. The ethical issue is well illustrated by Guba and Lincoln (1992) who state: "*An unethical case writer could so select from among available data that virtually anything he wished could be illustrated*". The difficulties of reliability are linked to repeatability; how can we know if the findings described by this researcher are repeatable or are they a function of the individual and the way that they have conducted the research? A second key concern is regarding generalisation from the particular case to a broader theory. Yin (2003) makes it clear that the case method can yield 'analytic generalisation' i.e. generalisation to theoretical propositions rather than 'statistical generalisation' to frequencies. A third criticism relates to the time and cost associated with doing case study research and the size of the data and reports that can result from the method. This can make it an impractical and unwieldy research approach. All this means that the case method is not an easy option when it comes to doing research but actually is very difficult to do well. He argues that all these criticisms can be overcome and that the case study method can be successful as long as a systematic and rigorous approach is used. The following sections will set out how this research has been conducted in order to meet these standards of rigour.

3.3.4.2 Case study design

Yin (2003) suggests that there are five key steps in the design of case study research, namely:

1. a study's questions;
2. its propositions;
3. its unit(s) of analysis;
4. the logic linking the data to the propositions; and
5. the criteria for interpreting the findings.

The following sections will set out the proposed approach in relation to these key questions.

The questions that the case studies are seeking to answer are the research questions set out in section 3.2. In particular the case studies will focus on questions 4, 5 and 6 i.e.

4 What are the relative strengths and weaknesses of different techniques in simulating certain supply chain problem types?

5 What experiments can be done to test and compare alternative approaches?

6 How can these conclusions be used to generate recommendations for practitioners on how they should deploy these tools in achieving their supply chain objectives?

Given the case study approach is strong on the 'how' and the 'why' there might be an additional question:

7 Why are certain approaches more suited to particular supply chain problem types?

The unit of analysis in this case study research will be the supply chain problem type. What this means in practice is that the cases will be "bounded systems" which themselves encapsulate a supply chain problem and the attempt to investigate that problem. The case may not necessarily involve or aim towards the solution of that problem i.e. the arrival at a point solution. It may represent a complex system which allows for the investigation of a problem. The cases should be significant, in other words they should represent supply chain problems that are important or representative of a class of problems which may be encountered by supply chain practitioners.

Yin (2003) suggests that it is useful to think about how data collected during the case studies will be interpreted in relation to the key propositions in advance of starting the case studies. Each case study will involve the 'back to back' modelling of a system using two different simulation techniques. The choice of cases will ensure that the propositions are investigated. This will require the selection of appropriate cases which themselves exhibit the characteristics required. The selection of appropriate cases and the 'back to back' modelling process will ensure the logical linkage from data collected to the propositions themselves.

Data will be gathered both on the modelling process itself as well as the results of the model and the interpretation of those results. The collection of this data will allow the following questions to be answered in relation to the propositions above:

- How do the two methods differ in the modelling process? Are there particular advantages/disadvantages between the methods?
- Are any particular difficulties encountered in the modelling process?
- How do the results of the models differ?
- What is the explanation for these differences?
- Can the technique model the characteristic required?

- How does the concept (feedback, level of the problem, role of decision makers, purpose) affect the suitability of the technique?

3.3.4.3 Quality

As has been previously explained, the case study method has been criticised for lacking rigour, reliability and generalisability. It is thus important to be mindful of ensuring quality throughout research of this kind. This section will describe how the approach has been designed to address these concerns.

One key concern of case study research is that it involves subjective rather than objective methods of data collection. Moreover, the constructs themselves are qualitative rather than quantitative. How can the researcher guard against the risk that these concepts and propositions are interpreted inconsistently? How can the researcher avoid the risk of collecting data that is biased? Yin (2003) proposes three tactics for addressing these weaknesses, namely: using multiple sources of evidence, establishing a chain of evidence and finally, having key informants review the draft case study report. In this research, as well as using a 'classic' case, 'typifications' and 'theoretical abstracts' are also used. The above tactics are not relevant in these cases. How can construct validity be achieved in these examples? There are a number of potential approaches that can be used. For example, McCutcheon and Meredith (1993) in describing how to achieve rigour in research describes a process he calls 'controlled deductions' where 'formal logic is applied to verbal propositions'. Essentially this means that we have to be careful to use consistent terms and to carefully apply logic to these terms. Another tactic here is to ensure that where possible constructs are related to accepted definitions in the literature so that we can more confident in the consistency of definitions.

Another concern is internal validity. Internal validity, according to Yin (2003) is concerned with where a claim is made for a causal link i.e. that 'a' causes 'b'. In this case we must be sure that there is not some other factor 'c' which we have overlooked. Given the exploratory nature of this research it is unlikely that this will be an issue. In case study research, external validity must also be considered. This test concerns whether findings from a single case can be generalised. This requires that the theory be tested in further cases in order to validate the theory or confound it. One approach to achieving this is the multiple case design approach. In this research the multiple case approach has been used. The embedded units of analysis are tested in more than one case situation. The aim is that by using the multiple case approach, findings can be validated in this way.

A further concern is reliability. Reliability concerns whether the results of the case studies would be replicated by a researcher following the procedures described. Yin (2003) recommends using a case study protocol, as well as developing a case study database recording all the relevant data on the case. In this research, since it involves modelling and simulation, this author has been careful to do a number of key things to increase reliability. The first has been to follow the accepted approach with a given modelling method. For example, when building a System Dynamics or an Agent Based Model, the author has followed the steps proposed by respected authors and practitioners in the field. The second key step has been to ensure that these steps have been clearly documented in the report so that a researcher following this approach again would more than likely arrive at similar results. A final tactic has been to share findings with experts in order to test their robustness.

3.3.5 Case Study Method and Protocol

The overall approach to a multi-case approach is described in Figure 23 (Yin, 2003). Individual cases are used to develop findings individually, but are also used together to draw cross-case conclusions. Together the individual cases and the cross case conclusions lead to the modification of theory and the development of policy implications.

3.3.6 Research techniques

Within the overall framework of the case study approach, certain research techniques have been used for data collection and analysis. During the purchasing case study, data was collected using semi-structured interviews, participation observation and from documents. Documents (academic papers and text books) were used to provide the data for the 'typification' case studies and the 'theoretical abstraction' cases. Simulation was used as a key method with all the case studies.

In order to improve reliability, it is important in case study research to follow a protocol. Eisenhardt (1989) provides a good model to follow, Table 9 shows how this has been followed in this research.

3.3.6.1 Semi structured interviews

Interviewing is a key method for obtaining data in qualitative research (Lee and Lings, 2008). Interviews can be unstructured or semi-structured. Unstructured interviews are used when it is felt that even a basic structure may bias the conversation and lead to misleading results. In this research, the goal was to explore a particular theme in the context of the case study. Thus it was appropriate to guide the conversation in order to gain the maximum benefit. Semi-structured interviews were used during the model building process in order to surface the decision making process and to test the model at various stages of the model building process.

3.3.6.2 Participant observation

Participant observation is where the researcher is taking a part in the process that is the focus of the research (Cresswell, 2003). During the purchasing case the author was working as a consultant in the client organisation. This provided an on-going opportunity to observe conversations and individual and group dynamics first hand. This was a rich source of data for developing the model of the situation and the decision making process.

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Figure 23 Multi-case study method (Yin, 2003)

Step	Activity	How tackled in this research
Getting Started	Definition of research question	Personal interests and literature review
	Possibly a priori constructs	Constructs developed from theoretical analysis
	Neither theory nor hypothesis	Exploratory research, open 'how' and 'why' research questions
Selecting Cases	Specified population	Supply chain problem types
	Theoretical, not random sampling	Cases selected in relation to key constructs i.e. supply chain problems that allow investigation of problem level, feedback, role of decision making and modelling purpose
Crafting Instruments and Protocols	Multiple data collection methods	Interviews, participation observation, documentation

	Qualitative and quantitative data combined	Qualitative : Interviews and observation Quantitative : Simulation modelling
	Multiple investigators	Not applicable since the researcher was working as an individual. However, input was sought from supervisors and experts in various fields.
Entering the field	Overlap data collection and analysis, including field notes	Model building is iterative and on-going from initial development of concept through to model coding and testing
	Flexible and opportunistic data collection methods	During the Purchasing Case, the researcher used interviews and project activities to obtain data for analysis.
Analysing Data	Within-case analysis	Individual cases written up during and after analysis phase
	Cross-case pattern search using divergent techniques	Using multiple cases with common embedded units of analysis allows for cross-searching
Shaping Hypotheses	Iterative tabulation of evidence for each construct	Using a sequential case study approach allows for the development of evidence for each construct
	Replication, not sampling, logic across cases	Multiple cases are used to refine or disconfirm the propositions
	Search evidence for 'why' behind relationships	Use qualitative data
Enfolding Literature	Comparison with conflicting literature	Explore literature which appears to contradict findings
	Comparison with similar literature	Explore literature which appears to support findings
Reaching Closure	Theoretical saturation when possible	A level of certainty is reached through controlled deduction as applied to the concepts

Table 9 Case study protocol

3.3.6.3 Simulation

Simulation has been used as a core method within this research, as the focus of the research is on the comparison of different simulation approaches. Simulation is a relatively recent development in management research, these methods dating back to the early 1960s. The role of simulation in the development of theory is still being debated by academics. Two key themes have emerged from the debate on this subject (David et al., 2010), namely a debate about methodology and another on epistemology. The methodology debate concerns the question of how simulation should be carried out in such a way that its results are reliable and credible, this concerns the rigour and robustness of the simulation process itself. The epistemology debate concerns the kind of knowledge that simulation provides. In terms of methodology, reliability and rigour are related to transparency, in other words are the methods used clear and repeatable? What this means practically is that the approach to simulation, whether SD, DES or ABM should follow a clear methodology. The response to this challenge in this research has been to use a clear and well documented approach each time which follows the accepted practices in the given field. In terms of epistemology, the nature of claims to knowledge by simulation relates to how closely the 'symbols' in the model correspond to acceptable real world empirical phenomena. Claims to knowledge are not automatic, and simulations are after all imitations of the real world they purport to represent. In practice this means that the modeller must be clear about the concepts and 'symbols' used in the model and how they correspond to the real world phenomena they represent.

3.3.6.4 Simulation software

Many practitioners will in fact use commercial software packages to build their models. Sometimes modellers will build their models using software code languages, especially academics, but many practitioners in business and industry will use commercial packages. Pidd (2004b) suggests that as many as 90% of models may be built using these packages. It is important therefore to be aware of the primary packages and how they relate in particular to the simulation world views. These packages can be either discrete, continuous or contain hybrids of both. Some examples of these packages and their capabilities are shown in Table 10. Some packages are primarily discrete event packages which have some capability of modelling continuous processes within them. Some packages are primarily continuous or system dynamics packages. Finally some are multi world view packages which claim to be able to include elements of all the world views within their capability. Commercial competition drives firms to make claims about their software in order to differentiate themselves from their competition. This may particularly be the case given that the industry may be in its mature or saturation phase (Hollocks, 2006). Given this situation, there are a number of implications. For example, firms may emphasise or even exaggerate the relative benefits of one approach over another, for example the benefits of an agent based approach compared to a traditional discrete event or continuous approach. Other firms may do the opposite by providing hybrid solutions and thus promote the idea that these are all equally valid or compatible approaches and thus different world views can easily and seamlessly be used together in one model. It should also be pointed out that selection of one software package does not necessarily imply the modeller must be wedded to a particular paradigm. For example, agent based models have been built using system dynamics packages such as Vensim (Vensim, 2012) as well as through other techniques, even Excel.

Software Package	Event Scheduling	Process interaction	Object orientation	Agent Based Modelling	Continuous
Simul8	Yes	Yes			Can model continuous processes in a discrete environment
Arena	Yes	Yes			Can model continuous processes in a discrete environment
ProModel	Yes	Yes			Can model continuous processes in a discrete environment
Witness	Yes	Yes			Can model continuous processes in a discrete environment
Simio	Yes	Yes	Yes	Yes	Yes
Anylogic	Yes	Yes	Yes	Yes	Yes
FlexSim	Yes	Yes	Yes		Yes
NetLogo				Yes	
Vensim					Yes
Powersim					Yes

Table 10 Commercial simulation software and capabilities

For this research, the following modelling software has been used:

- System Dynamics : Vensim PLE
- Discrete Event Simulation : Simul8
- Agent Based Modelling : Netlogo

The choice of software has been influenced by the software in use at Aston Business School and thus the degree of support available to this researcher in using it.

3.3.7 Alternative approaches

The overall approach to the research has been described. However, a there are a number of alternative approaches that could have been used but were rejected. The following sections will explain why these techniques were rejected and an evaluation of how the research would have been different if such an approach had been used.

3.3.7.1 Action Research / Action Science

Action Research is an approach where the researcher is also an active participant and change agent in an organisation. Gummeson (2000) prefers the term Action Science which he defines as "*Action Science always involves two goals: solve a problem for the client and contribute to science. That means you must be a management consultant and an academic researcher at the same time*." In the context of this research, this would have involved the researcher working with real problems in real organisations, using modelling and simulation to build models of supply chain problems and using this to compare and contrast their strengths and weaknesses. There are a number of positive aspects of this approach. The methods would be tried out in a real context and this could be a rich learning environment. The models would be built in an interactive team environment, testing the 'soft' people aspects of the process as well as the 'hard' model building. However, there were two key constraints to this approach. Firstly, the research required a focus on a particular set of problem domains resulting from the literature review and theoretical analysis. During the period of this research the author was employed as a management consultant and so was working with clients on a variety of problems, but unfortunately, these problems were not suitable in many cases. The second issue was to do with the practicalities of combining the role of management consultant with researcher. As a paid consultant, the client has a particular problem that needs solving, they are paying for the work to be done and conducted in a certain way. The focus of the research is the use of modelling and simulation as a problem solving technique, this could not be at the forefront of the activities being carried out. It must be acknowledged that this would be an interesting and productive mode in which to conduct research of this kind if circumstances allowed, and this researcher will be looking for potential opportunities to do this in the future.

3.3.7.2 Surveys

Surveys can be used to collect data to test theories and can be descriptive or analytical in nature (Gill and Johnson, 1997). Given the research questions, the problem with the survey approach would have been the availability of an appropriate target population to survey. In the early days of this research the author considered surveying populations of either supply chain practitioners or modellers to investigate the relative strengths and weaknesses of the different techniques. However, the problem is that very few practitioners are trained in and familiar with all three simulation techniques. The exploratory nature of the research means that much of the comparative modelling work has never been done and as a result, the population does not exist to survey. Surveys would also be prone to perpetuate the received wisdom. For this reason the survey method was not considered suitable for this research.

3.3.7.3 Experiments

The experimental method requires that the researcher meets certain key conditions (Gill and Johnson, 1997), namely that the experimenter must be able to:

1. manipulate the independent variables through direct intervention,
2. measure the changes in dependant variables,
3. control the effects of extraneous variables.

In the context of this research, which concerns the modelling of complex socio-technical systems, the pure experimental approach is not suitable.

3.4 Summary

The importance of research design has been stressed by authors, for example Professor Michael West in Allwood and Lee (2005) states "*The more carefully, completely and thoroughly you plan your research, the better it will be*." A realism philosophy has been used which sits part way between a positivist approach and a purely inductive approach. This can be seen as theory building and testing very much in a real world setting. The strategy has been mainly qualitative within a broad hypothetico-deductive framework. The case study method has been used, with three 'flavours' of case being a classic case, typifications and theoretical abstractions. The discussion of methods and techniques has also addressed some of the classic criticisms of the case study approach in terms of its rigour, reliability and generalizability. Methods have been chosen specifically to address these potential weaknesses to ensure that the findings of the research are reliable, robust and meaningful theory can be developed from them.

A summary of the research approach is given below in Table 11. The next chapter will examine the approaches from a historical perspective, as well as from first principles. The claims from the literature are then challenged and new propositions developed.

Philosophical choice	Realism
Research strategy	Hypothetico-deductive, Qualitative
Research methods	Case Study (Case, typification, theoretical abstraction)
Techniques	Semi-Structured Interviews
	Participant Observation
	Simulation
	Documents
Tools	Simul8
	Netlogo
	Vensim PLE

Table 11 Summary of research method choices

Chapter 4 Theoretical analysis

Chapter 2 identified the main modelling approaches in supply chain analysis: Systems Dynamics, Discrete Event Simulation and Agent Based Modelling. Chapter 3 described the methodological approach followed by this research, of which the starting point is a "first principles" or theoretical analysis of the capabilities of these methods. This chapter will deal with the theoretical analysis, focusing on the basic building blocks of simulation and how each one of the approaches tackles them.

4.1 Introduction

Previous comparisons of these approaches (System Dynamics, Discrete Event Simulation and Agent Based Modelling) have lacked conceptual rigour. In addition, too much reliance has been placed on custom and practice rather than an objective examination of the approaches. As explained in Chapter 3, the role of the theoretical analysis is to refine the concepts. This means taking the findings of the initial literature review, the 'received wisdom' and subjecting it to more rigorous scrutiny. This will lead to a set of propositions that can be examined through the case studies.

4.1.1 How the theoretical analysis was performed

The purpose of the theoretical analysis is to examine the approaches from first principles. This first principles review will identify their inherent characteristics and building blocks. The theoretical analysis will take place in two parts. The first part of the theoretical analysis involved a review of the literature. Other authors have traced the development of simulation through history, and the literature is a rich source of information regarding this development process. Studying the evolution of the techniques sheds light on their internal workings. This review was used to distil out the key characteristics of the approaches and how they model and represent the key characteristics of systems.

The second part of the theoretical analysis required a more analytical process. This involved taking the broad claims from the literature review, and subjecting the claims to scrutiny in the light of the first principles analysis. Thus, certain claims will be found to be supported from a first principles perspective, but others will be challenged. This process leads to a more refined and specific set of propositions. Thus, the theoretical analysis also influences the selection of cases, since the cases are selected in order to test the propositions.

4.2 The history of simulation

The origins of simulation techniques influence their underlying mechanics and how they actually work. Over time, the details of these inner workings may be less obvious to the user, particularly as the simulation approaches themselves are often presented within a package which may hide them from the user. Pidd (2004b) suggests that although not everyone will need to know about simulation world views there are some that do: *"Finally, there is a small group – probably those specialising in computer science or operational research, who need to know how to make simulation software sing and dance. This final group do need to understand about simulation world views, for then they will understand what can go wrong in a simulation model and why".* In understanding the suitability of the methods to different problem types, it is important to return to the origins of the approaches, and to understand them from a first principles perspective. This then allows a more rigorous foundation from which to carry out a comparison.

Robinson (2005) provides a broad overview of the development of discrete event simulation from the 1950's to the present day. In a fascinating review of simulation from 1955 to 1986, Nance (1993) classifies simulation into three partitions, namely; discrete event, Monte Carlo and continuous simulation. He further points out that the existence of different world views was recognised very early in the development of the field by Lackner (1962). The three world views Nance (1993) identifies in relation to DES are event scheduling, activity scanning and process interaction. It is very interesting that he mentions system dynamics as a key development. He justifies this inclusion by pointing out that SD had a significant impact on the development of DES. Also very interesting is that he mentions two conferences on simulation held during the mid-1960s which included key players from both the DES and SD communities. For example, the IBM Scientific Computing Symposium held in New York in 1964 included both J.D.Tocher and Jay Forrester as presenters. Later, in 1967 at the IFIP Working Conference on Simulation Programming Languages in Oslo included many of the key players of the time presenting on various aspects of DES and including A.L.Pugh presenting DYNAMO, the SD programming language of the time. This seems to suggest that in the earliest days of development people did not see the same divisions that seem to have come about subsequently.

A further interesting aspect of this historical review is the description of the development of the language SIMULA around 1961, the work of Nygaard and Dahl. The concepts introduced in SIMULA of data types, classes and inheritance for example, created the foundations of what was later to become object-oriented programming. The development of discrete event simulation languages during this period is shown in Figure 24. Another perspective is provided by Pegden

(2010), who uses the terms world view, paradigm and approach interchangeably. He identifies three primary world views or paradigms within discrete event simulation. These are event, process and object. Interestingly, he argues that *"Agent based modeling is typically implemented using an object-oriented simulation tool. Hence this is not a new discrete event world view, but rather a group of applications that are modelled with the object world view."* He explains the three phase approach as one example of a world view within the Discrete Event area. A summary of this examination of the three techniques from a simulation world view perspective is given in Table 12 (Pidd, 2004a ; Pidd, 1995 ; Pegden, 2007 ; Kiviat, 1969).

A separate, but linked issue is the concept of the paradigm. Kuhn (1996) describes a paradigm as being a scientific community with a shared set of ideas and rules about how to go about studying the world and solving problems. A paradigm shift, the emergence of a new paradigm may occur when the rules and 'taken for granted' assumptions of the existing paradigm are not sufficient to solve the problem faced. Interestingly, Kuhn (1996) maintains that "*The existence of a paradigm need not imply that a full set of rules exists*". So, for example, although agent based modelling may lack clarity in its concepts and methodology, that does not preclude it from being a new paradigm. If these are three separate paradigms, that could create difficulties in comparing them. Forrester (1983) certainly sees SD as a paradigm as he explicitly uses this term in his presidential address at the 1983 International System Dynamics Conference. Elsewhere Meadows and Robinson (1985) describing SD state *"System dynamics, however, includes not only the basic idea of simulation, but also a set of concepts, representational techniques, and beliefs that make it into a definite modeling paradigm. It shapes the world view of its practitioners..."* In the same way, Macal and North (2006) claim that ABMS is a new paradigm and state *"Agent based modelling and simulation is a new modelling paradigm and is one of the most exciting practical developments in modelling since the invention of relational databases."* So advocates and proponents of SD and ABM claim them as new paradigms and to this extent at least they are paradigms in that they have communities who share a certain world view and approach to tackling problems and systems in the real world.

4.2.1 Early Critique of SD

A review of the history of simulation is not complete without some reference to the early controversy surrounding SD which was then known as Industrial Dynamics (ID). Ansoff and Slevin (1968) provide a detailed critique of the approach. In the first place they review the steps to constructing a simulation model as outlined by Forrester (1961) on page 384 of their critique. They point out that this set of steps, from identifying a problem, through model formulation, experimentation and changes to the system in the real world could describe most management science approaches to studying management problems. From this perspective at least, they argue, there is nothing new in Industrial Dynamics. They criticise the approach for trying to quantify soft intangible variables such as the attitudes of managers elicited through interviews. They suggest that *"the rules which the managers verbalise may not be the ones they actually use."*

They criticise the use of the table function which allows a relationship to be established between two variables. They suggest that whilst this might be convenient, it is also potentially dangerous since it allows models to be built with hidden arbitrary assumptions. Much of the critique focuses on the difficulties of model validation. They criticise Forrester's approach which seeks to find dynamic validation rather than validation through results. They question whether this is an acceptable approach to achieving validity. They question the reliability of the approach, and whether two industrial dynamicists will arrive at the same result. They see this as a problem due to the lack of a robust approach to validation. In terms of application, interestingly they suggest that Industrial Dynamics may be more useful in solving 'hard' problems where there is quantifiable data such as production, inventory control and distribution systems, rather than in areas such as marketing, for example. In terms of feedback, they point out that ID views the firm as a feedback system. They concede that many management problems can be conceived as feedback control systems, but that does not mean that this representation will always be the most appropriate approach. Indeed, they suggest that in many cases there may be more suitable approaches to use. Finally, they suggest that ID is not a theory because it does not meet the criteria for a theory. In particular, ID does not provide the ability to make predictions, rather it provides an approach to building models of systems.

Even in this early period of development, the key building blocks of the SD/ID approach are apparent. The focus on the feedback system approach which originated from Forrester's background in control engineering is central to the method. However, as the critique points out, there is the question of whether such an approach is suited to a given problem and indeed how such an assessment of suitability can be made. The issue of validity is clearly a defining issue for SD/ID because of the approach proposed by Forrester. The issue of how SD/ID includes both hard and soft variables and to what extent the soft variables can be validated is raised. The use of opaque relationships such as the table function is also identified.

	Discrete Event Simulation Simulation World Views						System Dynamics
Elements	**Three phase approach**	**Activity Scanning**	**Event Scheduling**	**Process Interaction**	**Object Orientation**	**Agent Based Modeling**	
The role of the Simulation Executive	A Phase - time scan - search for next event - move clock on to this time. B Phase - execute B's C Phase - attempt all C's	The simulation executive operates in a two phase sweep. 1. Check the time cells to find the time of the next event. Move the clock to this time. 2. Repeatedly scan through the activities , trying each test-head to see if that activity is now due or able	The event based executive has just two phases: 1. Examine the event calendar to find when the next event is due and move the simulation clock to this time. Move all event notices that are scheduled for this new clock time onto the current events list. 2. Holding the clock constant, perform each of the event routines whose notices are in the curent events list. Empty the current events list.	The role of the executive is, at each time point of the simulation, to move the entity as far through the process template as possible. Each process has contain reactivation points at which they had control back to the executive.Each entity record will contain - reactivation time and next reactivation point. Executive maintains two records: future events list (chronological list of entities which are unconditionally delayed); Current events list (unconditionally delayed entities due now), Entities subject to conditional delays. The process executive then follows a three phase approach:. 1. Future events scan, determine the time of the next event, advance clock to this time; 2. Move between lists; those entities with future event time= current time move to current events list; 3. Current events scan; move entities on if conditions are met.	The simulation executive has no knowledge or access to an object's state transition network. The simulation executive is solely responsible for instructing an object to update itself at the appropriate time. The executive therefore does not contain any simulation logic and exists to schedule events for each object in the correct order. Essentially the executive exists to synchronise objects.	The simulation executive has no knowledge or access to an agent's state transition network. The simulation executive is solely responsible for instructing an agent to update itself at the appropriate time. The executive therefore does not contain any simulation logic and exists to schedule events for each agent in the correct order. Essentially the executive exists to synchronise agents.	Not applicable.
Basic Building Block	B and C Events	Activity	Event routines	Process	Classes, Objects, Messages	Classes, Agents, Messages	Stocks, Flows, Causal Loops
Phases	Three	Two	Two	Three	Not prescribed	Not prescribed	Not applicable.
How is logic manifested in the model	Two types of activity - B (bound) events which must happen at a given time. C (conditional) activities requiring certain conditions. Each entity has a record containing time cell, availability and next activity. The executive cycles through these activities in a three phase cycle.	Each activity has a test head. When the conditions in the test head are attained, the activities are carried out.	Logic is built into the event routines. An event routine is a set of statements, in some programming language, which captures the entire set of logical consequences that can flow from an event.	Each entity in the model belongs to at least one process class. The process class defines the sequence of operations through which the entty must pass. The progress of the entity can be halted temporarily by: Unconditional delays, which can, in principle, be defined in advance, Conditional delays, based on certain conditions.	Each simulation object has a state (e.g. running, idle, absent, moving, etc) and the state will vary during the simulation run. State changes are handled internally by a mechanism known as the state transition network. The state transition network contains the core simulation logic: it is used privately by an object to trigger the appropriate state changes. Each object can access the world clock. Objects use date and time information supplied by the clock and their own time and state records to decide what state to change to, if at all. Because of the access to the clock, each object is able to ascertain the time of the next event for themselves. Each object will calculate the time of the next event and request the simulation executive to schedule the event.	According to Odell (2002), the difference between Agents and Objects is that Agents have their own thread of control, localizing not only code and state but their invocation as well. Such agents can also have individual rules and goals, making them appear like "active objects with initiative." In other words, when and how an agent acts is determined by the agent. Behaviour of an agent is defined by the state chart which defines the different states that the agent can be in and the conditions for moving between these states. Active agent classes include company, machine, part, person, but also state chart and timer.	Built into the individual mathematical and logical equations in the stocks and flows.

Table 12 Simulation World Views

4.2.2 Discussion

What is interesting is that from a simulation world view perspective it could be argued that there are in fact two paradigms i.e. a discrete paradigm which includes the discrete event world views such as three phase, event scheduling, activity scanning and process interaction, but it also includes object orientation and the agent based approach. Then there is a separate paradigm which is continuous simulation, of which System Dynamics is an example. The object orientation world view has developed out of the discrete event world view, and in particular the SIMULA language. Agent oriented modelling has developed from the object oriented world view.

For this research, and for clarity, the word 'approach' will be used to describe the three different simulation methods SD, DES and ABM. This term will be used because the term method or methodology is focused very much on the specifics of how the technique is used in practice. It does not capture the overall philosophy or world view. For this reason, the term approach will be used, and intended to mean both the overall philosophy, and the methods and techniques used in application.

In conclusion then, what can we say about the three terms discrete event simulation, system dynamics and agent based modelling? On one level these are three paradigms. They have separate concepts, approaches and 'taken for granteds' as well as to some extent separate communities and conferences. There is definitely some overlap and communication between the communities, but they fulfil the requirements of a paradigm according to Kuhn (1996). At the same time, when it comes to developing a simulation model, we can see perhaps two distinct paradigms, a discrete and a continuous paradigm. There are several world views, but in this perspective, an agent based realisation in a model is simply an additional discrete event world view. The implication of this is that for comparative work, the key difference is likely to be a continuous versus a discrete representation of a system. The difference between an agent based model and a discrete event model may be a lower level difference. For this reason, in this research the 'back to back' comparison modelling will be between a continuous model versus a discrete model of the same system.

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Figure 24 The history of DES (Nance, 1993)

4.3 A comparison of key modelling elements

Following the historically based review above, this section will compare and contrast the approaches in relation to how they model key aspects of systems. The literature review has identified some of the key aspects of systems that need to be modelled and the way that each approach meets these modelling challenges. This section will take these items in turn and identify how the simulation approach represents the item, as well as the associated modelling implications. Table 13 shows key system elements and how these are represented in each of the three approaches, along with the modelling implications of this. The following sections will develop these ideas further.

4.3.1 Model Elements

An important distinction between the approaches is the way they treat system structure. For example, System Dynamics practitioners believe that the important aspect to understand is a system's underlying dynamic structure, the interplay of factors that drives its dynamic behaviour. The discovery of this underlying structure and its description through causal loop and stock and flow diagrams lies at the heart of SD. Discrete Event Simulation requires knowledge of the process structure of the system, the processes, how they are linked together, how entities flow between them. Which resources are used, and how they are allocated. By contrast, Agent Based Modellers believe that the system structure is an emergent property of the interaction of the individual agents. The structure itself does not exist per se in isolation of the agents, rather it comes into existence as a result of the agent behaviours.

4.3.2 Individual entities

The individual entities are represented in different ways by the three approaches. In SD, entities are aggregated together into stocks and flows. There are mechanisms to allow flows to be subdivided into more detail. For example, the concept of co-flows allows flows to be separated out in parallel, or aging flows can be used, for example to represent different aged cohorts within a population. In more advanced versions of SD software, individual entities within a larger population can be identified. For example, individual firms within a population could be identified using subscripts. These approaches are used to divide a homogenised flow into a more defined set of individual flows. The flows themselves still consist of numbers of entities. Entities in DES models can be individual items or combined together as batches. Each entity can be given its own characteristics. In a DES mode, the way that entities are treated can vary depending on the characteristics of the entity itself. In an ABM model, entities are represented by agents. As with DES, individual agents may have their own characteristics defining their own particular features.

4.3.3 Treatment of time

SD treats time as continuous. SD models can represent changes at moments in time, i.e. sudden changes to rates or flows. However, the measurement of the effect of such changes on stocks and flows are observed over time .This means that results are arrived at by integrating flows over time. In both DES and ABM, there is a discrete aspect to time. In DES the time advance can be a fixed time increment or a variable time increment (Nance and Sargent, 2002). Both DES and ABM can model individual events and changes in the circumstances of individual agents at specific points in time.

4.3.4 Spatial relationship between entities

SD cannot effectively model the distance between individual entities since the entities are combined into stocks and flows. Both ABM and DES can incorporate the distance between elements of the system into the model. This means that SD may not be suitable for investigations where physical distance and space are important aspects of the enquiry.

4.3.5 Feedback

Feedback is explicitly represented in SD models the causal loop structure. Feedback of information or material can be achieved in a DES model, but the feedback is intrinsic rather than extrinsic. In an agent based model feedback may be a function of the interaction between individual agents, or it may be achieved through taking information from one part of the model and applying it elsewhere in the model. As with DES the feedback in an AB model is intrinsic rather than extrinsic. In the context of the supply chain, the concept of feedback is relevant in a number of ways. Firstly, in terms of the flow of information, for example the transfer of demand information downstream from customer to supplier, and also upstream from supplier to customer in terms of information on inventory levels. Secondly, in a more general sense, the concept of reverse logistics and the return of products for reuse or recycling represents a form of feedback of material in the supply chain.

4.3.6 Treatment of randomness and uncertainty

Randomness in an SD model can be represented using noise and random functions in input signals. This equates to variation in rates, so the randomness is at an aggregate rather than an individual entity level once again. In DES, randomness can be modelled as different distributions for arrival rates of entities, for duration of processes or for occurrence and duration of process breakdowns for example. In an agent based model, the individual agents can have individual characteristics. It is in the interaction between the agents that causes the randomness and uncertainty in an ABM. Thus in this case the randomness is an outcome rather than an explicitly programmed input.

4.3.7 State changes

In an SD model, state changes are to aggregate phenomena such as flows and stocks. Changes tend to be smoother and over time rather than step changes, although the facility to perform a step change in SD does exist. In DES, the state changes are controlled by the programme executive and can be discrete and associated with the features of the individual entity.

4.3.8 Human agents

In SD, human agents tend to be modelled in two ways. As passive entities, humans are modelled as stocks and flows, for example individual members of a certain population are represented as an homogenous grouping. Alternatively, human agents can be represented as decision makers within causal loop diagrams. However, the association between an individual human agent and a given decision making process is not always explicit or clear in an SD model. In a DES model, human agents can be explicitly modelled as entities which move around the model, operating within certain behavioural and decision making parameters. They can be modelled as relatively passive entities passing through a model, or as more active entities which are controlling processes in the model. In ABM, humans can be modelled as individual agents with their own particular decision making characteristics manifested as within their state charts.

4.3.9 Proactiveness and self determination

Proactiveness and self-determination are inherently ‘intelligent’ human characteristics. Whether these can be truly represented in a model is a somewhat philosophical question which is being investigated in the artificial intelligence research community.

Modelling Aspect	System Dynamics	Discrete Event Simulation	Agent Based Modelling	Modelling Implications
Model Elements	Stocks, flows, causal loops, delays	Entities, resources, flow charts	Agents, rules, state charts	**SD** - if structure is known, but dynamic response of structure is aim of the investigation. **DES**- requires knowledge of structure, how things are related to each other. Requires definition of entities, resources. **ABM** - key is to define agents and the rules for their interaction. Key modelling feature is the agent. Does not require structure to be defined.
Individual entities	Aggregated and represented as stocks and flows	Can be represented as entities	Can be represented as agents	**SD** - systems being modelled need to consist of reasonably homogenous entities (is there a limit to this? If so, what is it?) Possibly more efficient at systems consisting of large numbers of entities (populations) rather than small groups or individual entities. SD also suited to modelling continuous phenomena such as liquids and processes rather than physically distinct phenomena. **DES** - Individual entities can be represented, with resources treating them differently depending on what they are. Able to model heterogeneous groups of entities. Maybe more efficient at modelling from small groups to large groups (the middle ground?). **ABM** - Individual entities can be represented with their own rules for how they interact. So perhaps inherently more suited to modelling individuals / small groups / heterogeneous populations.
Treatment of time	Continuous	Event based	Event based	**SD** - Continuous treatment of time. Inherently suits system where changes occur gradually over time and are cumulative / integrative rather than where change is inherently discrete i.e. the level of detail change and the treatment of individual events is a priority in modelling the system. **DES and ABM** - both treat time as discrete. Suited to systems where modelling the detailed (and differentiated behaviour) of individual entities and resources is the paramount requirement.
System structure is represented by	Stocks, flows, causal loops.	Flow charts connecting resources through which entities flow.	Structure is an emergent property of the system which comes about from the interaction of agents.	**ABM** - If system structure is unknown and the study intends to investigate how interaction between individual agents creates structure, ABM could be the correct tool. **SD** - If the system is already known, but the study intends to investigate the response of the system to dynamic changes, SD is suitable. **DES** - Allows evaluation of different system structures in relation to each other.
Spatial relationship between entities	Is not represented in the model explicitly because entities are aggregated.	No reason why distance between entities in the model cannot be calculated and used in logic to drive system logic.	Can be calculated and can be a key driver in model. For example, in Anylogic Bass Diffusion model, distance between entities is used as a factor in calculating likelihood of user adoption.	**SD** - if the spatial relationship between entities is important then SD will not be the best modelling approach. **DES** - Can take account of distance between entities and resources (I think - need to check this) **ABM** - this is a strength of ABM. Individual agent behaviour can be influenced by spatial relationship.
Feedback	Explicitly modelled through causal loops.	Can be intrinsically modelled through flow chart.	Intrinsically modelled through agent behaviour (state chart)	SD - If the intent of the modelling exercise is to understand the impact of feedback in the system, SD is a good fit, DES - Limited feedback of entities can be modelled, but taking a systems view is more difficult, ABM - Feedback is not modelled 'overtly' but is a

				function of the interaction and behaviour of the agents. Better suited for open, investigative modelling exercises where very little is known or understood about system behaviour?
Treatment of randomness/uncertainty	Can be represented as 'noise' or 'randomness' in the system input	Different distributions of entity arrival time can be modelled. Resource breakdowns can be modelled based on different distributions.	Randomness in the behaviour of individual agents is defined within the agent state chart	**SD** - treated at an aggregate level as noise in the system or variation in the input signal of the system. **DES** - good for modelling the detail randomness or uncertainty in the behaviour of individual entities in the population. If the behaviour of interest is in the random behaviour of individuals then DES could be a suitable tool. **ABM** - any randomness in behaviour is reflected in the decision making logic in the state chart of the individual agent. Thus ABM could be good for studying randomness in behaviour as an emergent phenomena based on the decision making of individual agents - (consider the program 'Boids').
State changes	Changes in state are typically continuous and are driven by formulas. However, 'step changes' can be modelled.	Changes in state of entities are controlled by the logic of the model and the executive.	State changes are controlled by the state chart associated with the agent.	**SD** - models assume that state changes are smooth **DES** - model efficiency good because executive advances from event to event rather than in equal time steps. Suitable when state changes are not continuous and maybe the focus of interest. **ABM** - suitable if the focus of the modelling is the individual agent and the changes that it experiences?
Human Agents typically represented as	Either as stocks and flows (if entities within the model) or as decision makers via causal loops	As entities or resources.	As agents.	**SD** - Best suited to modelling aggregated behaviour of people in large groups or populations where the assumption of homogeneity stands **DES** - Good for the middle ground, representing groups and individuals and their interactions. **ABM** - Agent based modelling has some particular strengths for modelling individual's behaviour and small groups, especially if heterogeneous nature is important.
Proactiveness / Self determination	Decision making structures can be modelled in causal loop diagrams	Individual entities can be given decision making rules	To some extent, can be modelled within the logic of the individual entity	**ABM** is the only approach where this can be modelled?
Mathematical formulation	Coupled mathematical equations	Logic based	Logic based	**SD** - inherently suited to phenomena that can be represented by linked mathematical equations - i.e. continuous phenomena **DES and ABM** - suited to modelling systems where focus of interest is logic based interactions between entities.

Table 13 Representing system elements

A less controversial question is whether such behaviours can be modelled in a simulation. All three techniques provide some facility to model decision making processes. Agent based models, perhaps, provide the strongest clarity of relationship between an individual human and their decision making processes. This means that the ability to model this aspect of human behaviour is perhaps stronger in ABM than in the other two approaches.

4.3.10 Mathematical formulation

SD consists of linked mathematical equations. Building models involves developing mathematical relationships between different variables. DES and ABM are built on the basis of logical relationships between entities in the model. That said, mathematical formulas are also often extensively used in DES and ABM models.

4.4 Development of concepts

The literature review identified a number of key areas of comparison for the three techniques, and these were summarised in Table 7. A consideration of the theoretical perspective can serve to refine these concepts further, by asking whether the ideas developed in the literature review are in any way supported or contradicted. Each of these areas will be considered in turn and then a final conclusion section will pull together the key concepts for further testing through the experimental case studies.

4.4.1 Problem domain

As has been described in the literature review, many authors consider that the level of the problem, whether strategic and policy, tactical or operational should influence the choice of simulation technique. In the supply chain domain, Chopra and Meindl (2007) defines three levels of decision making, these being : supply chain strategy or design; supply chain planning and supply chain operation. As well as the nature of the decisions being different, the authors consider that the time frame of the decisions also vary, strategy being over several years, planning being between a quarter and a year and operational being weekly or daily. These levels of decision making provide a corresponding model to the strategic, tactical and operational levels identified in the literature review. From a theoretical perspective, there appear to be no real reasons why historically SD has predominately been used in the strategy and policy arena whilst DES has been mostly used on tactical and operational problems. Clearly, SD models deal with aggregate treatments of phenomena. Strategic and policy models are often being developed at a level where the focus is on the macro behaviour of the system, rather than the behaviour of individual agents. The selection of SD may be driven by the perception that it will be a more efficient approach to strategic modelling than discrete methods. However, perhaps an agent based model can be built just as efficiently as an SD model if the selection of agents is appropriate. There are signs of DES being used to tackle strategic problems (Gunal and Pidd, 2007) but this is limited. It is perhaps too early to say where ABM is mainly used, but its advocates appear to suggest it can be used across the whole range of problem types. Thus a key area to investigate in the experimental phase of this work is the extent to which the three approaches can be used to tackle supply chain problems on this spectrum. If there are limitations to their applicability then where do these limitations lie?

4.4.2 Representation

The three approaches use different ways to represent different aspects of the system being modelled. These differences may influence their suitability for use in particular situations. For example, SD has no way to model space. As a result it will be unable to model supply chain problems which involve the movement of items in space or where this movement is important. An example of this might be the detailed layout design of a warehouse or a logistics terminal. No further experimental testing is required to test this, it is provable from first principles. However, a very different example concerns feedback. The received wisdom from the literature review is that SD is particularly suitable for modelling systems where feedback is an important feature. However, it is not clear what this means in practice. From the theoretical analysis, there seems to be no reason why DES and ABM cannot adequately represent feedback and thus this is an area for further investigation through experimentation. The way that human behaviour, including decision making is modelled is different in the three approaches, is another area that merits further investigation. Agent based modellers claim that ABM is a more faithful and intuitive way to model many systems because of the natural correspondence between agents and the entities being modelled, be they individual people or firms. ABM proponents also claim that their approach can model other aspects of human behaviour that other techniques cannot, such as proactivity and self-determination. From a theoretical perspective, there seems no reason why this could not also be achievable by object oriented approaches developed in DES.

4.4.3 Purpose and interpretation

The way in which model behaviour is explained by modellers varies by approach used. System Dynamicists look for underlying structures to explain the behaviour of systems. They believe that once the structure of the interacting causal loops has been uncovered the dynamic behaviour of the system can be understood. DES modellers, on the other hand take a process view, explaining system behaviour in terms of stochastic effects such as the variation in entity arrival times and process durations. Agent Based Modellers argue that the system behaviour is an emergent property of the interactions of the individual agents. The purpose of the modelling is also seen to vary according to the approach. System Dynamicists are more interesting in understanding the system behaviour than they are in problem solving or predicting the future. For example, there has been some controversy regarding the SD approach to model validation which is more to do with dynamic accuracy i.e. does the model show the same dynamic behaviour as the system, rather than point validity. DES has traditionally been more focused on the problem solving aspect and identifying the best solution rather than necessarily being concerned with the underlying causes for model behaviour.

Finally, ABM has been used to explore systems so is potentially even more open minded in that it does not necessarily seek to optimise or problem solve, but to explore the behaviour of agents in certain situations and see what if any system level behaviours emerge. The purpose of the modelling exercise in the supply chain domain may influence the suitability of the choice of modelling technique and this also needs further investigation.

4.5 Conclusions from theoretical analysis

The purpose of the theoretical analysis was to challenge the received wisdom by examining the three approaches from first principles to see whether the claims are supported or challenged by the inherent capabilities of the tools themselves.

The first key conclusion concerns the classification of the techniques themselves. Although separate paradigms, there are two main World Views in this area, namely continuous and discrete simulation. ABM is an extension of object oriented modelling which itself emerged from discrete event simulation. The implications of this work are important, because the main comparison in the experimental case studies will be between a continuous approach to modelling the system (SD) and a discrete method i.e. ABM or DES.

The next conclusion relates to the level of the problem being studied. It seems clear that, from a theoretical standpoint at least, there is no reason why all three techniques cannot be used on the full range of supply chain problems from strategic through to operational. Therefore a key goal of this research will be to investigate the use of the approaches in the different problem levels to test the limitations of the approaches in particular contexts. Secondly, there seems to be a claim on behalf of SD that it is more suited to problems where feedback is a key feature. This claim lacks rigour and requires further investigation. Thirdly, the modelling of individual behaviour and decision making differs by technique hence this is an area that needs further research. Finally, the purpose of the modelling itself may influence the choice of modelling approach. The purpose may be to further understanding, to solve problems, or it may be more exploratory in nature. These conclusions will now be used to inform the selection of case studies for the research. The intention will be to build models of the same supply chain system using more than one of the techniques. This 'back to back' modelling will be used to gain insights into the relative strengths and weaknesses of the approaches in particular in relation to the four key areas identified above i.e. level of model, the role of feedback, human decision making and the purpose of the modelling activity.

4.5.1 Case study propositions

The literature review showed some of the limitations in the current comparisons of the different approaches. In particular, a number of assumptions about the different approaches remain untested. The key assumptions identified at that stage were:

- System Dynamics is more suited to strategic and policy type problems
- Discrete methods are better suited to operational problem types
- System Dynamics is better suited to modelling problems where feedback is an important feature

In the literature review, supply chain problem types were defined at the different levels of detail, from strategic, through planning to operational. In the theoretical analysis, the concept of feedback has been examined in the context of the supply chain domain.

The theoretical analysis has shown no support for the above assumptions and so these will form the basis of propositions that can be explored and tested through the case studies. The first three propositions, therefore are intended to explore the application of these methods in areas where theyhave not traditionally been applied. The propositions are stated as follows:

Proposition 1 (P1): Discrete methods of simulation can be useful in investigating strategic problem types in the supply chain domain;
Proposition 2 (P2): Discrete methods of simulation can represent supply chain feedback effects in models;
Proposition 3 (P3): System Dynamics can be useful in modelling supply chain problem types at the operational end of the spectrum as well as the strategic.

In addition, the literature review and the theoretical analysis have identified a number of other factors that should be important in terms of the selection of the appropriate approach. These are captured in the remaining two propositions which aim to explore these areas further:

Proposition 4 (P4): The nature and role of decision makers in the problem may influence the selection of simulation technique;
Proposition 5 (P5): The purpose of the modelling (exploratory, problem solving or explanatory) may influence the selection of simulation technique.

Chapter 5 Case studies

5.1 Introduction

The range of problems presented by the supply chain domain has been reviewed earlier in the literature review and summarised in Table 1. In Chapter 3, it has been shown that the case study method is suitable for investigating the research questions that have been identified. In Chapter 4, the theoretical basis of the three simulation approaches has been reviewed, and this has led to the development of a set of propositions which will be the basis of the investigation. The following chapter will start by explaining the choice of cases in relation to the research questions. In particular, it will be demonstrated that the cases are representative of the range of problem types in the supply chain domain. In addition, the reason why, in each case, two simulation methods are deployed.

5.2 Selection of cases

5.2.1 Types of cases used in this research

The selection of cases is critical to the success of the approach. In this research, the cases must provide adequate coverage of the range of scenarios and problem types described in the literature review. Simulation is a core technique in this research. The relationship between simulation and theory building has been the subject of some discussion amongst authors recently and has been the subject of a workshop reported by Frank and Troitzsch (2005). One contribution to this debate was the development of a taxonomy of models proposed by Boero and Squazzoni (2005). The authors propose three types of model i.e. a case based model, a typification and a theoretical abstraction. A case based model is embedded in empirical data, is a rich and detailed, time bound and relates to a contemporary real world situation. This corresponds well to a conventional view of a case study. According to the authors (Boero and Squazzoni, 2005): "*Typifications are theoretical constructs intended to investigate some properties that apply to a wide range of empirical phenomena that share some common features*". A typification does not aim to represent all the possible permutations of that class in reality, but rather provide a representation of the class itself. The authors contend that typifications can provide an effective way to conduct research. There are challenges to validation, because the typification does not correspond to real empirical data and thus cannot be validated to that data. Validation must proceed by demonstrating that the typification can be shown to be faithful to the class it purports to represent. The third type of model the authors describe is the theoretical abstraction. The theoretical abstraction is defined as "*a metaphor of a general social reality*". The theoretical abstraction sits above the other two types of model, is more general in nature, does not link to a particular real world case, but nonetheless represents a real phenomenon. A theoretical abstraction is thus a theoretical construct. This taxonomy is useful in classifying the different cases that have been used as all three types of cases are used in this research approach.

Yin (2003) describes a number of different potential designs for case study research, ranging from a single case and context, to multiple cases in multiple contexts with several embedded units of analysis. This last description best suits the approach adopted in this research. The selection of individual cases will be driven by the propositions which have been developed by the theoretical analysis (Chapter 4).

The case studies will involve the modelling of a supply chain problem using at least two of the three main techniques. One of the two techniques will be SD and the other will be a discrete simulation technique, either DES or ABM. Another requirement of the case studies is that they provide sufficient data to allow a thorough comparison of the techniques to be achieved. The following sections describe the cases selected and explain why they were selected. The author was involved in a number of other consulting assignments in the broad supply chain but these were rejected as being unsuitable, either due to access to data being a problem or because the cases did not provide adequate coverage of the concepts which are the focus of the research. In fact this was one of the drivers for using 'typification' cases since these were suitable to the research questions and also readily available in the literature. Thus the choice of cases was not driven by convenience or coincidence of the author's own work but rather as far as possible by the requirements of the research. In addition to the four cases, in the case of the work on feedback a number of theoretical abstractions were used. These were classic System Dynamics archetypes which represent classic dynamic structures in complex systems. The modelling of these archetypes using discrete methods was part of the investigation into feedback which will be explored in more detail in the relevant case study section.

5.2.2 Real World versus academic cases

Real world cases bring an additional potential to learn, since they may involve the attempted solution of a complex problem. This provides the potential to learn more about the application of the technique as well as comparing the techniques themselves. However, real world cases are not without their problems including availability of data, gaining access and availability to the researcher. During this research this researcher was employed as a management consultant working at one of the largest global consultancies in the field of operations and supply chain. This gave the researcher access to real world problems, but there were two key constraints in relation to the suitability of these projects to this research. The first issue concerned commercial sensitivity and the practicality of mixing the practice of consulting with conducting research. In some cases this researcher was unable to conduct research at the same time as doing the consulting assignment due to the pressure of time and the access to and availability of data. The second limitation concerned the suitability of the cases. Although this researcher worked on a range of assignments during this period, not all of them were suitable for this study, because they did not have the relevant characteristics. However, one large assignment did meet the criteria both in terms of the nature of the work, but also the access to relevant data. Due to commercial sensitivity, the identity of this organisation must remain anonymous. The characteristics of the case however meant that it was ideally suited to this research. Academic cases have the advantage that all the data is clearly available. In these cases the researcher is more able to focus on the actual comparison of the techniques. In addition, academic cases can be selected to best match the criteria required. There are three main cases on the themes of purchasing, demand amplification and logistics. The rationale and criteria for the selection of cases was as follows:

- The case represents a real and significant supply chain problem type
- The problem type relates to the four key concepts, the research questions and the propositions
- Sufficient data is available to build a model

5.2.3 Description of the cases selected

The following sections will introduce the details of the cases selected.

5.2.3.1 Bullwhip case

This case was chosen because it represents both an important supply chain problem, demand amplification, it is a strategic problem and feedback is known to be an important aspect of the problem. Human decision making is also incorporated within the system. This case is considered as a ‘typification’ because a representative model of a multi-echelon supply chain has been developed using System Dynamics by Sterman (2000). We can have a degree of confidence that this is a robust model since it has been developed over time by the SD community and therefore, although not the model of a real system, nonetheless is representative of the class of supply chain problems. System Dynamics as a field searches for the underlying dynamics in complex systems. There are a number of classic system archetypes defined within SD which represent the basic underlying structures of systems. In testing the extent to which discrete methods can model feedback effects, these archetypes were used as test cases. These archetypes are theoretical abstractions according to Boero and Squazzoni (2005). Received wisdom suggests that central to the SD approach is the modelling of feedback. However, in their original critique, Ansoff and Slevin (1968) question the extent to which industrial systems are inherently information feedback systems. They challenge "*This suggests that the appropriateness of the information feedback viewpoint should be determined on the basis of the relative influence of the feedback information on the decision in any given situation*." (p.392).

The Bullwhip effect is a very well know phenomenon of supply chains. First identified by Forrester (1961), the Bullwhip effect concerns the phenomenon that demand is amplified as you go upstream in a supply chain. So for example, a change in demand at the retailer will be experienced at an amplified level in the wholesaler and producer echelons. Each echelon of the supply chain will experience an amplified version of the demand experienced by the previous echelon. The Bullwhip effect models the information feedback and the impact of delays and human behaviour on the demand signal transmitted through the supply chain. The Bullwhip effect is a strategic supply chain problem because the Bullwhip effect examines the relationship between several echelons of the supply chain and thus is studying the relationship between several organisations, rather than the behaviour within one company. It is thus a examining a phenomenon at a strategic level. The Bullwhip effect has been used to consider strategic issues such as how to share information between partners in a supply chain. Lee et al. (1997) have indicated that the Bullwhip effect is caused by "*strategic interactions among rational supply-chain members*". Thus the Bullwhip case study is relevant in that it is a strategic supply chain problem involving decision making and feedback effects. The modelling of this case will provide insights in several key areas.

5.2.3.2 Strategic purchasing case

This case was a full empirical case based on a consulting assignment conducted by this researcher. The problem was a real strategic problem faced by a large company. The researcher worked on this complex assignment and used it to build models of the decision making process. The case involves a strategic problem, i.e. the centralisation of procurement to gain increased value. It involves human decision making and provided a good opportunity to test the capabilities of the different approaches to modelling. The case company, Company A is a large construction firm in the UK. With sales of £ several Billion, the company operates in four main divisions: Building, Building Management and Services; Civil and Specialist Engineering and Services; Rail Engineering and Services and Investments. The company spends £4.3 bn with 3rd parties, of which £3.1 bn is spent with sub-contractors and £1.2 bn directly with 3rd parties. Company A consists of 13 operating companies (OpCos). Traditionally, the company has had a decentralised, federated model, where decision making has tended to be taken at the operating company, rather than the group level. There is a group procurement function, but involvement is to some extent voluntary, and companies can decide whether they want to opt in or out of Group negotiated deals. Currently, approximately £200 million of the £1.2 bn total spend has been addressed by the central procurement function. The £1.2 bn of spend can be categorised into three high level 1 categories i.e. plant, material and general spend. The current supply base is highly fragmented with 27,000 suppliers with few shared across the operating companies. Significant savings are available to Company A through aggregation of spend and coordinated procurement. However, it was not clear the extent to which the company should move towards a centre led model of procurement, both in terms of which categories should be subject to central procurement, but also, to what extent would service and performance be compromised by taking ownership away from the operating companies. The modelling challenge was to help to understand the potential benefits and risks from a centralised model of procurement, versus a decentralised model. What was the optimum way to procure categories by Company? Which procurement model would achieve the best value (i.e. combination of performance and cost)? This problem was considered to be a suitable case study since it was a strategic problem type, involved decision making in a supply chain context, and was a real problem that needed solving. For these reasons this case study was selected for a modelling comparison.

5.2.3.3 Coffee pot case

This case was chosen because it addresses a key problem area in the supply chain i.e. key decisions regarding plant location, whether to have an efficient or responsive supply chain, how to manage inventory to deliver a certain level of customer service, how to manage transportation and logistics on a global stage. This case is another 'typification' since it does not concern a real supply chain in the real world, but rather a representative abstraction of a supply chain. The problem ranges from strategic through to operational, and involves human decision making.
The two previous cases are good examples of strategic supply chain problem types, one concerning the dynamics of demand transmission and the other concerning the organisation of purchasing in a federated business model. Additional cases were needed to explore the more tactical and operational end of the problem domain spectrum. Taylor et al. (2008) explore a global supply chain and investigate the trade-offs between cost, inventory and customer service. They use a coffee pot supply chain to investigate the impact of a number of variables on cost and customer service performance. These variables include production cost (low and high); an efficient or a responsive factory; different methods of transporting the product (air or sea freight) and capacity (constrained or unconstrained). The coffee pot case allowed them to explore the relative importance of these factors in achieving a particular level of customer service. This case is useful in this research in that it spans the range from strategic to operational. At one extreme,

this case involved strategic supply chain decisions such as where to locate factories and what type of manufacturing strategy to adopt, whether efficient or responsive. At the other extreme, this case involved the detailed modelling of daily production including, for example, the production of a coffee pot every 9.6 minutes. In addition, this case includes decision making because the placement of orders is done in order to keep customer service maintained at a target level of 95%. This case is useful for exploring use of simulation techniques to model a problem which spans the strategic to operational spectrum.

5.2.4 Supply chain problems addressed by the cases

In the literature review, the scale and complexity of the challenges presented by the supply chain were reviewed. The details of the problems related to the level of the challenge i.e. strategic, planning and operational were described in section 2.2.5 and summarised in Table 1. In addition to the types of problem, the SCOR approach to defining the supply chain domain was described. Supply chain complexity was also considered in relation to the length of the pipeline and the depth i.e. the number of suppliers in each echelon. In this section, the cases will be mapped against these ways of describing the challenges and problems presented by the supply chain. The purpose of this mapping is to demonstrate that the cases tackle a significant set of problems in relation to the whole scope of the domain. Table 15 shows the results of mapping the cases against these problem types. A case is classified as a'yes' if that case tackles this particular problem. What this shows is that the cases between them cover a significant range of the problem types. Some of the areas that are not covered, are associated with the internal operations aspect of supply chain such as production strategy, process choice and master production schedule. These areas are more usually associated with manufacturing operations and the internal workings of the firm rather than the the supply chain. There are some other problems that have not been covered by these cases, however, the overall coverage demonstrates that these cases cover the majority of the problem types presented.

In addition to considering the level of the problem, it is also important to consider the different processes in the supply chain domain. The SCOR model is particularly useful here because it defines the processes and thus can be used to test the coverage of the cases in relation to the domain. In relation to SCOR, each of the three cases has been assessed in relation to the main processes of Plan (P), Source (S), Make (M) and Deliver (D). These four high level processes are known as level 1 processes in SCOR. Each of these level 1 processes divides into a number of level 2 processes as shown in Table 14. In order to assess whether a case is testing a level 2 process, they were in fact assessed against the constituent level 3 processes. The details of this assessment are contained in Appendix 1. Each case was evaluated in terms of whether or not it models the level 3 process as defined in the SCOR model. If the case models 50% or more of the level 3 processes, then it is considered to have modelled the level 2 process. Table 14 shows that the cases achieve the best coverage in the planning stages of the SCOR model. They achieve some coverage in the Make and Source stages and more limited coverage in the delivery stage. This is partly due to the fact that SCOR level 3 processes for delivery are very detailed in order to cover the wide range of different types of delivery that are possible in a supply chain. In terms of demand model, the cases are focused on the Make to Stock (MTS), rather than Make to Order (MTO) or Engineer to Order (ETO).

Finally, in terms of supply chain complexity, each of the cases models a different arrangement of suppliers and customers. In terms of the complexity in terms of depth, the purchasing case considers fourteen separate operating companies ordering from either a local or a centralised framework supplier. Thus this case deals with quite a high level of supply chain complexity in terms of supply chain depth. The Bullwhip case involves a single customer ordering from a factory which itself orders from a supplier via a supply line. The model is quite comprehensive in that it represents all the internal operations of the factory as well as the ordering and inventory control functions. The Coffee Pot case involves a single customer ordering from a warehouse which is replenished by two factories, one of which is efficient and one which is responsive.

Level 1	Level 2	Purchasing Case	Coffee Pot Case	Bullwhip Case
Plan	P1 Plan Supply Chain	YES	YES	NO
Plan	P2 Plan Source	YES	YES	NO
Plan	P3 Plan Make	NO	YES	YES
Plan	P4 Plan Deliver	NO	YES	YES
Plan	P5 Plan Return	NO	NO	NO
Source	S1 Source Stocked Product	NO	YES	YES
Source	S2 Source Make-to-order Product	NO	NO	NO
Source	S3 Source Engineer-to-order Product	NO	NO	NO
Make	M1 Make-to-stock	NO	YES	YES
Make	M2 Make-to-order	NO	NO	NO
Make	M3 Engineer-to-order	NO	NO	NO
Deliver	D1 Deliver Stocked Product	NO	LIMITED	LIMITED
Deliver	D2 Deliver Make-to-order Product	NO	NO	NO
Deliver	D3 Deliver Engineer-to-order Product	NO	NO	NO
Deliver	D4 Deliver Retail Product	NO	NO	NO

Table 14 Cases mapped against the SCOR level 2

Strategic		Purchasing Case	Coffee Pot Problem	Bullwhip Problem
Procurement				
Make versus buy			YES	
Strategic sourcing		YES		
Network configuration				
Location and capacities of plant and warehousing			YES	
Design of the distribution network				
Postponement				
Logistics				
Transportation strategy			YES	
Where to hold inventory			YES	
Distribution strategy			YES	
Internal operations				
Production strategy				
Process choice				
Planning				
Procurement				
Supply contracts		YES		
Pricing and volume decisions		YES		
Network configuration				
Medium term location decisions for production or warehousing			YES	
Logistics				
Medium term inventory policy			YES	YES
Reorder levels			YES	YES
Internal operations				
Master production schedule				
Operational				
Procurement				
Placing purchase orders / call offs		YES	YES	YES
Network configuration				
N/A				
Logistics				
Daily or weekly inventory decisions			YES	YES
Kanban triggers				
Shipping			YES	YES
Goods receipt			YES	YES
Internal operations				
Order fulfillment			YES	YES
Delivery			YES	YES
Batch sizes			YES	YES

Table 15 Cases mapped against supply chain problem types

5.2.5 Modelling approaches for the cases

In Chapter 4, the Theoretical Analysis, it has been proposed that conceptually, agent-based modelling sits within the discrete-event world view and is in fact an extension of object oriented programming. There is some further evidence that, from a practitioner perspective, agent-based modelling can be considered as an extension of the discrete event world view. For example, Karnon et al. (2012) describe agent based modelling as follows: *"This "agent-based modelling [29,30]"—an extension of DES—provides more detailed representation of interactions between agents. An agent is an entity with embedded logic that determines how it responds to circumstances (e.g., will intimate interaction be accepted)."* In addition, in the discussion on the differences between discrete event simulation and agent based modelling held at the Operational Research Society Simulation Workshop in 2010 (Siebers et al, 2010) it was suggested that it may be possible for discrete event simulation to embody the characteristics of agents, for example, *"Finally a panel member referred to ongoing discussions he is having with Averill Law (Averill M. Law & Associates, Inc.), who produced a DES model with active entities and concluded that it was unclear what ABS had to offer beyond what DES already offers.*

In terms of the practitioner community, one simulation business (Goldsim, 2013) describes agent based modelling as follows: "*This is a special class of discrete event simulator in which the mobile entities are known as agents. Whereas in a traditional discrete event model the entities only have attributes (properties that may control how they interact with various resources or control elements), agents have both attributes and methods (e.g., rules for interacting with other agents). An agent-based model could, for example, simulate the behaviour of a population of animals that are interacting with each other."*

Thus from both a theoretical and a practitioner perspective, the difference between System Dynamics, a continuous simulation approach, and both DES and ABM is a more significant difference. Thus the key comparison for each case will be between SD and either ABM or DES.

5.3 Bullwhip case study and SD archetypes

5.3.1 Introduction to modelling approach

Demand amplification has been known about in the SD community from its inception. In fact, the SD community can claim to have contributed significantly to the investigation of the sources of dynamic effects in systems due to the role of delays and human behaviour. In particular, the SD community developed the 'Beer Game' (BeerGame, 2012) as a way to educate management and students on the causes and effects of this phenomenon. Sterman (2000) develops a system dynamics model of a two echelon manufacturing supply chain with a customer. This model is then used to demonstrate demand amplification and oscillation through the supply chain caused when there is a step increase in customer demand. In this case study, the SD model will be used as the base case. A discrete 'agent' model will then be built of the system in order to investigate the differences between using SD and ABM to model the Bullwhip effect.

5.3.2 Description of the SD model

SD models are built using a number of key concepts including stocks (or levels) and flows (pipes between the levels). Arrows can be used to denote the flow of information between different parts of the model. Causal loop diagrams (CLDs) can be reinforcing (amplifying) or balancing (reducing) the flows in the model. This model of a two echelon supply chain consists of a number of these stocks, flows and causal loop diagrams developed to represent the different functions of a supply chain. This model does not represent a particular example, rather a generic supply chain. The detailed code for the model is contained in the Bullwhip models folder in the accompanying CD.

5.3.2.1 The customer

The start point of the model is the demand signal. Customer orders are generated as a customer order rate (see Figure 25). Customer orders run for 5 weeks at 10,000 per week and then experience a step change of 20% rising to 12,000 for the remaining weeks. This pattern of demand is generated by using the step function in the Vensim (Vensim, 2012) 'Input' formula.

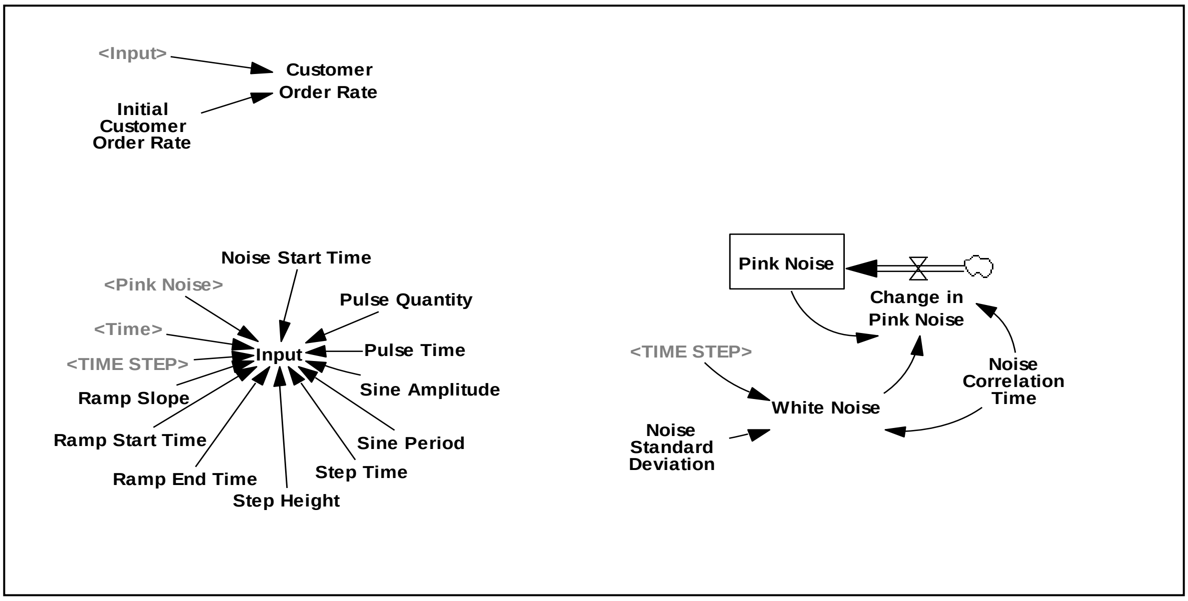

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Figure 25 Customer demand (Sterman, 2000)

5.3.2.2 The overall firm model

The overall structure of the model of the firm is shown in Figure 29. A system dynamics model consists of stocks (the boxes), flows (the pipes) and rates (the taps). Other variables are represented and linkages between them are denoted by the arrows. This overall model shows the key stocks and rates and relationships between them. Each section of the model attempts to represent a generic aspect of the manufacturing supply chain. The following sections will describe the function of each of these key sections.

5.3.2.3 Order fulfilment

In this model a backlog of orders is maintained which is the difference between the actual shipment rate and the customer order rate. This difference in rates is a consequence of the target delivery delay, as the desired shipment rate is calculated from the backlog divided by the target delivery delay. The shipment rate itself is driven from the desired shipment rate, but also it is constrained by availability of inventory.

The shipment rate is calculated by applying the order fulfilment ratio to the maximum shipment rate. The order fulfilment table reflects the fact that as the maximum shipment rate possible rises in relation to the desired shipment rate, so does the actual shipment rate. However, it also restricts the shipment rate as the maximum shipment rate falls (Figure 26).

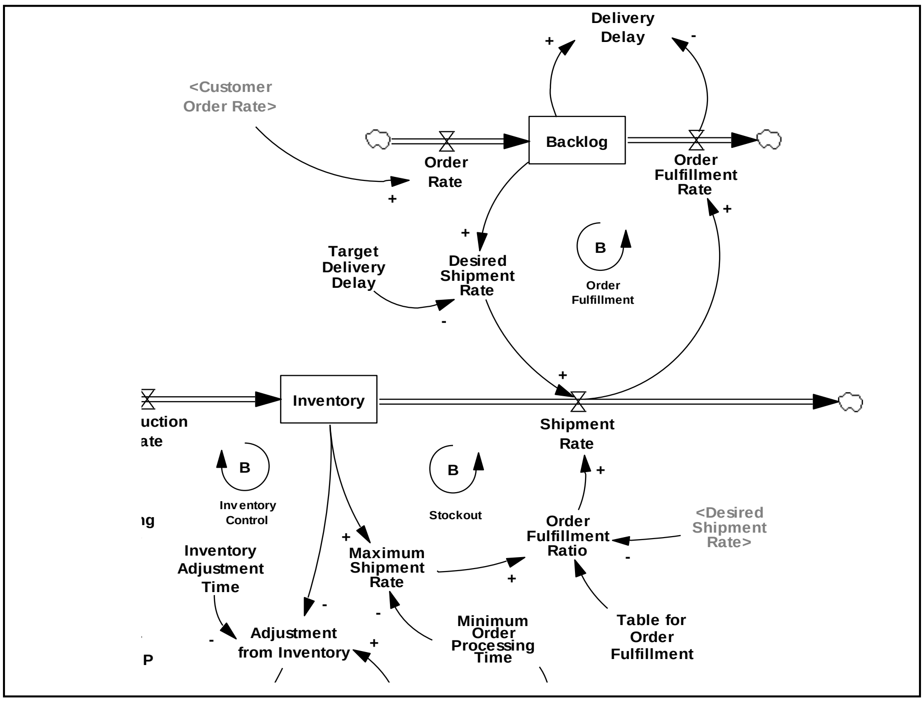

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Figure 26 Order fulfilment and backlog (Sterman, 2000)

5.3.2.4 Production

The production process replenishes inventory by converting work in progress. In this model, the production rate is a third order delay of the production start rate, with the delay time being the manufacturing cycle time (see Figure 27).

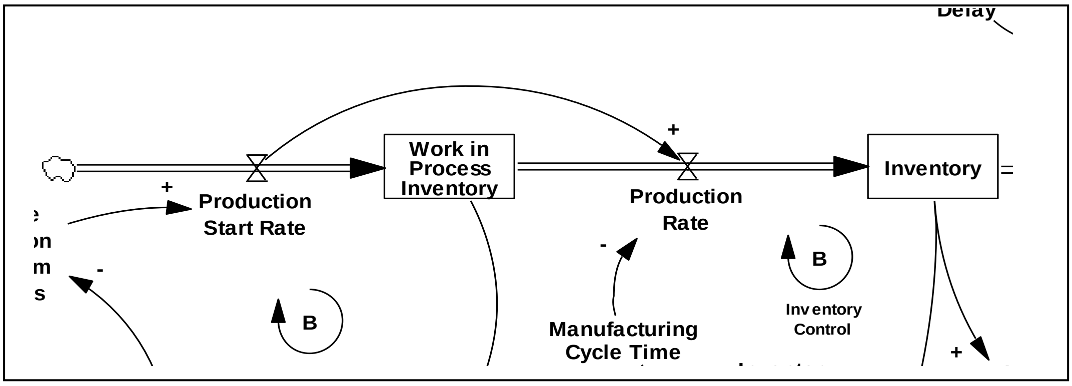

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Figure 27 Production (Sterman, 2000)

5.3.2.5 Production starts

The production start rate is driven by two variables, firstly the adjustment for Work in Process Inventory (WIP), which is an 'order up to' heuristic attempting to maintain WIP at a desired level. It is also influenced by the desired production rate, itself driven by two variables, firstly an adjustment for WIP and secondly an exponential forecast on customer orders. The desired production start rate is however constrained by the availability of materials inventory, so this becomes an input to the materials inventory section (see Figure 28).

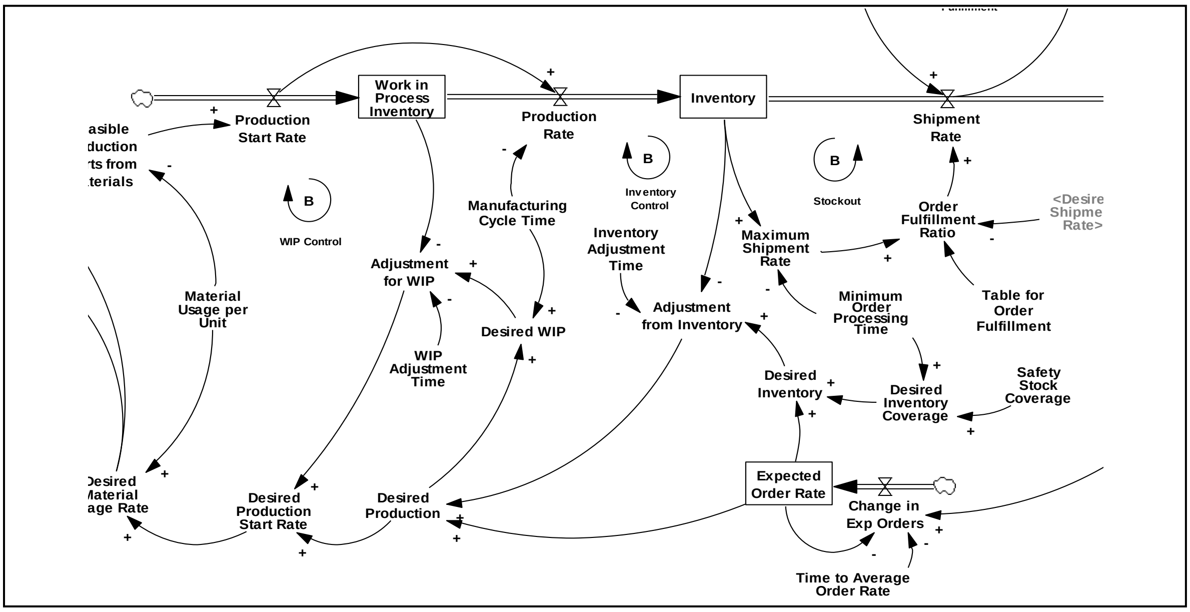

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Figure 28 Production starts (Sterman, 2000)

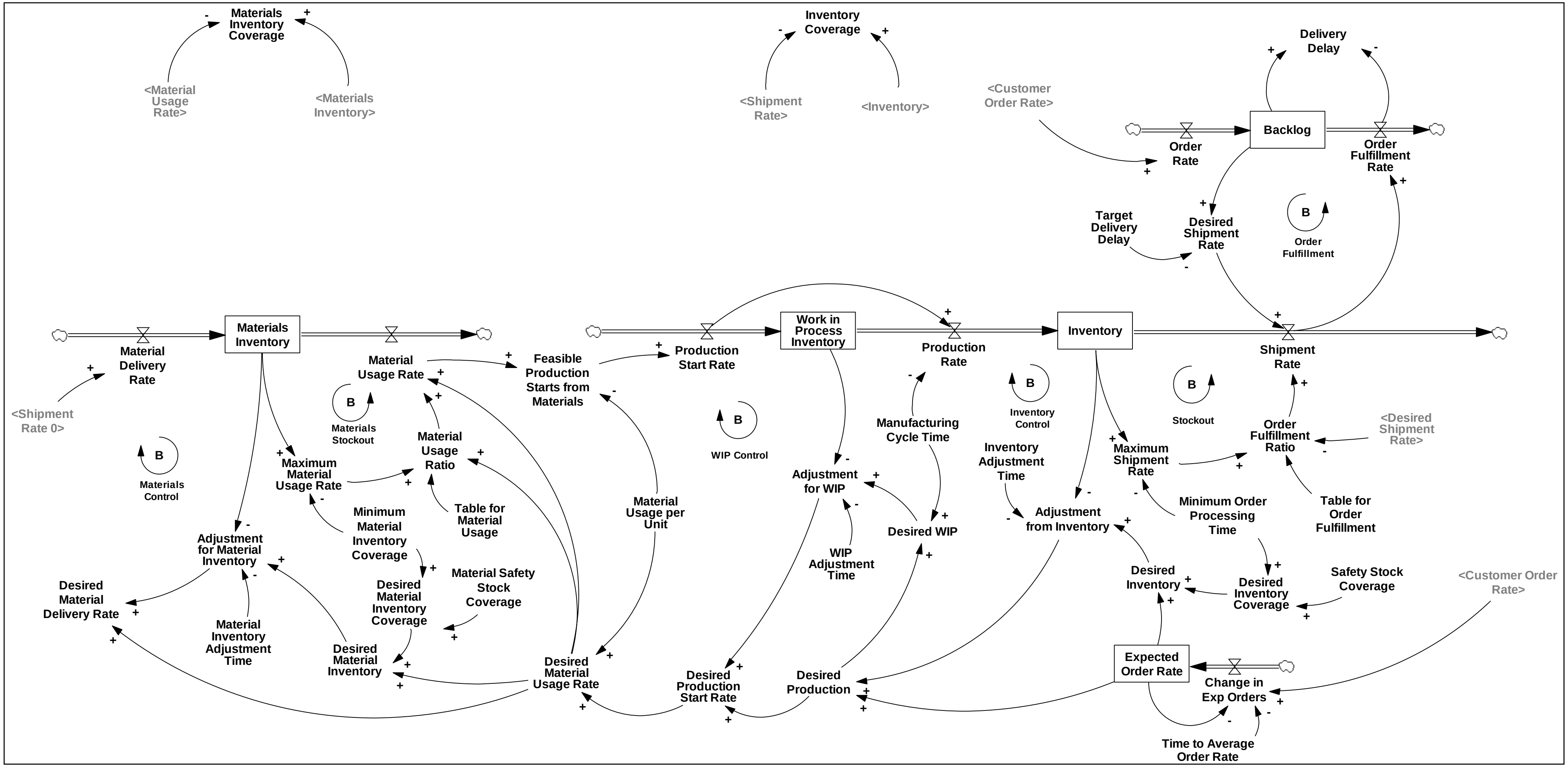

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Figure 29 Overall firm model (Sterman, 2000)

5.3.2.6 Materials inventory

Materials inventory is depleted by material usage to support production starts, and replenished by material delivery rate. Material usage rate is also constrained by the maximum material usage rate in line with the table for material usage. The desired material delivery rate is driven by an adjustment for material inventory as well as the desired material usage rate transmitted from the desired production rate. In this linked supply chain model, the material delivery rate is actually the shipment rate of the supplier factory (see Figure 30).

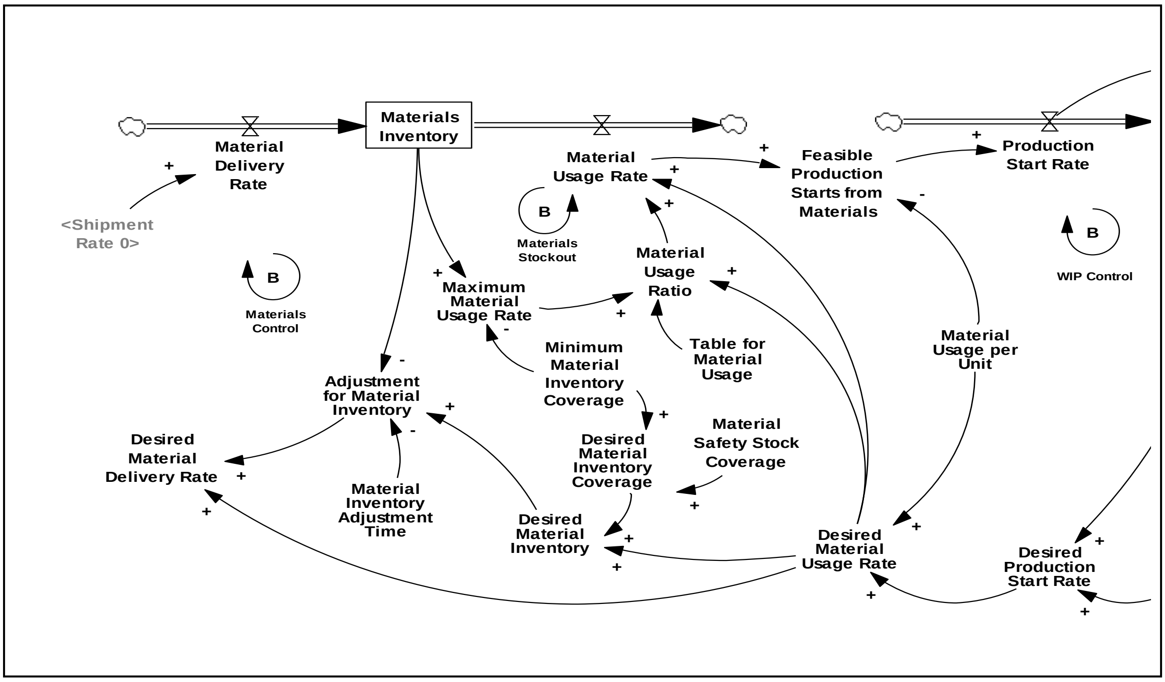

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Figure 30 Materials inventory (Sterman, 2000)

5.3.2.7 Materials supply line

In order to link together the two firms in this two echelon supply chain model, it is necessary to have a materials supply line. The goal of the supply line is to maintain sufficient materials on order to keep the delivery delay down to that expected. In the model this is achieved through the desired materials on order variable. The desired materials order rate is adjusted to meet this target in line with the supply line adjustment time (see Figure 31).

5.3.2.8 Overall supplier model

The materials supply line transmits the demand signal to the supplier. The supplier model is a replica of the firm model described above. It takes as its input the desired material order rate from the supply line, and delivers as its output 'shipment rate 0' which is the input to the materials inventory section of the firm model. Thus this model overall represents two firms linked together by a materials supply line, thus a two echelon supply chain with exogenous customer orders (see Figure 32).

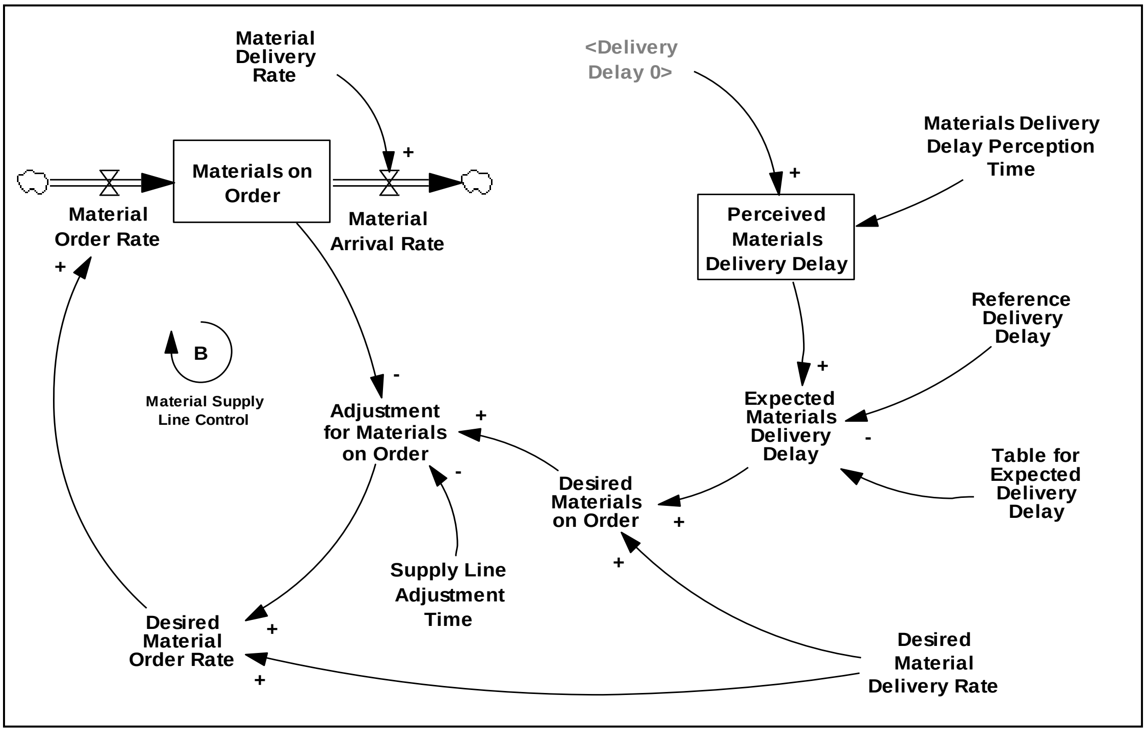

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Figure 31 Materials supply line (Sterman, 2000)

5.3.2.9 Results from the SD model

This model runs for 50 weeks. The customer demand signal is 10,000 units per week from weeks 0 to 5. At week 5 the demand increases by 20% to 12,000 units per week. System Dynamics models of supply chains display three key characteristics namely amplification (the ratio of demand as we move upstream in the supply chain), phase lag (the delay in the response to the demand signal) and oscillation (the return of the system to equilibrium), (Sterman, 2000). Figure 33 shows the results mapping six key variables in this model, namely: customer order rate, production start rate (firm), material delivery rate (firm), production rate 0 (supplier), production start rate 0 (supplier) and material delivery rate 0 (supplier). We can see that the step change in customer demand is amplified as we move down the supply chain, the amplification being larger in the supplier than in the firm itself. We can also see phase lag i.e. a delay in the response of the system which increases as we move upstream in the supply chain. Finally, we can see evidence of oscillation, for example in the production start rate 0 which seems to return to an equilibrium position between weeks 35 and 40.

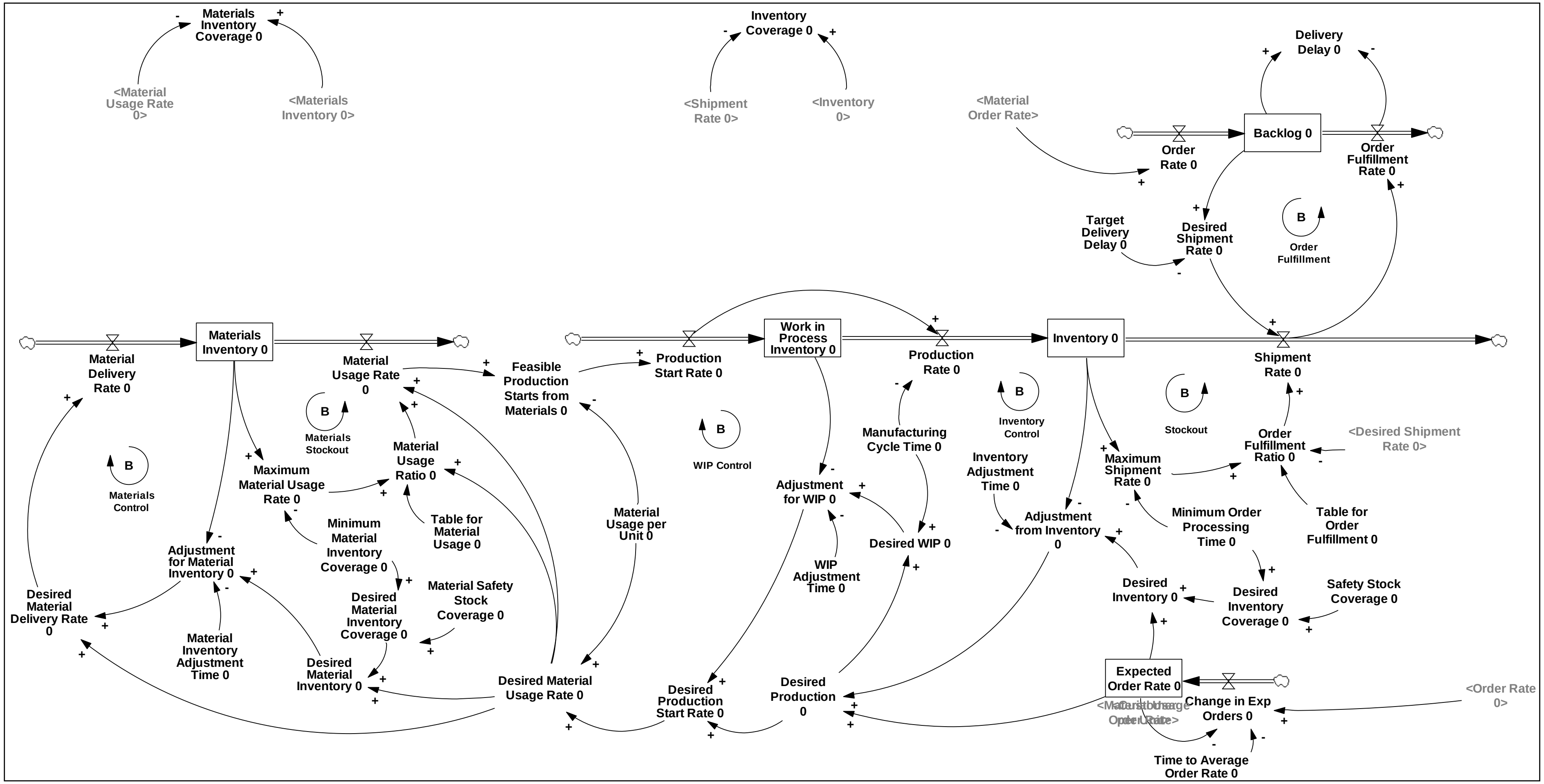

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Figure 32 Overall supplier model (Sterman, 2000)

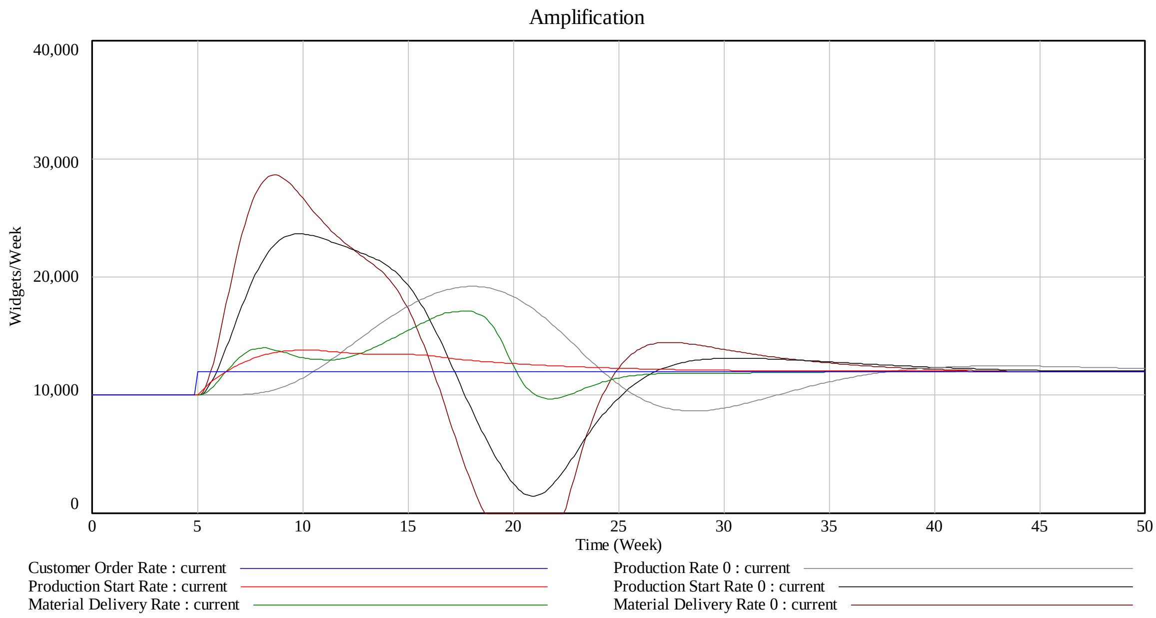

Figure 33 SD model results

5.3.3 Description of the Agent Based model

5.3.3.1 Introduction to Netlogo

Netlogo (Netlogo, 2012) is a programmable modelling environment which allows users to develop agent based models. Netlogo has a simple programming language. Mobile agents (turtles) move over a grid of stationary agents (patches). Link agents can connect agents together to create networks. Netlogo was selected as the programming language for this case study because it is a well-known agent based language, it is relatively straightforward to learn and yet it can also be used to develop models of complex systems.

5.3.3.2 Modelling approach

The aim is to develop an Agent Based version of the John Sterman System Dynamics (SD) two echelon supply chain model described in the previous sections. The approach to the development of the agent based model is based on steps recommended in North and Macal (2007). In order to develop this agent based model, the first step was to define the structure of a generic agent in this system. Agents in the supply chain model have many roles and responsibilities, but they can be summarised as being related to the flow of either information or material. A generic agent structure was developed as shown in Figure 34.

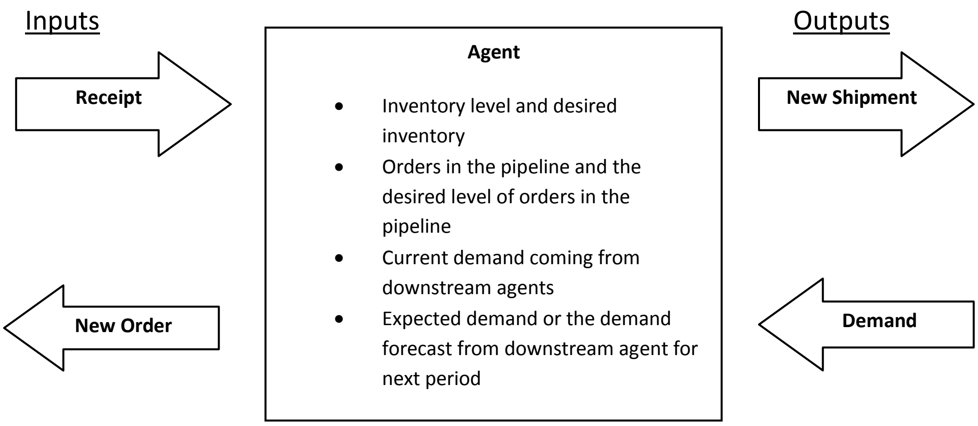

Figure 34 Generic agent structure

Having conceptualised the structure of a generic agent, the next step was to identify the different agents in the model. There are eight agents in the model in total starting with the customer agent, in the producing firm there is a shipping agent, a production agent, a materials controller agent and a buyer agent. In the supplier firm there is a shipping agent a production agent and a materials controller agent.

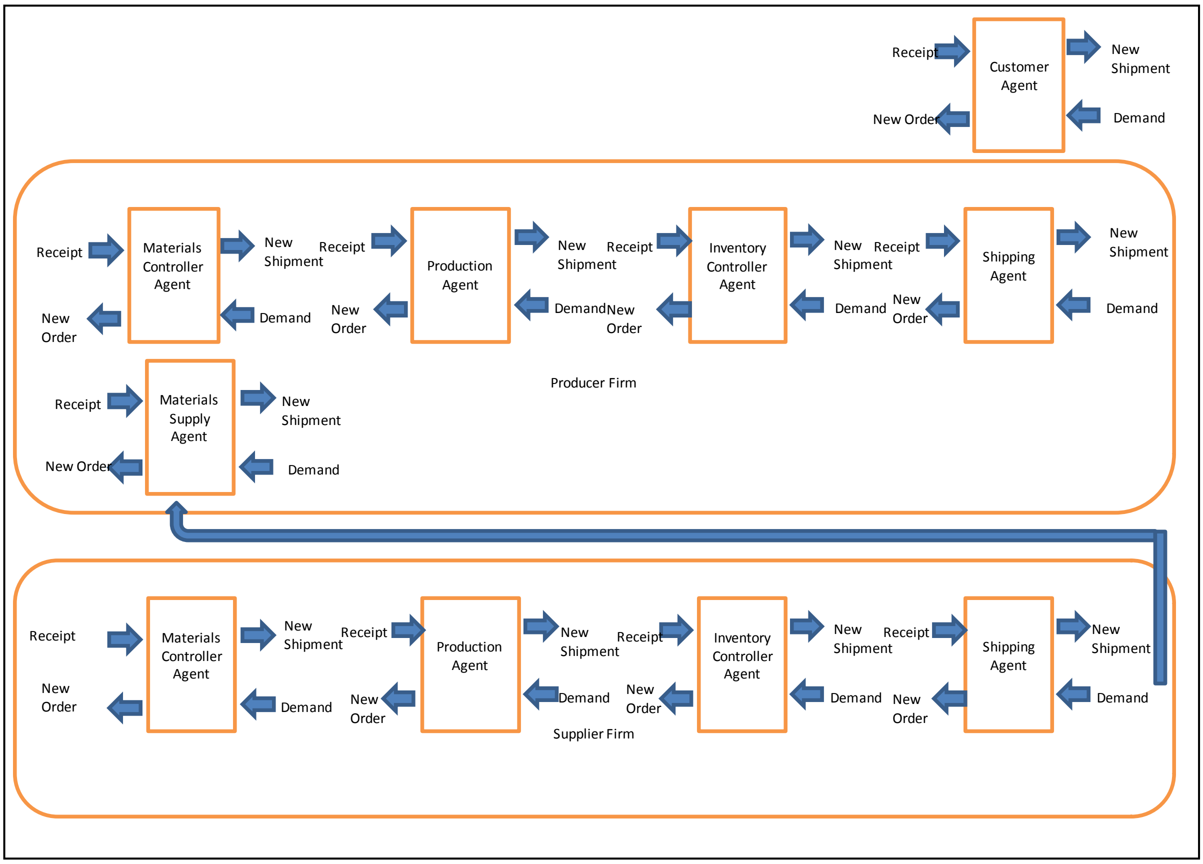

Figure 35 Agents in the supply chain model

In order to link the agents to the SD model, the following diagrams show the agent definitions superimposed on the SD model. The customer agent is the same as (Reprinted from Business Dynamics:

Systems Thinking and Modeling for a Complex World, by John Sterman pages 231-249, Copyright (2000), with permission from The McGraw Hill Companies).

Figure 25. Shipping, production and materials control agents are defined in Figure 38.

The buyer agent is defined in (Reprinted from Business Dynamics: Systems Thinking and Modeling for a Complex World, by John Sterman pages 231-249, Copyright (2000), with permission from The McGraw Hill Companies).

Figure 30. Having defined the agents, North and Macal (2007) recommend developing state diagrams to describe their behaviours. Figure 36 shows the state diagram for the shipping agent.

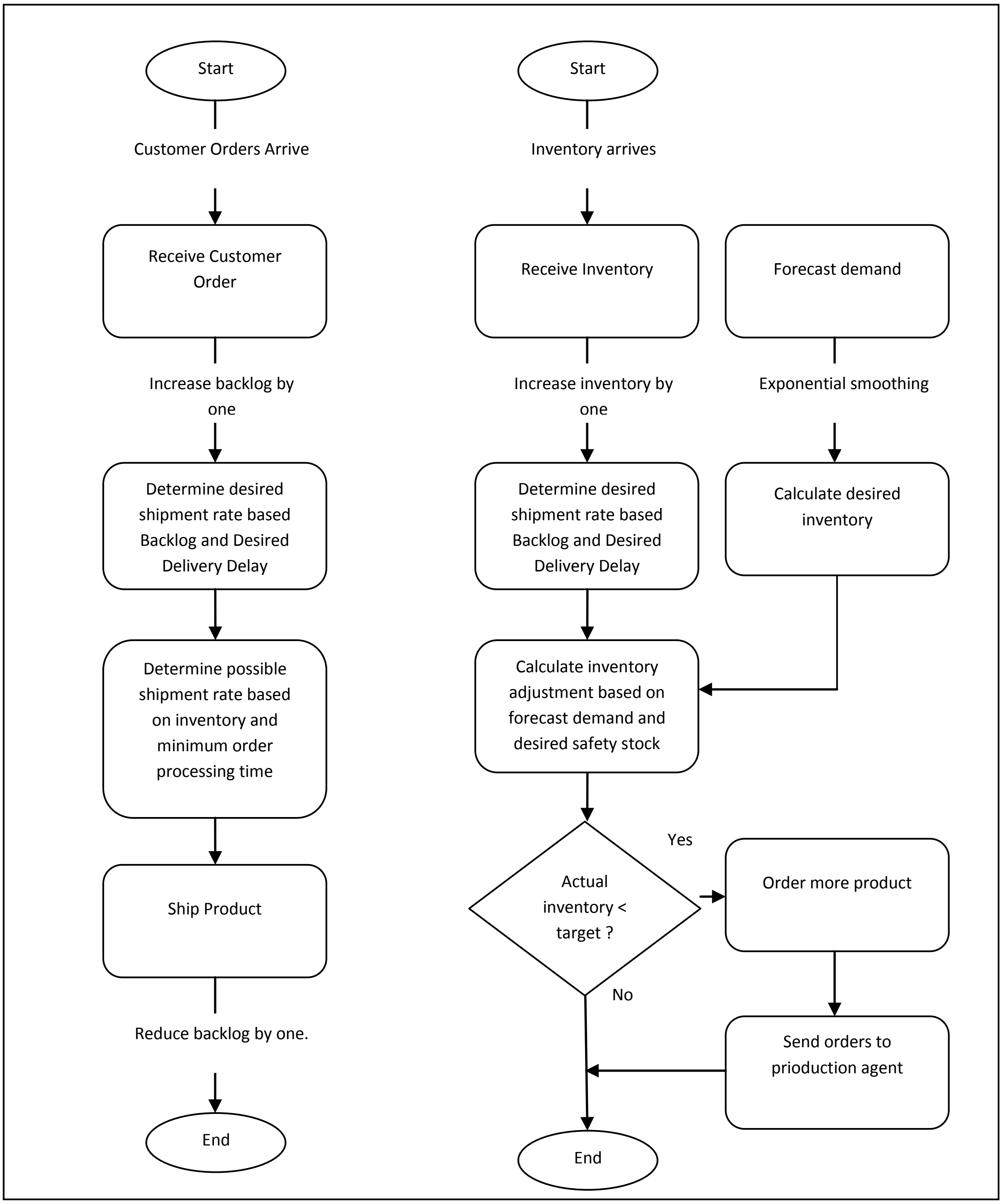

Figure 36 Shipping agent state chart

Figures 37, 39 and 40 show the state chart diagrams for the production agent, the materials controller agent and the buyer agent.

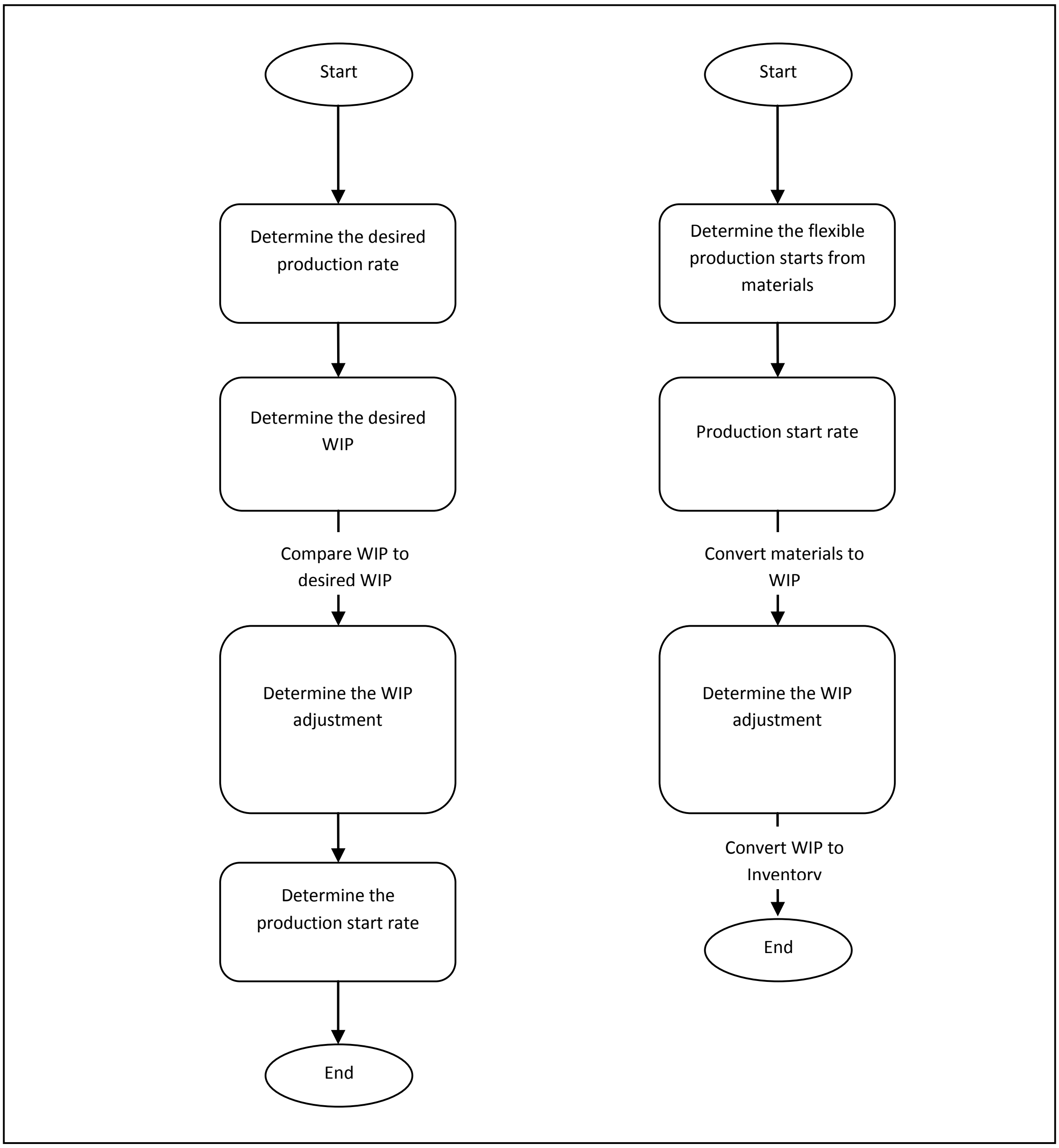

Figure 37 Production agent state chart

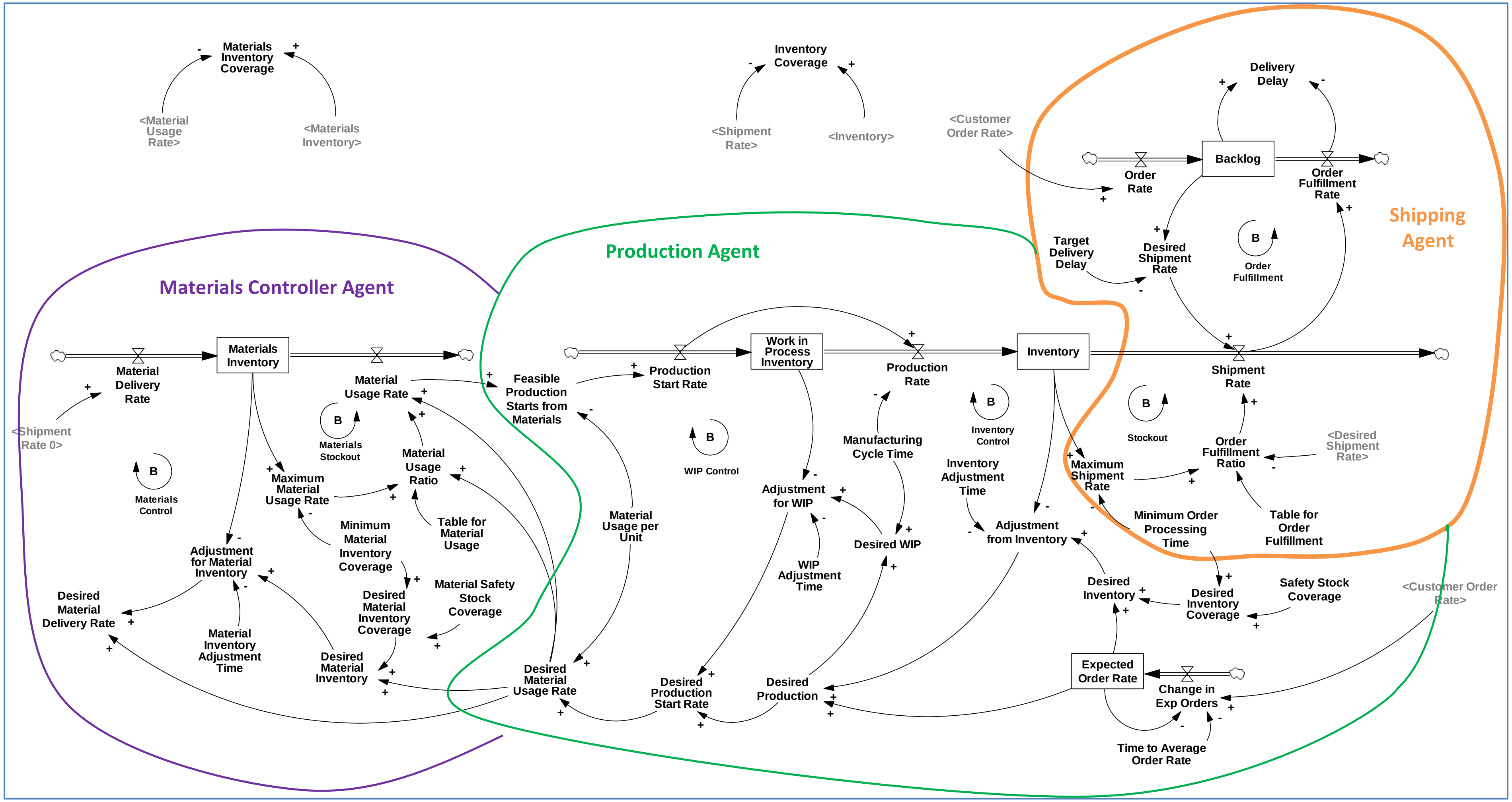

Figure 38 Agents superimposed on SD model

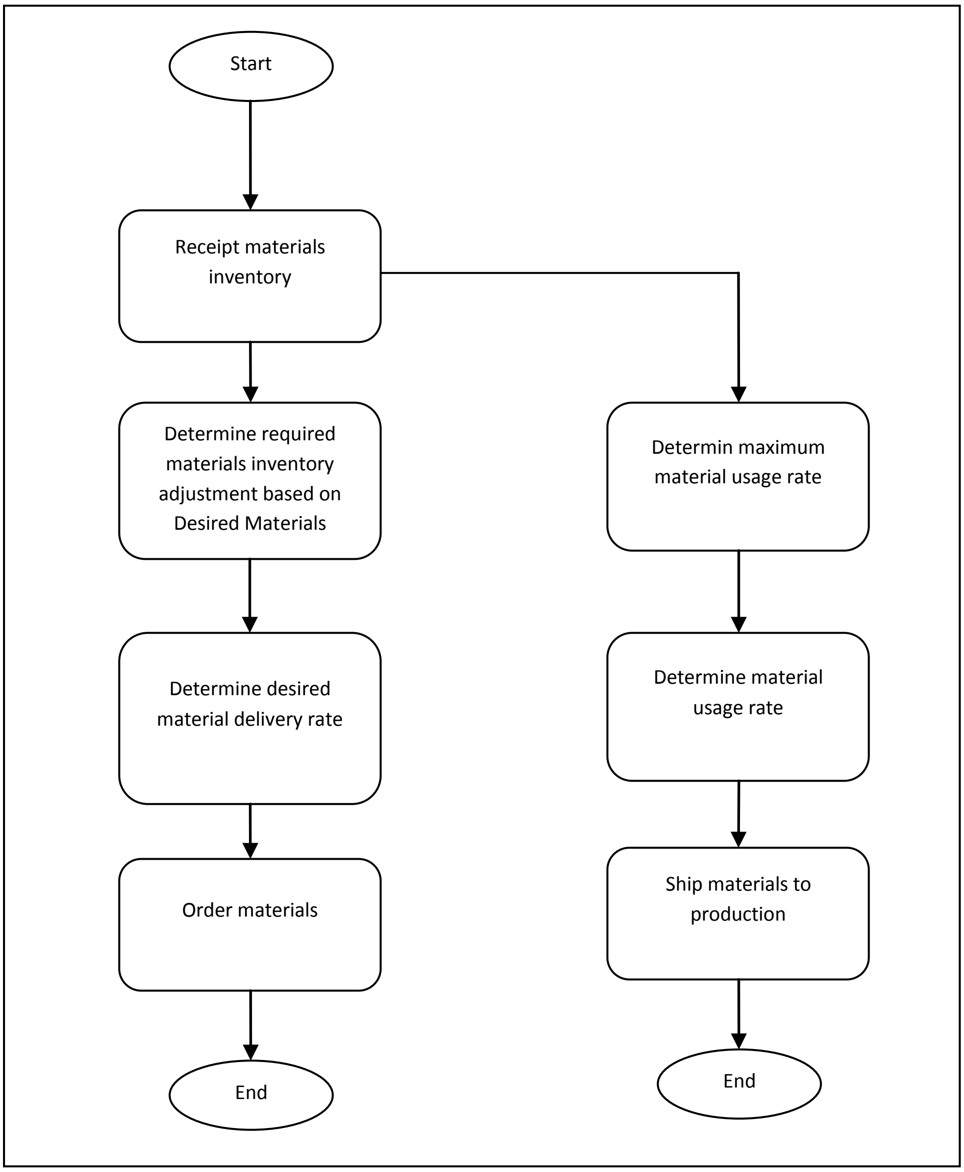

Figure 39 Materials controller agent state chart

5.3.3.3 Key differences in ABM Approach

In developing an agent based model of this generic supply chain, the overall approach is different to System Dynamics. The key differences will be explored in the following sections.

The overall structure of a Netlogo model consists of a number of key stages. The first is a declaration stage where the different agent types and variables are declared. Agent types are known as 'breeds'. The declaration stage is followed by a 'set up' phase where the model is initiated, all key variables are set and the agents are positioned in the agent space. This is followed by a 'run' stage in which the model is run including the calling of any sub-routines that may be required.

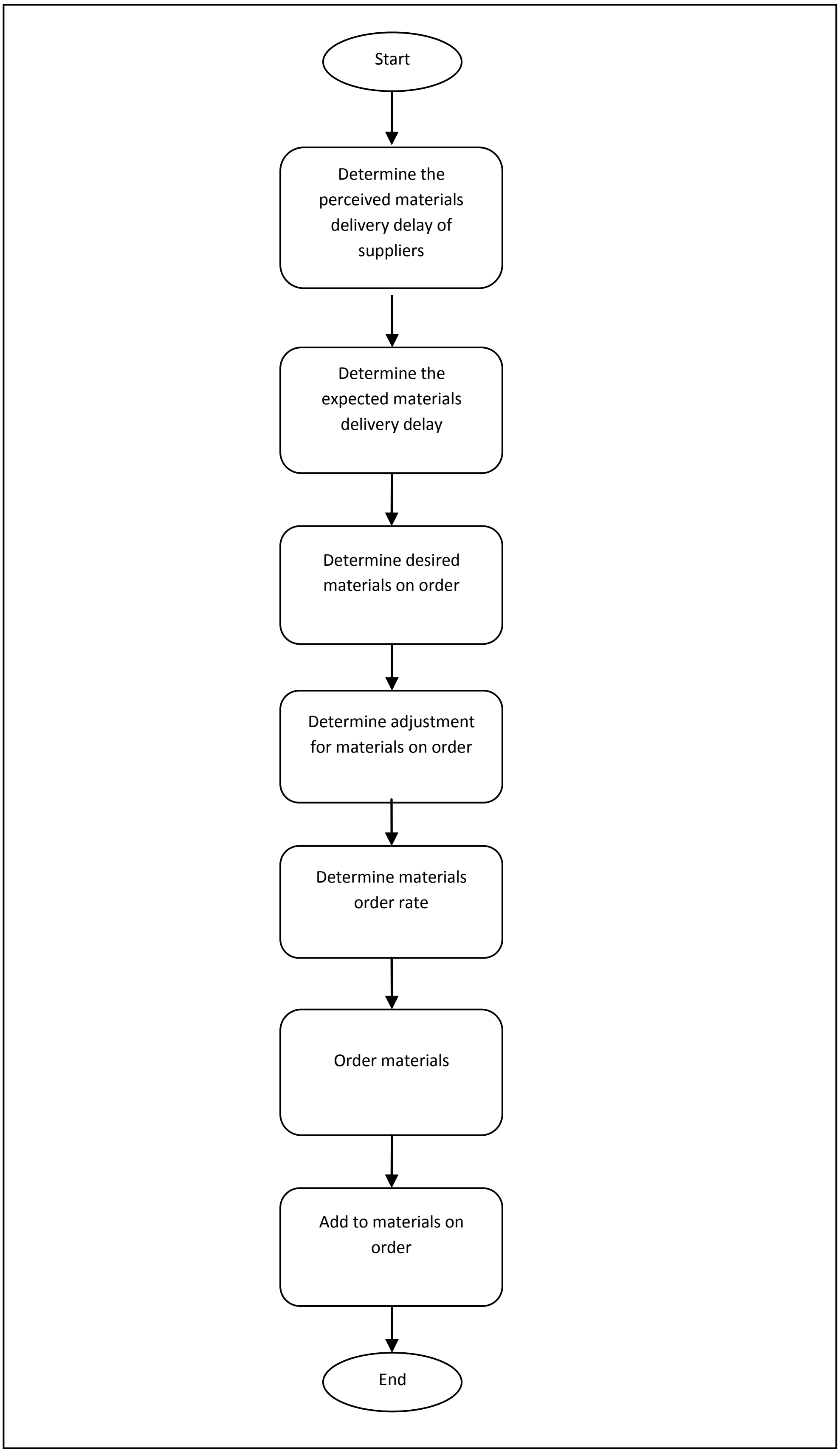

Figure 40 Buyer agent state chart

In Netlogo, connections between agents are achieved through agent links. In this case there is a need for two links i.e. a demand link through which to transmit the demand signal, and a supply link through which to supply the items. Thus in Netlogo there are two additional agents required to represent the supply chain i.e. a demand-link and supply-link.

The SD model of this supply chain uses look up tables to create certain values. There are three look up tables in the model, namely ‘Table for Order Fulfilment’, ‘Table for Material Usage’ and ‘Table for Expected Delivery Delay’. These tables allow for an output variable to be calculated based on an input variable. An example of this is shown in Figure 41.

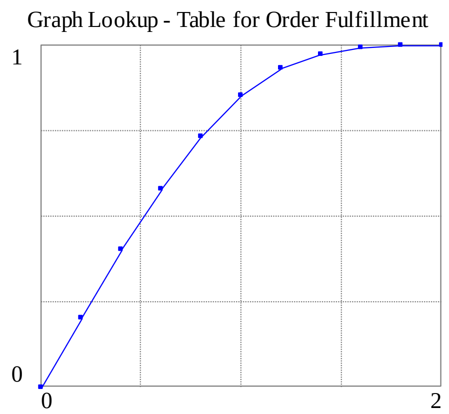

Figure 41 Table for order fulfilment from SD model

This represents the fact that as the desired shipment rate increases the actual shipment rate will rise towards the maximum shipment rate. This approach needed to be replicated in the agent based model so that it was faithful to the SD representation. This was done using nested ‘IF’ statements to mimic the effect of the look up table.

One challenge in building an agent based model of this system is how to represent delays. For example, in the Vensim model, the production rate is a third order delay of the production start rate. In Netlogo, the approach to representing the delay was to use the 'list' function. This means that a queue can be created by adding values to the beginning of the list and taking them from the end of the list each time advance. The length of the queue is equal to the delay being experienced. Thus the list function allows us to simulate the effect of a delay or a queue. This is not quite precisely the same as the delay function used in Vensim which is a mathematical third order delay.

The full code of the Netlogo model with explanatory text is contained in the Bullwhip folder of the accompanying CD. The graphical appearance of the Netlogo Agent Based Model is shown in Figure

42. The results of running the model over the same time period as the SD model are shown in Figure 43.

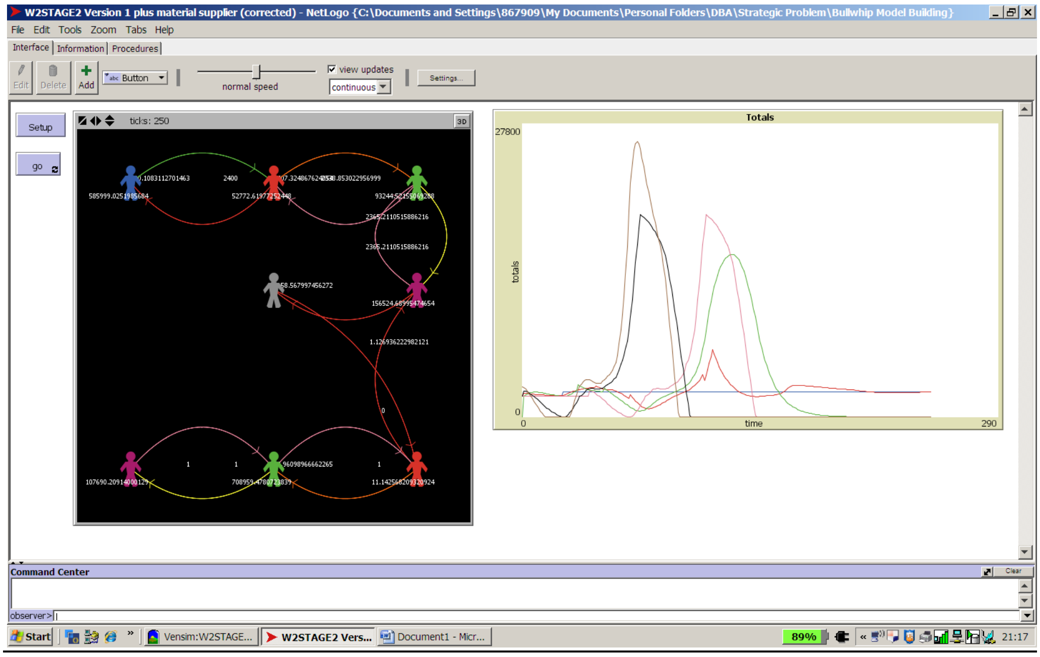

Figure 42 Netlogo supply chain model

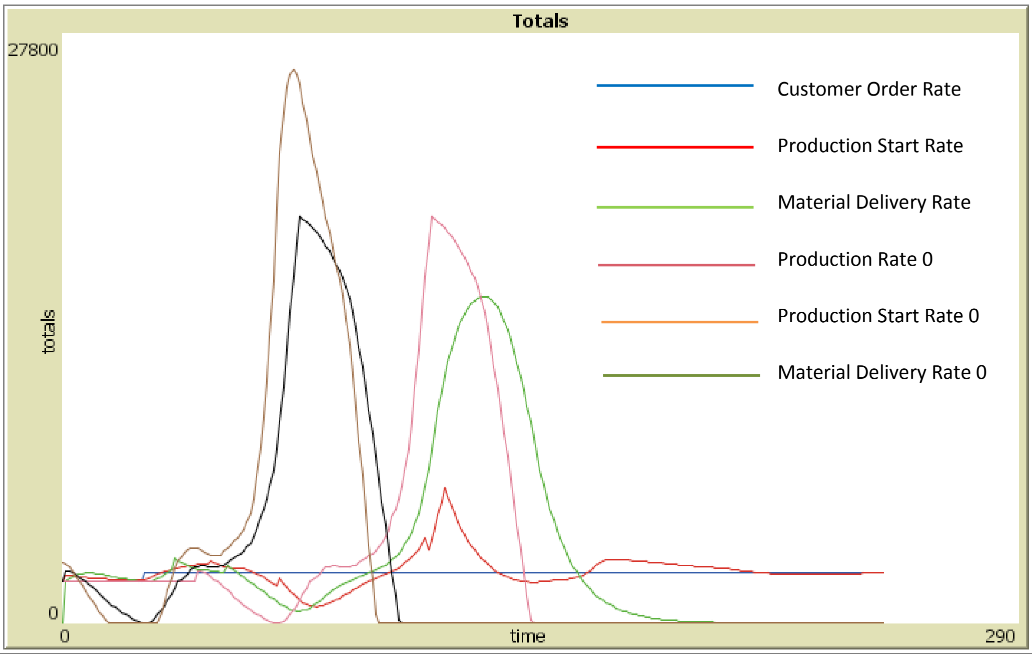

Figure 43 Results from Netlogo model

5.2.3.4 Discussion of results

Both models are intended to be the same and thus to produce the same results. However, there are differences in the way the models have been built and thus we might not expect identical results. In particular, the way that delays are modelled is different. In the SD, the delays are modelled as third order delays, whereas in the Netlogo model they are modelled as pipeline delays. The look up tables in the SD model are approximated in the Netlogo code but not replicated. In the results of both models we can observe the classic dynamic phenomena of phase lag, amplification and oscillation caused by the delays and ordering behaviour in the model. A relatively small 20% increase in customer demand in week five results in an amplified increase in the material delivery and production start rate in the first tier firm as it struggles to maintain inventories at target levels. These rates are further amplified in the supplier. The resultant oscillations do not die down until week 40 in both models. The differences in the behaviour of the models can be explained by the differences in the logic employed in the coding of the model. The overall behaviour of the models is however very similar.

5.3.4 SD archetypes

System Dynamics investigates and models the behaviour of dynamic systems. When building an SD model, the modeller attempts to discover the underlying dynamic behaviour of the system. SD has developed a number of types of dynamic behaviour and these can be described as system archetypes. Sterman (2000) identifies three fundamental modes of dynamic behaviour: exponential growth, goal seeking and oscillation. There are three other modes which are in fact a combination of these three modes and these are s-shaped growth, growth with overshoot and overshoot and collapse. These modes of behaviour can be described with causal loop diagrams and associated SD stock and flow models. At a certain point in this research, the author was unsure whether SD models could be represented using discrete modelling approaches such as DES and ABM. One way to test this is to discover whether discrete versions of the classic SD archetypes can be built using a discrete modelling approach. If this is possible, then in theory at least, any SD model should be able to be modelled using a discrete approach. This is because any SD model will consist of one or more of these archetypes linked together. The following sections describe the building of these models and the conclusions drawn. The detailed models for the SD archetypes are contained in the relevant folder of the accompanying CD.

5.3.4.1 Exponential growth

Exponential growth occurs due to positive reinforcing feedback. The larger the quantity is, the larger the rate of increase. An SD representation of this as a causal loop diagram is shown in Figure 44. A simple agent based model of this can be developed in NetLogo. In this program, turtles (agents) are created. In the first instance one turtle is created. Then each time advance the turtles multiply, reproducing themselves. This simple action of reproduction creates exponential growth. In the case of the agent based model, effectively the state of the model at any given time (i.e. the number of agents in the model) directly influences the rate of increase in the agent population. The results of this simple Netlogo model can be seen in Figure 46.

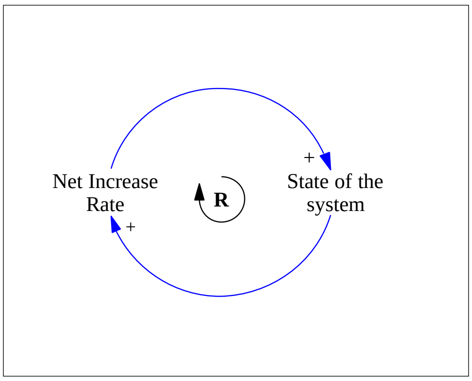

Figure 44 SD Causal loop model for exponential growth

5.3.4.2 Goal Seeking

Goal seeking behaviour occurs when a negative feedback loop serves to bring the state of a system in line with a desired state. The SD causal loop version of this behaviour is shown below in Figure 45. Again, a simple agent based model of this can be developed in NetLogo. In this case the number of turtles created each time step is determined by the gap between the current population and the target population. The results of running this model are shown in Figure 47.

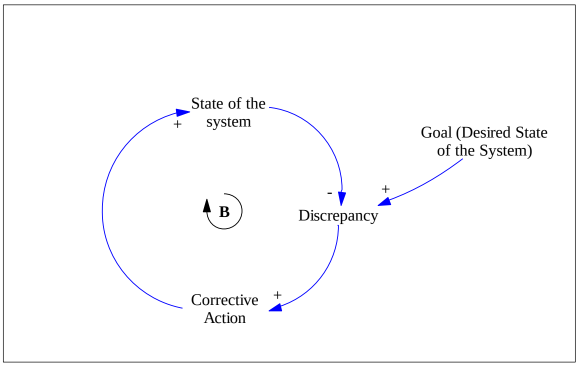

Figure 45 SD Causal loop diagram for goal seeking

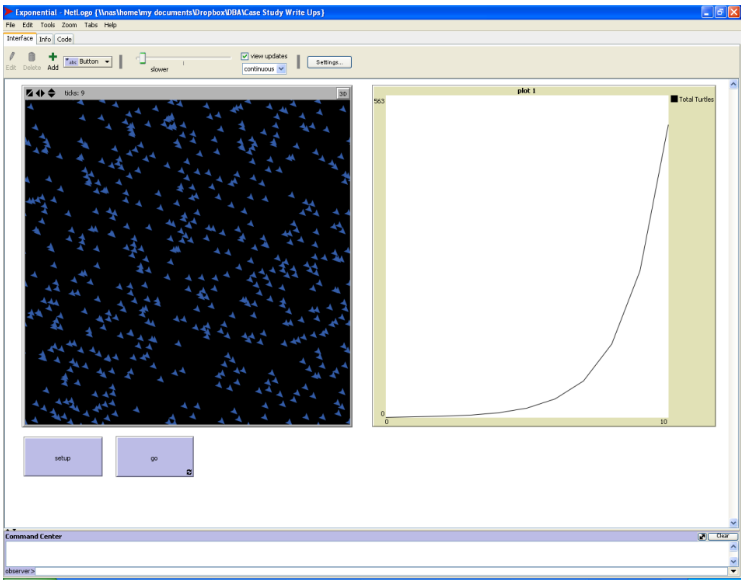

Figure 46 Exponential growth - agent based model

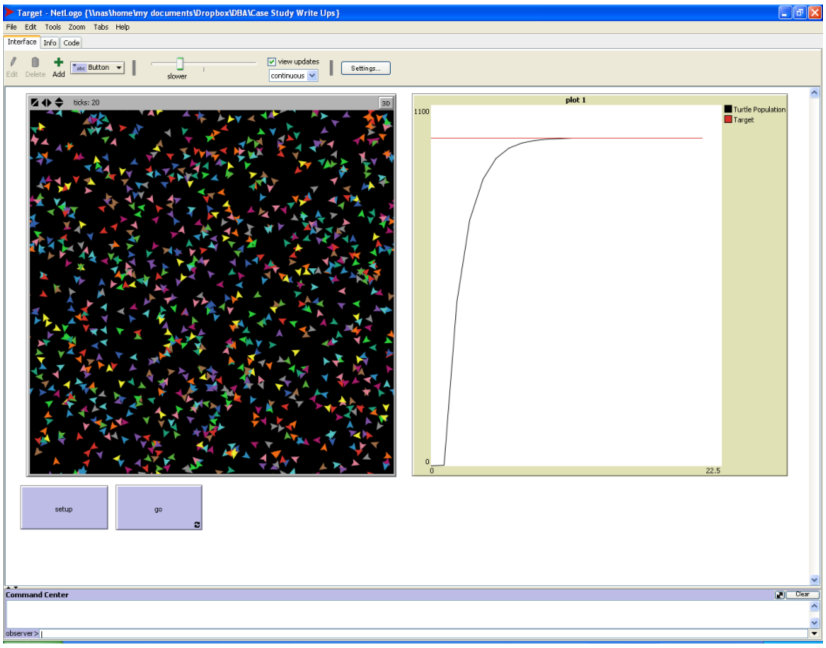

Figure 47 Goal seeking - Agent Based Model

5.3.4.3 Oscillation

Oscillation is the third fundamental system behaviour identified by Sterman (2000). Like goal seeking, oscillation is caused by negative feedback loops. However, in this case there are information delays involved. As a result, the system overshoots the target because the view of the current state of the system is delayed. This means that the system state oscillates around the target state. The causal loop diagram for oscillation is shown in Figure 48.

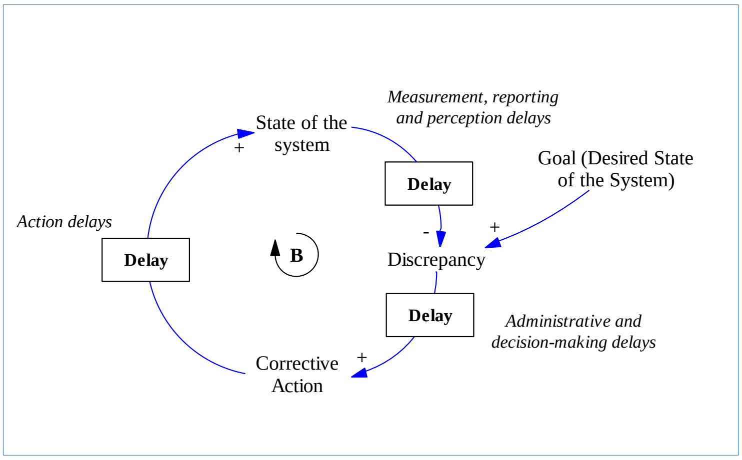

Figure 48 SD Causal Loop Diagram for oscillation

A simple agent based model of this can be built. In this model turtles (agents) are created in relation to a target level. The turtles go on being created until they meet this target. If the number of turtles exceeds the target level, then they are destroyed. However, in this case the number of turtles in the system is stored into a ‘memory’. This means that each time step the number of turtles considered to be in the system are the number that were in the system four time clicks before. This has the effect of introducing one of the delay types represented in Figure 48 i.e. a measurement delay. The consequence of this is that the model displays the classic oscillation behaviour, see Figure 49.

5.3.4.4 Discussion and conclusion on SD archetypes

The System Dynamics approach involves developing a model of a dynamic system. From an SD perspective, there are a number of fundamental dynamic behaviours or modes for systems. Fundamentally, these modes involve either positive or negative feedback and delays of either information or material flow. It has been demonstrated that it is possible to build discrete agent based models of the three fundamental system behaviours. What this means is that any model developed using SD can be replicated in terms of its technical operation, as a discrete model. That is not to say that the full method involving causal loop diagrams and the overall philosophy of the approach can be replicated, but rather that the technical workings of any model developed in SD can be replicated in a discrete model. The author contends that this is a significant finding, because although this may be expected, or even received wisdom, it has not been demonstrated analytically and from first principles in this manner before. Given that SD models are continuous in nature, it might be expected that any system modelled and represented as a continuous system could be reproduced as a discrete model, but by demonstrating that all the key building blocks of the SD approach can be replicated, this means that any model can in theory also be replicated. The implications of this are significant for practitioners or those trying to choose between different modelling techniques. This is because although any SD model can be built using discrete methods, the converse is not true. Thus for SD to be the method of choice in any given scenario, it must first of all be suitable and usable for the desired application. If this is the case then for SD to be chosen it should offer some additional benefits to the modeller above the technical modelling of information or material flow analysis.

5.3.5 Reflections on differences in modelling approach

As has been discussed previously, the ‘back to back’ modelling of the same problem or system using different approaches is likely to provide insights into the relative strengths and weaknesses of the techniques. The following section will provide reflections on the relative merits of SD and ABM in modelling the Bullwhip problem and in relation to the case study propositions.

Proposition 1 (P1): Discrete methods of simulation can be useful in investigating strategic problem types as well as System Dynamics in the supply chain domain.

The Bullwhip phenomena can be considered as a strategic problem type, since it can provide insights into the dynamic behaviour of supply chains. These insights could influence the design of the supply chain and other strategic aspects such as whether to outsource activities or perform them in-house, where to locate and choice of configuration (Chopra and Meindl, 2007).

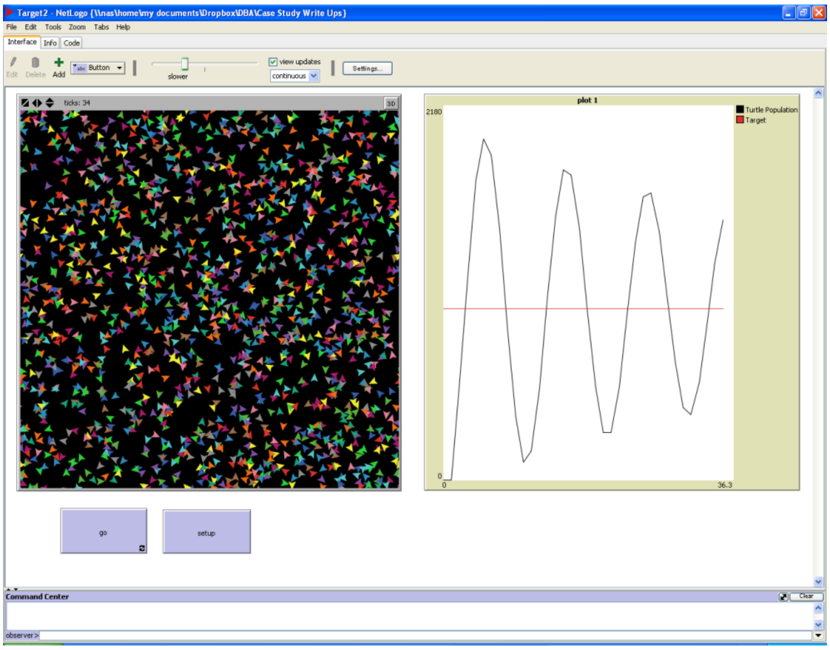

Figure 49 Oscillation - Agent based model

The use of SD in the strategy area is more established, the question is whether discrete methods can also be used to illuminate strategic problems. This case suggests that it is possible the model the Bullwhip effect very effectively using an agent based approach. The main difference observed between SD and ABM is the transparency of the model, its variables and the relationship between them. Although the same variables and formulae are effectively present in the ABM model, they are hidden in the software code. This might influence the usefulness of the model or its transparency to a group of senior level decision makers, for example.

Proposition 2 (P2): Discrete methods of simulation can represent supply chain feedback effects in models.

The modelling of SD archetypes demonstrates that discrete methods can be used effectively to model positive and negative feedback and information delay. The Bullwhip effect is a classic consequence of the interplay between the flow of information and material in a system. Feedback takes various forms in the model, for example where inventory levels feedback to production rates upstream in the supply chain. Another example is where the customer order rate is fed back through the system to trigger material and production rates upstream. As has been demonstrated in the case study, all these forms of feedback can be represented in the agent based model. Netlogo provides specific agent links to allow for the transmission of information and material between agents. However, what is different is the transparency of these feedback loops. In the SD model, the flows of information and material are explicitly represented, whereas in the agent model the feedback is hidden although present in the logic of the model and the agents themselves.

Proposition 3 (P3): System Dynamics can model supply chain problem types at the operational end of the spectrum as well as the strategic.
This case study is considered a strategic problem type although there are some operational aspects in the model. As a result, this case has not explored the use of SD to model operational problems, this will be the focus of later case studies. It is interesting to note that SD must employ look up tables in order to model certain aspects of system behaviour.

Proposition 4 (P4): The nature and role of decision makers in the problem may influence the selection of simulation technique.
A key difference observed when building the agent based model is the locus of decision making. In an agent based model, every decision must be located within an agent. This forces a clear association between a given decision making rule and an individual within the system. If an agent based model was being constructed in real life, the decision heuristics would be obtained from individuals through interviewing. In this case study, the decision making processes from the SD model had to be associated with the agents identified in the model. One advantage of this approach over the SD approach is that it is much clearer where decisions lie. In the SD model, the decision making processes are not associated with a particular agent. Thus, taking an agent based approach could provide more clarity in terms of surfacing the key decision making processes, but also make it easier to validate the processes. This is because the decision process can be validated with the human agent in the system to ensure that the behaviours are being faithfully reproduced in the model. On the other hand, one advantage of the SD model is the transparency of the decision making processes. The transparency is not complete, because the mathematical formulae of the model are hidden. However, the main stocks and flows, key variables and information flows are visible. Thus, arguably, the decision making process is more transparent than in the agent based model.

Proposition 5 (P5): The purpose of the modelling (exploratory, problem solving or explanatory) may influence the selection of simulation technique.

Three purposes for modelling were identified in the literature review i.e. understanding, problem solving and exploration. A particular model may be used primarily for one of these purposes or indeed for several at the same time. The case study models developed here could be used for all three purposes. There is perhaps an argument that the transparency of the SD model lends itself more readily to achieving these goals in a group situation, because the processes and decisions are explicitly there for the non-expert to see and interact with. The agent based model relies more heavily on the expert modeller to modify the agent behaviours. The expert modeller will be needed in the agent based model more so than in the SD model to act as the go between. The SD model perhaps provides more opportunity for direct interaction between the members of the real world system and the model itself.

5.3.5.1 Scalability

In the ABM the agents are defined once and can then be replicated in the model. This means that the agent based approach is inherently more straightforward to scale up than the Vensim SD model. The use of agent links to connect agents is also a feature which allows a degree of flexibility. Thus the ABM could more easily be scaled up to include large numbers of suppliers and customers and additional echelons. The SD model is inherently more difficult to scale up. Although the SD model contains generic structures for the different stages of the supply chain, it is more technically challenging to replicate these, link them together. It could become more challenging to create larger numbers of companies in the SD model.

5.3.5.2 Key stages of model construction

The approach taken in this case was to start with the SD model of the two echelon supply chain and replicate this using an agent based approach. This meant that the model had already been conceptualised as an SD model before it was then built as an agent model. The key stages of the generic OR modelling process can be defined as problem definition, conceptual modelling, model coding, model validity, model results and experimentation and finally, implementation and learning (Tako, 2008). Arguably, in this case study, the problem definition and conceptual modelling had already taken place using an SD approach. Some conceptual modelling was then done in ABM but it was more the translation of the SD concepts into an agent framework. In fact it was at this point that a number of problems of equivalence were encountered in terms of how to represent delays, look up tables and the transmission of information and material. Once this conceptual modelling phase was complete the model was then coded in Netlogo. The implications of this are quite important, because differences in modelling approach can occur at each stage of the modelling cycle. If the Bullwhip problem were approached for the first time by an agent based modeller, they might conceptualise the problem differently from an SD modeller.

5.4 Strategic purchasing case study

5.4.1 Introduction to modelling approach

The background to this case has been described in section 5.2.2. This case deals with a strategic supply chain problem which was the subject of a consulting assignment by this researcher. The approach in this case was to build a System Dynamics model of the problem using the overall approach as defined in Sterman (2000). The model was then used to provide insights into the appropriate policies that might be appropriate in achieving the overall goals of the project. The problem was then modelled again, this time using an agent based approach as recommended by North and Macal (2007). In this case the approach led to different results and conclusions. These differences are discussed and evaluated in later sections. The case description covers the 'entering the field', 'analysing data' and 'sharing hypotheses' phases of the case study protocol.

5.4.2 Description of the SD model

As described in Chapter 2, Sterman (2000) describes SD modelling as an iterative, five step process (see Figure 7).

5.4.2.1 Problem articulation

The first step in the process is problem articulation. Sterman (2000) recommends that at this stage the modeller defines the key variables, the time horizon and the dynamic problem definition. In this case the focus of the problem is the organisation of procurement in a large construction firm. At a strategic level the firm management has decided that procurement savings are available if spend that is currently fragmented and decentralised could be aggregated at the centre. To illustrate the overall vision of the firm, Figure 50 shows an overall description of the project vision and goals. Part of this vision concerns the organisation of the procurement activity. By aggregating the spend, better value procurement deals can be done with suppliers. For example, if at present individual operating companies are purchasing their own concrete, if a central deal on concrete can be done then a better price and service for the whole group can be secured. This idea does not apply universally across all categories, but overall it was a guiding principle for the project. Fundamentally, the problem concerns the degree of centralisation versus decentralisation of procurement. In a federated model, operating companies within a large group prefer to retain control of decision making. In terms of purchasing, this means that they are better able to control the process and ensure that suppliers conform to specification and that they perform. Thus there is an inherent tension between the drive to centralise and the drive to retain local control of procurement. The appropriate time horizon for this problem is in the order of 1-3 years because this is the time frame over which a change of this strategic nature would be implemented.

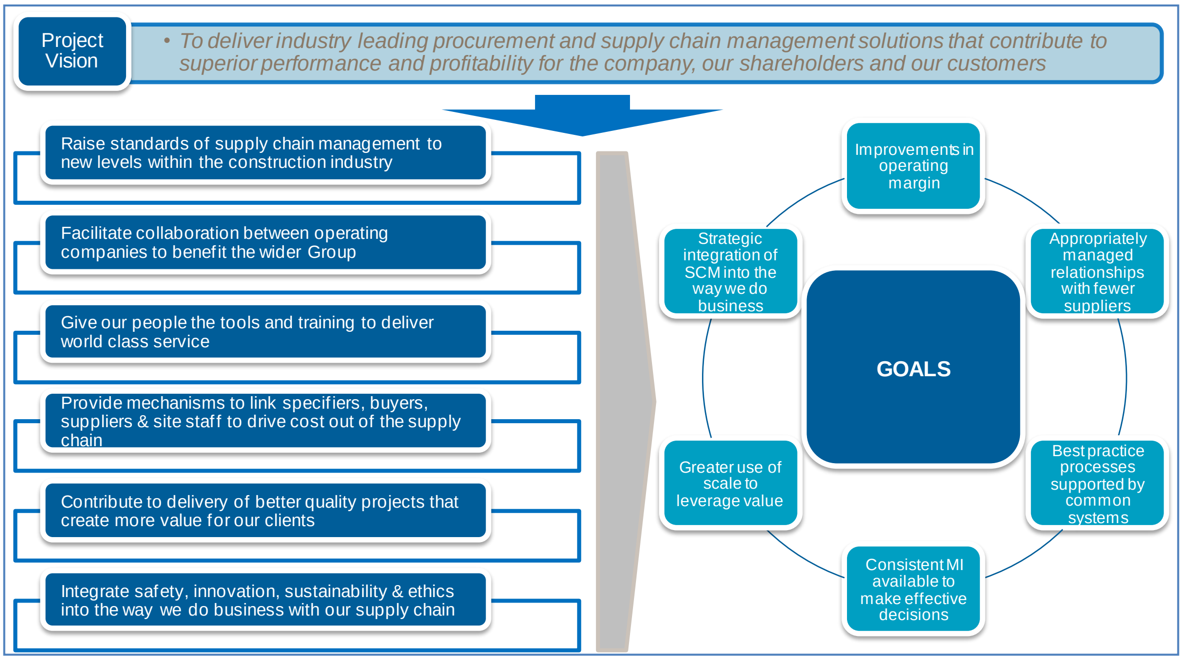

Figure 50 Overall procurement vision

This is because it would take several months to move procurement of a given category from one mode of procurement to another. In terms of key variables, these were identified by the author as:

- Spend value
- Categories of spend
- Operating companies
- Central procurement
- Savings
- Rebates
- Suppliers
- Performance
- Service
- Quality

The dynamic problem definition is described by Sterman (2000) as: *"What is the historical behaviour of key concepts and variables? What might their behaviour be in the future?"* Historically, in this firm, only a small fraction of spend has been centralised. The supply base has been highly fragmented, with a large number of suppliers and spend consolidation has been limited. The federalist culture is characterised by an appetite for local control and performance. In addition, there is a perception that local control of purchasing decisions improves the service and quality received. On the other hand, there are views in the firm, particularly in the larger business units that savings are possible if spend is consolidated and placed with fewer, more capable suppliers. Thus there is a drive towards more spend consolidation and central control of purchasing from some elements within the organisation. In terms of the future, senior management clearly require significant savings and believe that a key source of these savings will come from a more strategic and professional approach to procurement. The senior management of the firm have engaged external consultants to assist them in achieving this objective. The sources of data for this problem articulation phase were many and varied. Each source of data provided more information, but also triangulation. Table 16 shows the different data sources used for the problem articulation phase and what was learned from each one. Figure 51 shows the governance structure for the project, this shows the different groups responsible for the overall direction of the project. Attendance at these meetings allowed the researcher to start to develop an understanding of the goal of the project and also the likely dynamic process that would ensue based on the culture and features of the organisation.

Source of Data	Key Learnings	SD Phase informed	Relevance to Dynamic Hypothesis
Project Launch meetings - Consulting firm - Organisation	• Formal project objectives • Formal project approach and methodology • Project risks • Project structure	• Problem articulation	• Reinforcing Loop
Meetings with key stakeholders - Project Leadership Team	• Project strategy • Perception of key dynamics of the process	• Problem articulation • Development of dynamic hypothesis	• Reinforcing Loop
Project Initiation Document (PID)	• Project vision and objectives • Organisational structure of project and organisation	• Problem articulation	• Reinforcing Loop
Industry Day with Heads of Procurement for each Operating Company	• Reaction of the operating companies	• Problem articulation • Development of dynamic hypothesis	• Reinforcing Loop • Balancing Loop

Table 16 Data sources for Problem Articulation and Dynamic Hypothesis

5.4.2.2 Dynamic hypothesis

Following problem articulation, the next stage in the process is the formulation of a dynamic hypothesis. The first step is to define a model boundary chart, and to identify which variables are external to the model (exogenous), which are generated in the model itself (endogenous) and which are to be excluded. An initial view of these variables for this problem is shown below Table 17. From the initial project launch meetings and the PID, it was clear that the leadership of the firm anticipated that the consolidation of spending would lead to savings and service improvements. These savings and service improvements would serve as a stimulus and drive for further central deals. From an SD perspective, this is known as a reinforcing loop i.e. a set of variables which are increasing the degree of spend consolidation. In the early days of the project it was not apparent that there might be resistance to this seemingly beneficial policy. Although previous attempts to do this had only had limited success in the firm, the reasons for this were not initially apparent. Further clarity on this came during the industry day.

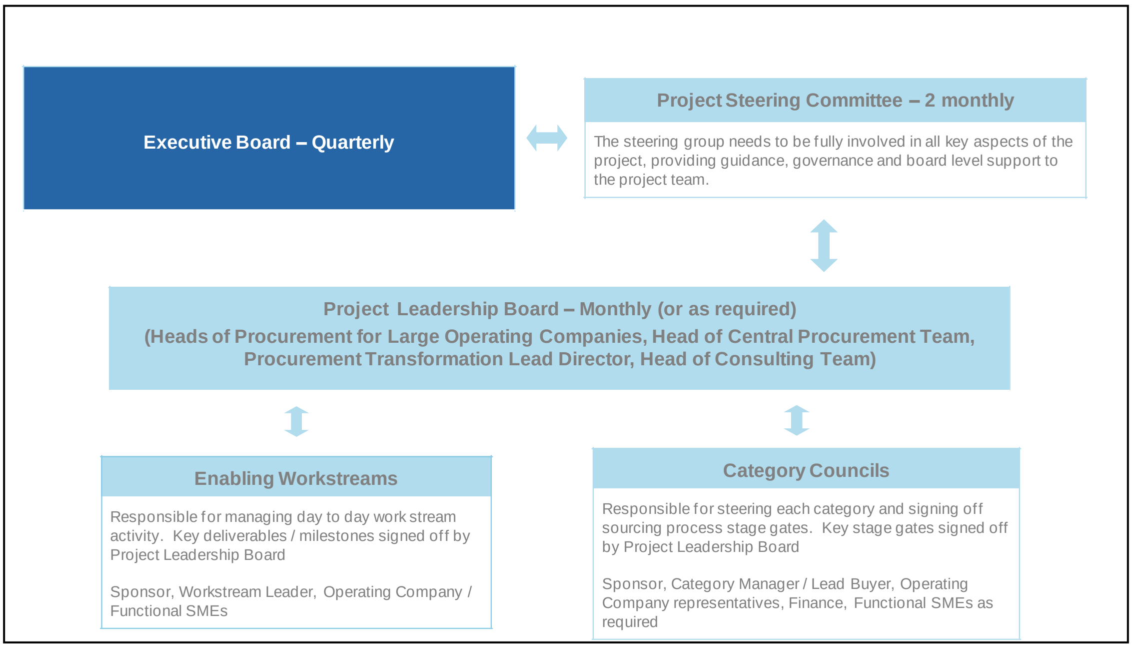

Figure 51 Project governance structure

The industry day was when the project was launched officially to the procurement managers for each of the operating companies. On this day, it became apparent that the purchasing managers were concerned about the loss of control over price and quality that they would experience through a centralisation of procurement. They prefer the ownership they currently enjoy through controlling which suppliers are used. The other issue that came to light was how savings would be calculated and shared. Local procurement managers are measured on the basis of the performance of the supply chain, but more importantly how they deliver savings to their operating company. If savings are delivered centrally, they argued, how would these savings be credited and to whom would they be credited? This issue exists on two levels. It exists at the company level, i.e. are the savings credited to the operating company or to the Group? Secondly, it exists at the level of the purchasing manager. Are their incentives and bonuses affected? Purchasing managers pointed out that in the past central savings had been delivered back to the operating companies as a rebate. However, they claimed, this rebate did not always arrive, and there was always a long delay before it was paid by the central group. Thus there appeared to be a potential resisting loop to the centralisation idea. An initial attempt to formulate a working dynamic hypothesis is shown in Figure 52. The reinforcing loop operates because the more that spend is consolidated, the greater the savings and thus the greater the perception of the benefits of consolidation. As the perceived benefits of aggregation increase, this serves to increase the aggregation of spend. On the other hand there is a balancing loop of factors which are serving to limit the extent of spend consolidation. The balancing loop operates to constrain this trend because the more spend is consolidated, the greater is the perceived loss of local control by the operating companies and the higher the concern over aggregation. The limiting factor to the spend consolidation is the limit placed by the operating companies themselves.

Exogenous	Endogenous	Excluded
Initial supply market liquidity Limit to local loss of control	Spend Savings Supply market consolidation	Number of suppliers

Table 17 Variables in purchasing model

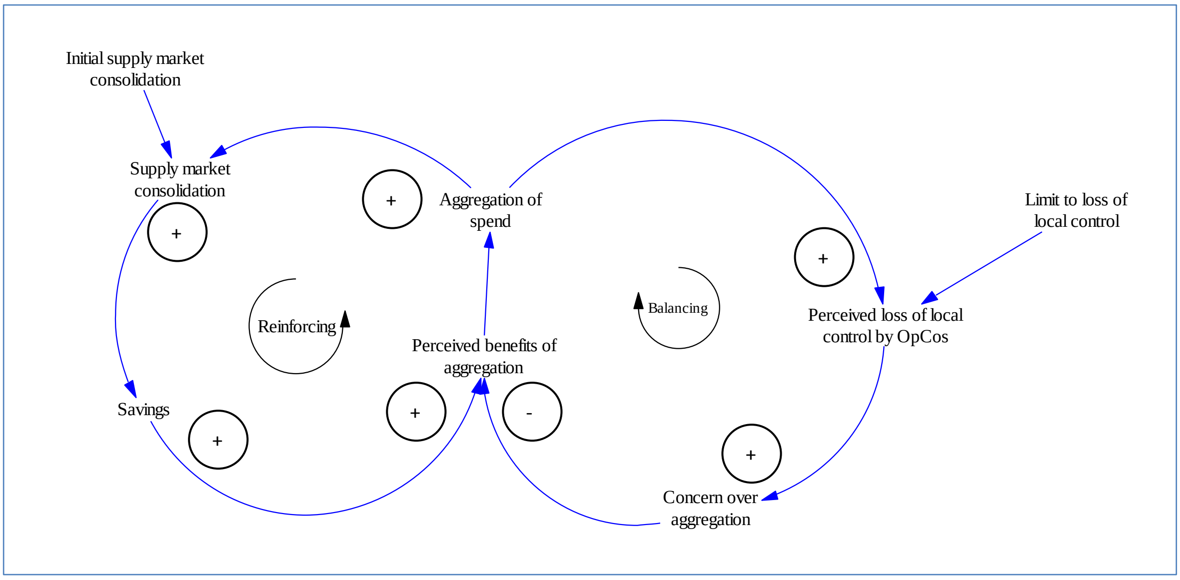

Figure 52 Purchasing problem - dynamic hypothesis

Having developed a high level description of the dynamic hypothesis, this was tested with colleagues in the consulting team to test whether this was seen as a robust description of the system given the understanding of the decision making process. At this stage, this was seen as a working dynamic hypothesis by colleagues.

5.4.2.3 Model formulation

Having developed a dynamic hypothesis the next stage is model formulation. The model in its current form cannot be run as a simulation model because we do not have a stock and flow diagram to test the behaviour of the key variables. So the next stage of model building is to develop a stock and flow diagram to describe the behaviour of the system. The initial stock and flow version of the model is shown in Figure 53. The reinforcing loop means that as spend is aggregated, due to benefits accrued this will serve to increase the level of aggregated spend. With no balancing loop, aggregated spend would increase exponentially until the maximum level of spend (£1.2 bn) was reached. However, we know that in the real world, this trend will be resisted by operating companies due to their perception of the loss of control. For the moment, this is modelled as a parameter called '*resistance to spend aggregation'* which is calculated with reference to the current level of aggregated spend and the parameter *'operating companies tolerance to centralisation'.* The calculation is:

Resistance to spend aggregation = aggregated spend / operating companies tolerance to centralisation

Fractional net increase rate = 1 – resistance to spend aggregation

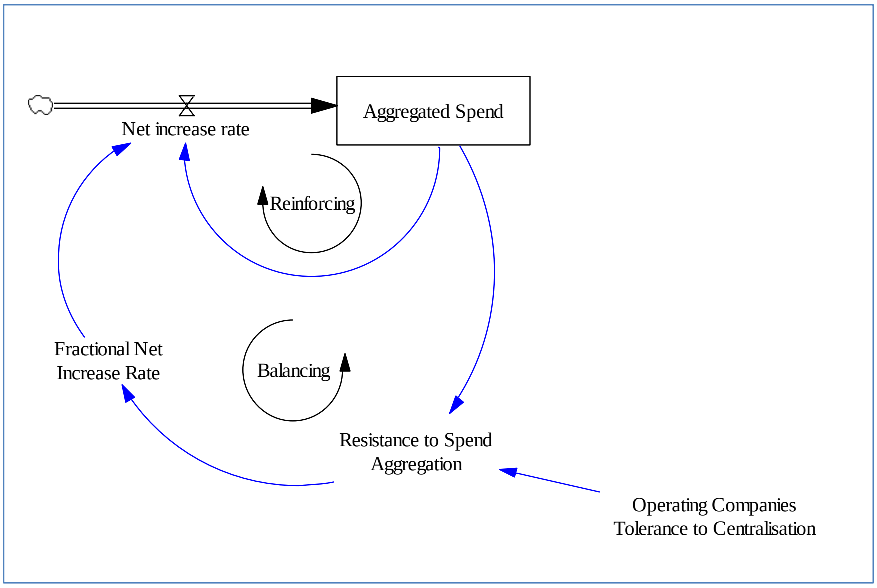

Figure 53 Purchasing problem - initial stock and flow model

The aggregated spend is the integration of the net increase rate. The net increase rate is given by the calculation:
Net increase rate = Aggregated spend x Fractional Increase Rate
As a start point the tolerance of the operating companies is set to £600 million i.e. half the total spend. This is an arbitrary figure, in reality this will depend on the attitudes of the local operating companies. With these initial conditions the result of running this model is given by Figure 54. The initial exponential increase in the aggregated spend will be resisted and the rate of increase will ultimately decline to a maximum of £600 million after 12 months. This period of 12 months is too short because in reality we know that in a company of this size and complexity it will take closer to 36 months to reach this position. This estimate is based on this researchers and other colleagues' experience of working with clients of similar size and complexity. This client has 16 major categories of spend, some of which will be easier to take through the sourcing process than others. As a result, the model needs to be calibrated to be more realistic. This can be achieved by

reformulating the equation for 'fractional net increase rate' to include a factor which is related to the speed with which categories are put through the strategic sourcing projects thus:

Fractional net increase rate = (1 – resistance to spend aggregation)/Speed of Centralising Spend Project)

Variables for this parameter correspond to overall estimates of the project for example 2 = 24 months, 3 = 36 months etc.

This delivers the same shape of aggregated spend growth but over a longer time frame (Figure 55).

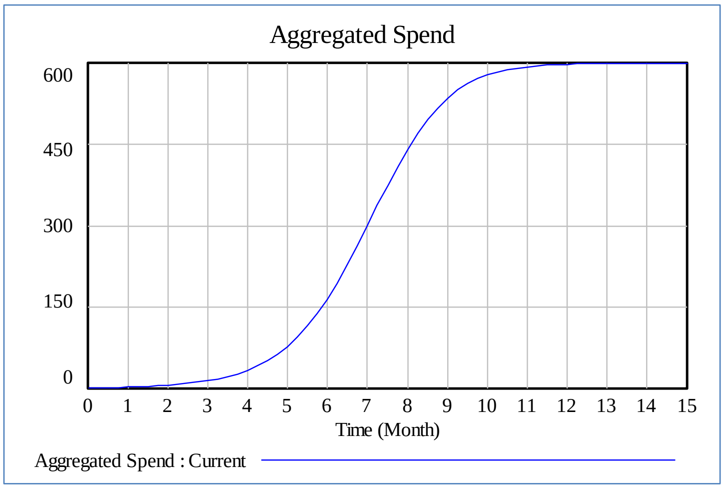

Figure 54 Results of simple purchasing stock and flow model

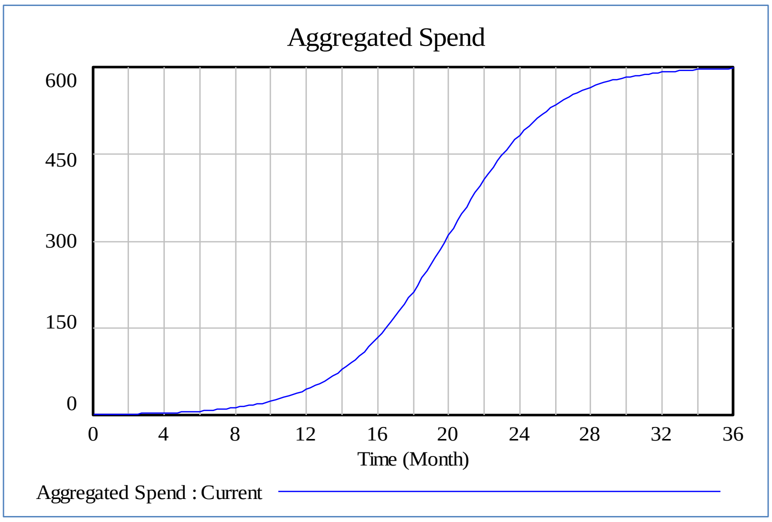

Figure 55 Results of simple purchasing stock and flow model post calibration

At the moment the operating companies' tolerance is modelled as a single parameter, and this parameter is static in the model. In reality, we know that the operating company itself will see the aggregation of spend both positively and negatively. They may see additional savings as a positive, since these savings will increase the bottom line profitability of the firms. This may lead to improved bonuses and remuneration for staff. On the other hand, they may see the centralisation of spend negatively and representing a loss of control. In addition, we know that the reaction of the operating company will not be static but will change in relation to the level of spend which is being aggregated. In discussion with colleagues, two new factors are introduced to the model in order to represent this. These factors are: perceived savings factor and perceived performance drop factors. These factors are applied to the current level of aggregated spend to create two new variables, namely: perceived savings by operating companies and perceived drop in performance by operating companies. An updated model is shown in Figure 56.

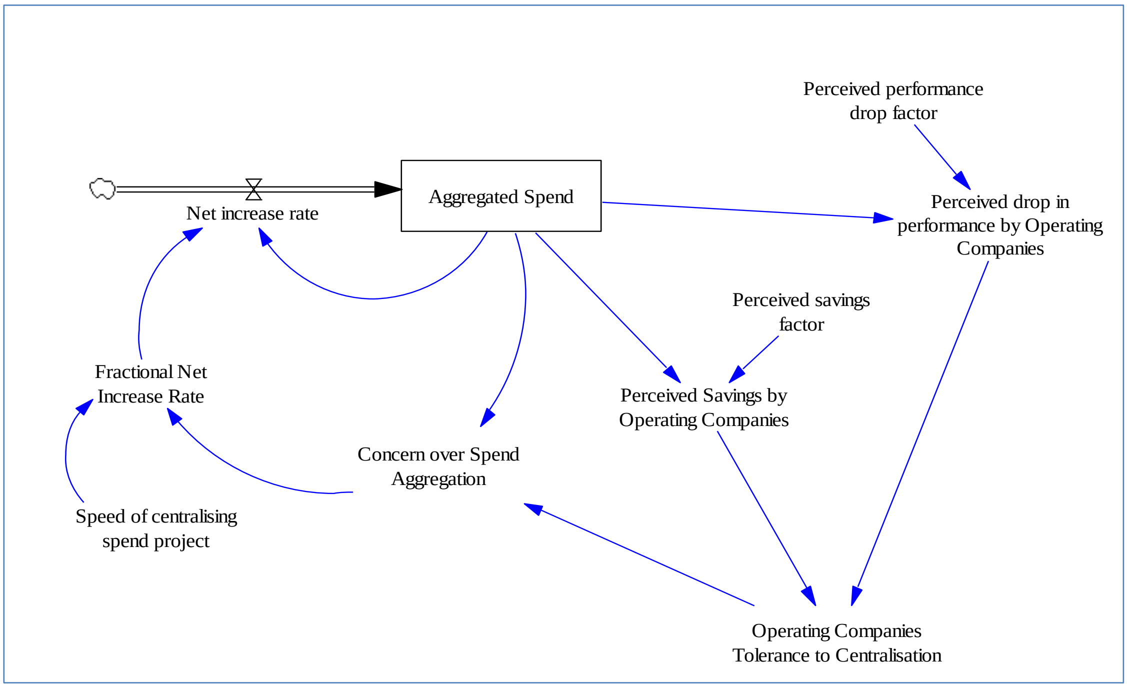

Figure 56 Purchasing Problem Stock and Flow Model

The two new factors can be between 0 and 1. Zero is the minimum, the company does not perceive this factor at all. One is a maximum, the company perceives this to be a key factor. The new parameters in the model are calculated as follows:

Perceived drop in performance by operating companies = aggregated spend x perceived performance drop factor

Perceived savings by operating companies = aggregated spend x perceived savings factor

Operating companies tolerance to centralisation = MIN (1200, 600+Perceived Savings by Operating Companies-Perceived drop in performance by Operating Companies)

The operating companies' tolerance to centralisation is formulated in this way because the maximum overall spend is £1200 million. Thus the formula must be constrained to a maximum of £1200 million. The mean figure is set at £600 million and this is increased based on the positive impact of perceived savings, and decreased by the perceived drop in performance in the model. The two factors can be valued between 0 and 1 and so the next step in the modelling is to test the different results obtained for extreme values of these parameters.

5.4.2.4 Model testing

According to Sterman (2000), model testing involves at least two things i.e. comparing the simulated behaviour of the model to the actual behaviour of the system. It also involves checking equations for dimensional consistency. The sensitivity of the model must also be tested against uncertainty in assumptions, both parametric and structural. The model must also be tested for extreme conditions. For example, he states "*Many widely used models in economics, psychology, management and other disciplines violate basic laws of physics, even though they may replicate historical behaviour quite well*." This relatively simple dynamic model of this system has three key inputs and one output. The three inputs concern the attitude of operating companies to savings (perceived savings by operating companies), the attitude of companies to the perceived drop in performance due to lack of control (perceived drop in performance by operating companies), and finally, the overall speed of the project. Sensitivity testing was carried out against extremes of these parameters. The first sensitivity test concerned the two company factors. The model was run testing these two factors (*perceived savings by operating companies* and *perceived drop in performance by operating companies*) testing them as vector values varying from 0 to 1 in steps of 0.5. The *Speed of Centralising Spend Project factor* was set at its default value of 3 equating to a project duration of approximately 36 months. The result of this sensitivity test is shown in Figure 57 in graphical form and in Table 18. As can be seen from the graph, the result of the model is sensitive to these two parameters, both in terms of the absolute value of aggregated spend that is achieved, as well as the time taken to reach this maximum. The worst case scenario is that aggregated spend reaches only £300 million, and the best case is that it reaches £1200 million. Given that savings achieved on aggregated purchasing deals can be in the order of 10% then the difference in savings achieved could be £30 million instead of £120 million. In terms of the time taken to achieve these savings, this varies from 27 to 36 months.

The other sensitivity test concerns the *Speed of Centralising Spend Project.* A sensitivity test was run with vector values from 2 to 4 in steps of 1. This equates to three scenarios, i.e. 24 months, 36 months and 48 months. The results of this test are shown in Figure 58. In this case the two operating company factors are set to the mid position i.e. both 0.5. In this case the final aggregated spend position is the same for all scenarios i.e. £600 million, but in this case the time to reach this position varies from 24 months to 48 months.

5.4.2.5 Policy design and evaluation

The power of the system dynamics model is the way it can influence the development of more successful policies. The insight provided by this model is that although the procurement project is a centrally led strategic initiative, the success of the programme will largely be driven by how it is received by operating companies themselves.

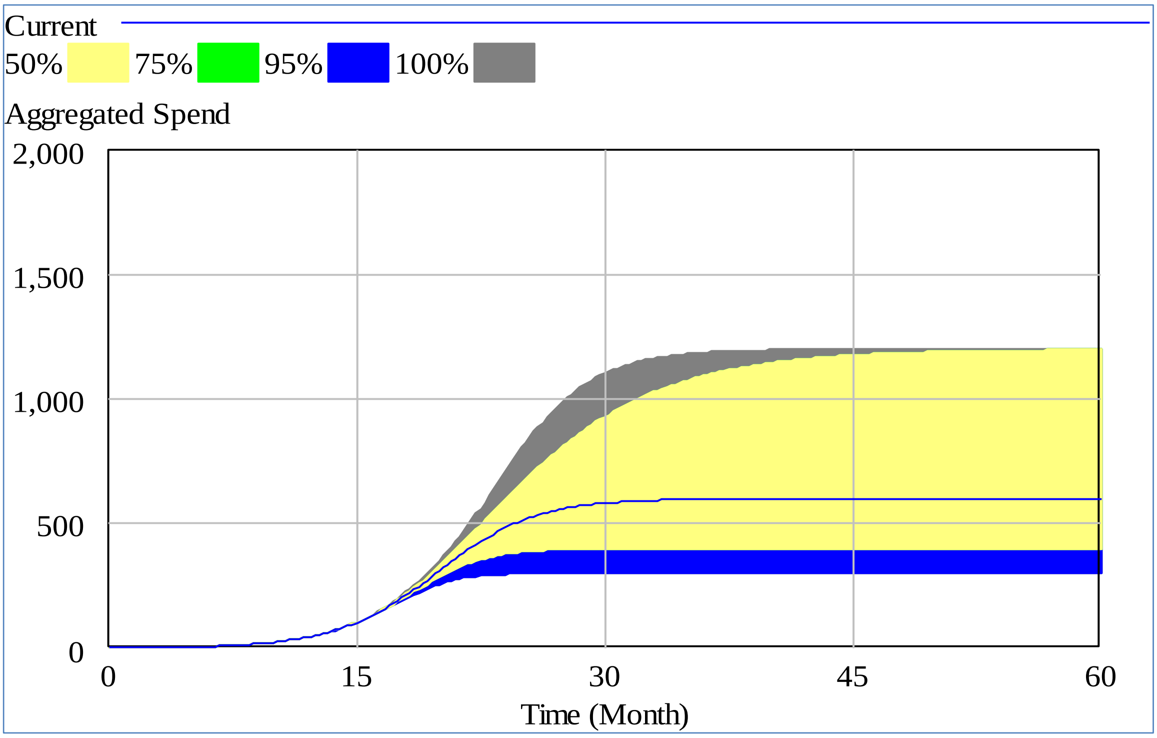

Figure 57 Sensitivity of Aggregated spend to Operating Company Factors

		Perceived Savings by Opcos		Perceived drop in performance by Opcos		Concern over spend aggregation		Operating Companies Tolerance to Centralisation		Aggregated Spend		Time to Max (Months)
Perceived performance drop factor	Perceived savings factor	Low	High	Low	High	Low	High	Low	High	Low	High	
0	0	0	0	0	0	0	1	600	600	0	600	36
0	1	0	1200	0	0	0	1	600	1200	0	1200	36
1	0	0	0	0	300	0	1	300	600	0	300	27
1	1	0	600	0	600	0	1	600	600	0	600	36
0.5	0.5	0	300	0	300	0	1	600	600	0	600	36
1	0.5	0	200	0	400	0	1	400	600	0	400	30
0.5	1	0	1200	0	600	0	1	600	1200	0	1200	54

Table 18 Sensitivity of aggregated spend to Operating Company factors

The extent to which they perceive the programme as delivering savings benefits to them is critical, as is whether they see the programme as removing control from them and imposing centrally selected suppliers which will deliver a poorer service and result to the local operating company. There are a number of conclusions that can be drawn from this model and there are a number of potential policy developments that might follow (see Table 19). As a researcher, but also a member of the consulting team, this is potentially a very powerful realisation, because it raises the vital importance of tackling the perceptions of the programme at the local OpCo level. The tendency is to focus on the activities at the strategic centre of the project without giving sufficient attention and priority to these local issues.

Factor	Issue	Policy Implications
Perceived savings factor	Incentives at OpCos may not drive the appropriate behaviour	Local OpCo incentives must be developed which support the development of appropriate central contracts
	Unless savings reach OpCo bottom line they will not be perceived as true savings	Central savings must be fed back to OpCos in a timely manner
		A mechanism must be created to 'credit' OpCos with local savings
Perceived performance drop factor	Operating companies may associate centralising spend as leading to performance drop in suppliers	Clear transparent measures of performance must be developed to demonstrate performance
		Clear communications plan must be developed to demonstrate benefits of the centralised procurement programme
	Operating companies prefer to retain local control	Clear communications plan must be developed to demonstrate benefits of the centralised procurement programme
		Potentially, the organisation structure of procurement may need to change from a local control model
Speed of centralising project	Speed of project will influence how quickly savings are delivered	Develop strategies for accelerating the benefits of the programme

Table 19 Policy implications

The other insight here concerns the importance of perception versus reality. Even though performance and savings may well be being achieved, unless they are perceived as such by the local OpCo then the resistance to policy will remain. This highlights the critical importance of communication and ensuring that the realities and potential benefits of the programme are clearly transmitted. This shows how the model delivers insights and how it can influence the development of practical policy.

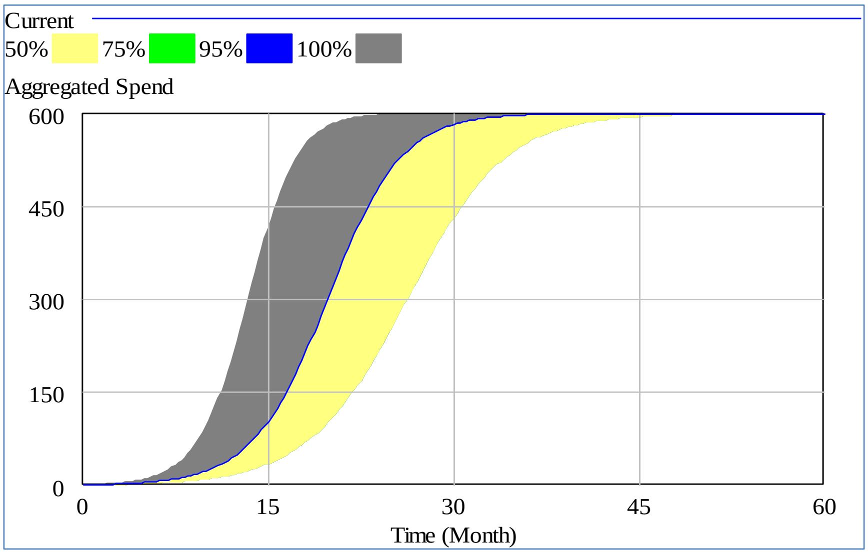

Figure 58 Sensitivity to speed of project

5.4.3 Description of the Agent Based Model

The development of the agent based model has followed the five stage process described in Figure 17.

5.4.3.1 Discovering agents

As North and Macal (2007) state, "..*modellers must carefully consider what the agents will be in a given model*" and "*Agents are generally the decision makers in systems*". In modelling the purchasing problem, there are a number of potential candidates for agents within the system:

- The category manager (strategic owner of the category such as concrete, office supplies etc)
- The supplier
- The purchasing manager in the OpCo
- The OpCo Managing Director

In order to investigate this question, this researcher decided to interview person A, the Head of Procurement for one of the largest OpCos. The reasons this person was chosen was twofold, firstly he was head of the existing group wide purchasing initiative and therefore had insights into how purchasing works across the business and secondly, as a head of procurement for an OpCo himself, he had an understanding of the details of decision making at a local OpCo level. The interview was semi-structured and intended to investigate the local purchasing decision making process and to identify the decision makers in the system. The two key questions around which this interview was conducted were:

1. *In the local OpCo, who decides when Group Framework deals are used?*
2. *What factors do they consider in deciding whether to use the central deal?*

The outcome of this interview was interesting, somewhat surprising, and was summarised as follows. The decision maker and decision making process is not consistent across different OpCos or across different categories. This is caused by variation in organisational structure and by different operational processes in parts of the business. As a result, there is not one simple answer to this question. Generally, OpCos will decide locally whether they will use the group deal or not for a particular purchase. They will base this decision on factors such as price, service and delivery. They will also consider risk, so they may trust a local known supplier over a group supplier for more critical commodities. OpCos may switch between using and not using a group deal depending on these local decision making factors and the characteristics of an individual purchase. OpCos deciding not to use the group deal is known as leakage, i.e. the percentage of spend that could go through the group deal which does not. During this interview, person A suggested that the spend category non-operated plant might represent a good area for further focus and investigation because it was a large category and in many ways representative of other categories in terms of understanding the buying behaviour.

The company had attempted to increase aggregated spend with group framework suppliers in the past and therefore it was a rich area to investigate both what has happened historically, but also to consider how to improve the situation going forward. In order to make practical progress the researcher decided to investigate this category in more detail. Non-operated plant spend across the group is £80M representing 6% of the total spend. Non-operated plant consists of a number of different sub-categories (see Table 20).

Access Equipment	Dumpers	Lifting & Hoists	Rollers
Accommodation & Furniture	Electric Tools	Lighting	Safety Equipment
Air Conditioning	Excavators	Loaders	Shoring Equipment
Air Tools	Fencing	Mixers	Survey Equipment
Bowsers & Tanks	Forklifts	Painting & Decorating Equipment	Telehandlers
Cleaning Equipment	Gardening Equipment	Plumbing & Drainage	Tools & Small Plant
Compaction Equipment	Generators & Electric	Powered Access	Transformers
Compressors	Groundcare Equipment	Pressure Washers	Traffic Management
Confined Space Equipment	Handling Equipment	Pumps & Water	Trenchless Technology
Concreting Equipment	Heaters	Rail Equipment	Welding Equipment

Table 20 Non-operated plant sub-categories

Spend on this category by individual OpCo is shown below in Figure 59.

At the time of this research, person A was responsible for the Group non-operated plant deal. Although there is a company framework deal in place with a supplier, leakage from this deal is running at 60%. This varies by company depending on the tolerance of that OpCo to the performance of the framework supplier. According to person A, the decision makers in this category would be either plant managers, quantity surveyors, estimators, managing buyers, central plant managers and buyers, depending on the particular OpCo.

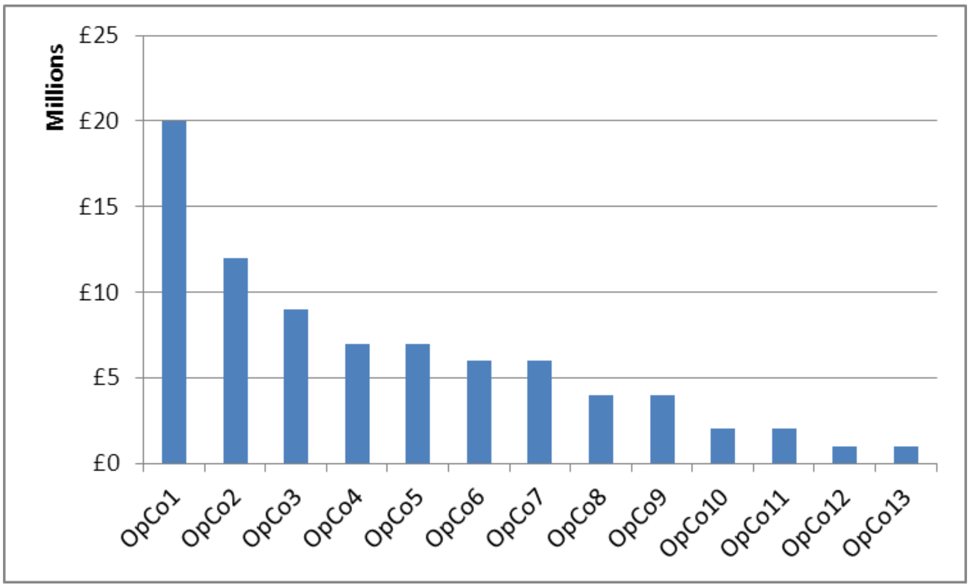

Figure 59 Non-operated plant spend by OpCo

The next stage of understanding the behaviour in the system required interviews with a sample of decision makers at the OpCo level, and this will be described in the next section.

5.4.3.2 Discovering agent behaviours

As part of the project, the researcher was required to visit a number of OpCos to have an initial meeting with the local OpCo purchasing representatives and management. As part of this visit, it was possible to go into some discussions regarding the group purchasing initiative and the responsibilities for procurement as well as the reasons for using or not using a framework agreement. Three different OpCo purchasing roles were interviewed as part of this process. There was a fairly high degree of consensus in these interviews that the decision making process followed a similar approach in each case. In the first instance, the interviewees pointed out that quite often the framework supplier was unable to meet the local requirement. This was because the central deal did not cover the wide range and variety of equipment required out on site. In addition, there were sometimes local responsiveness issues, i.e. the framework supplier had the piece of equipment, but could not supply it in the timeframe required. Thus, the first issue to deal with is whether the central supplier can even meet the local need. The second issue concerned performance in terms of quality and delivery. Often, although the OpCo professed to be keen to use the central deal if possible, they found that the service and quality of the equipment did not meet their requirements. If this happened over time then they would revert to using a local supplier. Interviewees commented that this bad feeling took a while to wear off and then they would give the framework supplier 'another go'. So effectively, the use of the framework deal was driven by these local decision making factors. OpCos vary in their sensitivity to supplier performance in this category. Some OpCos operate in an environment that requires them to be more responsive to customer requirements than others. As a result of these factors, a total of 60% of these orders are 'leaking' from the framework deal to local suppliers.

These interviews essentially constituted knowledge engineering interviews (North and Macal, 2007) because they were with domain experts who were able to explain the decision making rules they followed in the purchasing process. Although relatively simple, the decision making process as described by the domain experts is as shown in Figure 60.

5.4.3.3 Build Agent Based Model

Having defined the decision making process of the buying agent, the next stage is to develop the agent based model. Netlogo has been chosen as the software to build this model in to be consistent with the approach taken in the Bullwhip Case Study. Conceptually, the model consists of 13 buying agents. These agents represent the individual purchasing decision makers located in each of the OpCos. There are 13 local suppliers which are able to supply the plant needs of the OpCo locally. Finally, there is a framework supplier which is able to serve all the OpCos.

Graphically, this is represented by Figure 61. The agents in the centre of the diagram are the purchasing agents, those to the right of the diagram represent the local suppliers, and the individual agent on the left of the diagram is the framework supplier. The white lines represent the demand links between the purchasing agents and the suppliers. The value of orders placed on the supplier in each week varies by OpCo. Each purchasing agent must make a decision each time period (a week) whether to place the plant orders with the framework supplier, or with a local supplier. The purchasing agent makes this decision based on the performance of the framework supplier in the last period, and the tolerance of the OpCo to this performance. In order to model this, each OpCo is given a 'tolerance to performance' variable (in this case 85% to 95%). This quantity can be set in the model using a slider bar for each OpCo.

The values set in the model were informed by the researcher's knowledge of the individual OpCos. Thus there are six OpCos which would require a higher level of service than the others. The performance of the framework supplier is modelled as a random normal distribution, but the mean and standard deviation of this parameter can be set on a slider bar input (mean between 85% and 95% and standard deviation between 1 and 10%). The model is programmed so that as the purchasing agent switches between the local and framework suppliers, so the demand links change colour from green when there is demand, to red when there is not. The model is designed to run for 50 weeks to represent one year's activity. In terms of data collection, the two key variables of interest are the total number of orders placed with the framework supplier, versus those placed with the framework supplier. These totals are calculated within the Netlogo code.

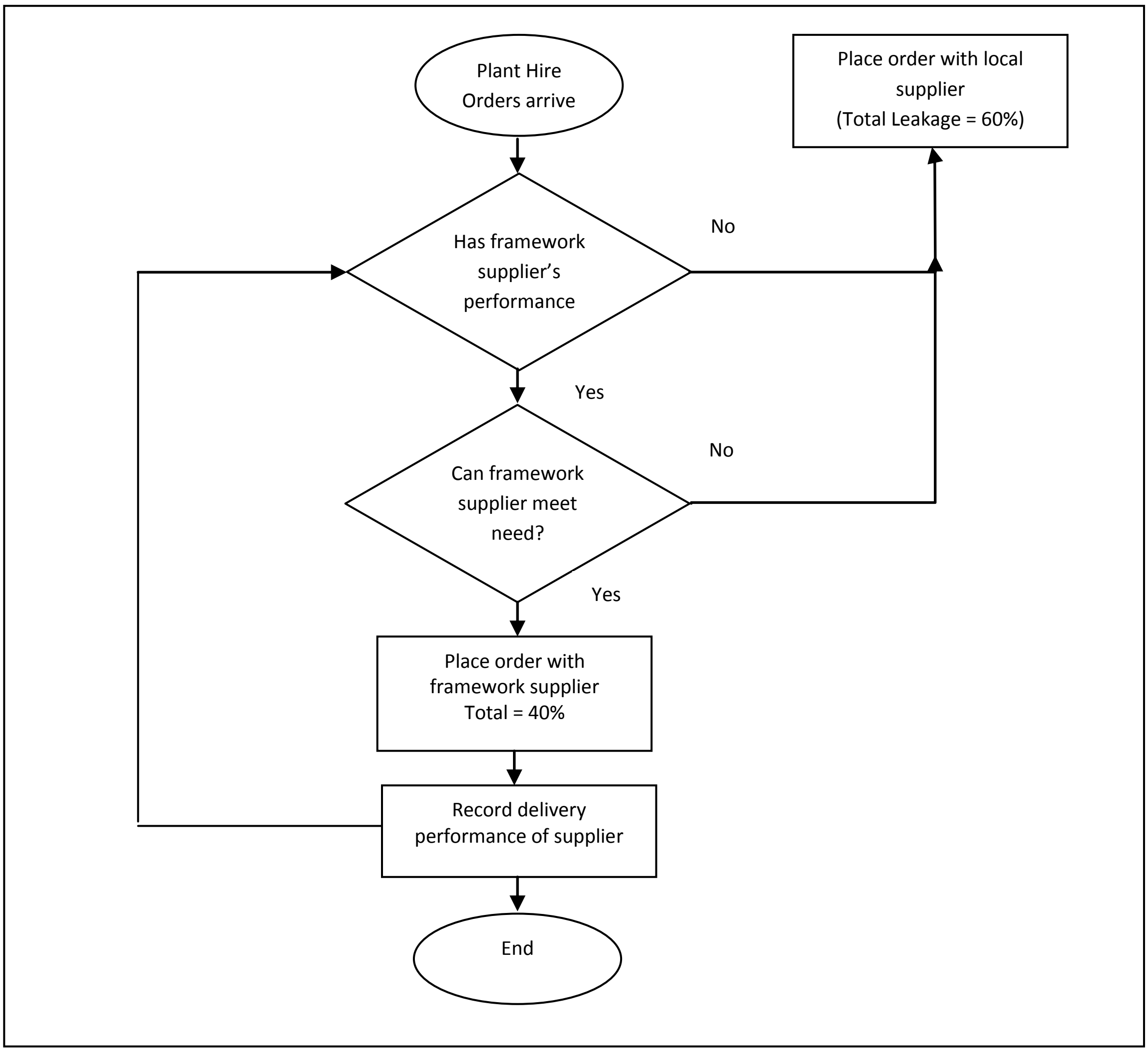

Figure 60 Decision making process at OpCo level

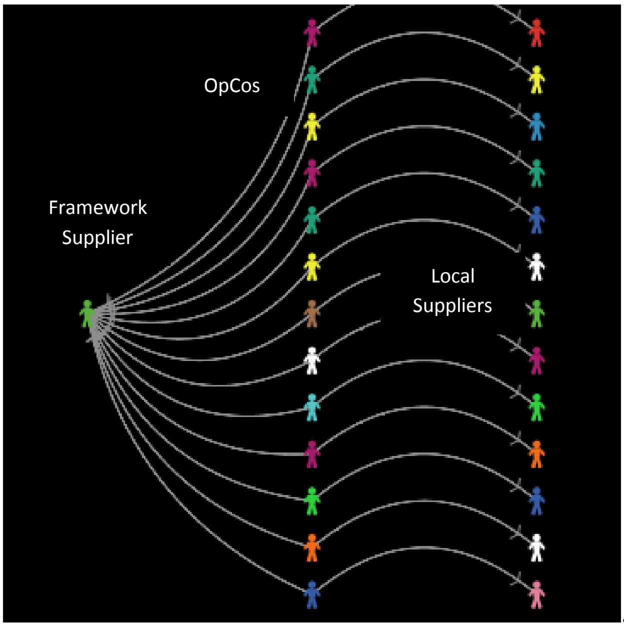

Figure 61 Agent model of purchasing problem

The initial parameters in the model are set as follows:

OpCo tolerance to performance 'high' = 95%

OpCo tolerance to performance 'medium' = 90%

Framework supplier performance = random normal with mean = 90% and SD = 5%.

The appearance of the model with these initial conditions set is shown in Figure 62. The total value of orders placed on the framework suppliers and those placed on local suppliers are recorded in the graph on the right hand side.

5.4.3.4 Verification and Validation

According to North and Macal (2007), verification and validation "*are essential parts of the model development process if models are to be accepted and used to support decision making*". The following sections will describe the steps taken in developing this model to ensure that it is useful for the purpose for which it is intended. It is important to point out that in this case the model is not being developed to solve a specific problem and to identify a particular numerical solution, but rather to investigate the modelling process itself. Thus what is required is to demonstrate that it is robust for this purpose.

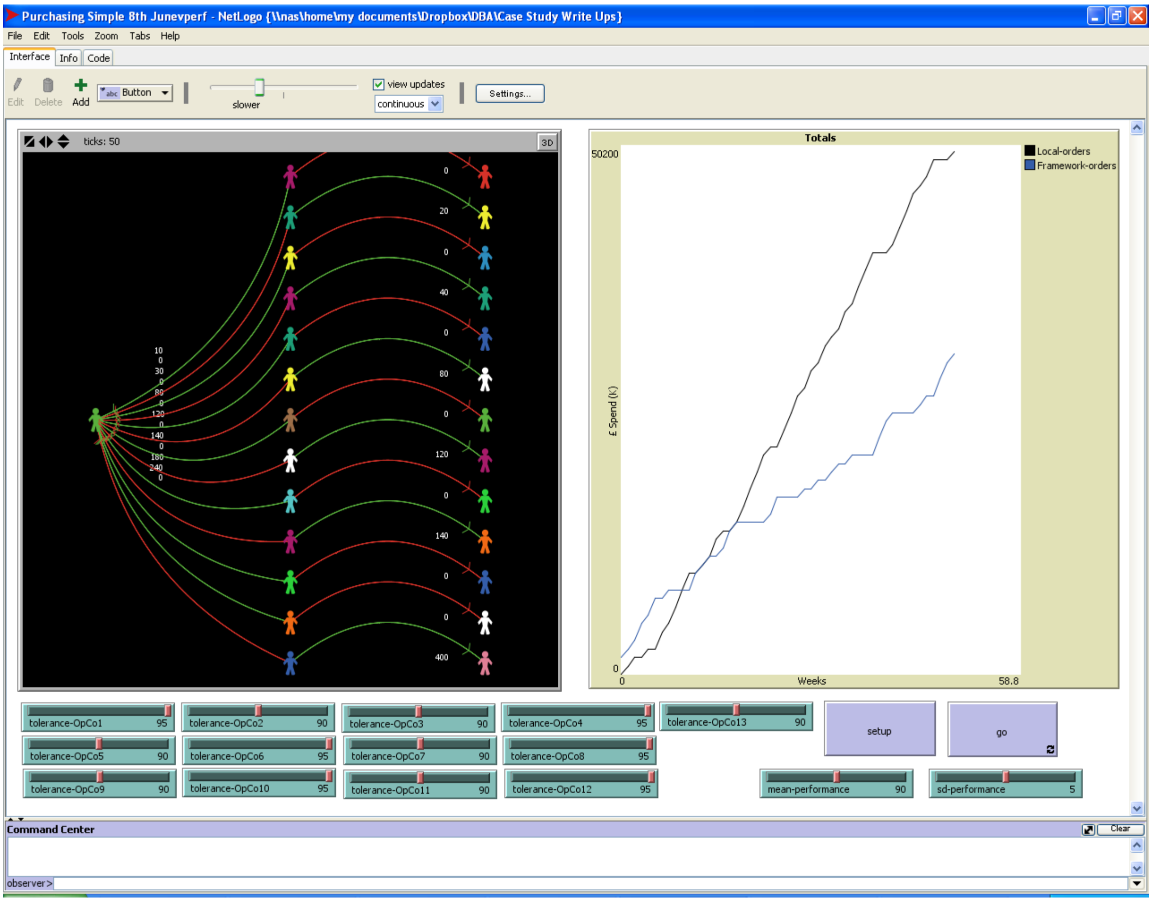

Figure 62 Purchasing case study ABM screenshot

The verification of a model concerns ensuring that the model works in the way intended by the modeller and that it matches the design specification. A model can never be 100% verified, but by following certain good practices modellers can ensure that the likelihood of errors is significantly reduced.

Unit testing and Modular Coding

Rather than building the model in one stage, the approach taken in this case was to first of all build a simple model with one buying agent and one local supplier and the framework supplier. This simplified model allows the testing of all the functionality of the agents before the model is expanded to include several buyer and supplier agents. Netlogo supports a modular approach to model coding. What this means is that the structure of the program follows a generic block structure as follows:

1. Declaration Section – declare variables
2. Set up Section – Initial Setup the model
3. Main body of the program – runs all the subroutines
4. Individual subroutines

This generic structure allows the programmer to ensure that each section of code is developed in a gradual way building up the functionality step by step. The individual sub-routines are self-contained sections of code that can be developed and tested individually. This modular approach to model building ensures that each element of functionality is built up carefully and systematically and this significantly reduces the risk of errors.

Built-in error detection and de-bugging

Netlogo has built in error checking functionality in its code editor. This means that as the code is entered and compiled, any basic errors are automatically detected, such as using undeclared variables for example or syntax errors. This ensures that at least the basic errors are mostly detected during the coding process.

Structured Code Walk Throughs

Another effective way to verify a model is to step through code in a structured way. This can be done before running the code off-line. Each section of code is examined individually to identify any errors. One way to enhance the effectiveness of this process is to get another experienced modeller to inspect the code separately. In addition, the model execution can be tested during the execution cycle. Netlogo offers some functionality to support this, for example there is a 'watch' function that allows the modeller to observe the value of an agent or agent link as the code executes. This combination of activities has ensured that the likelihood of errors in the model has been significantly reduced.

Validation can be defined as "*whether a model represents and correctly reproduces the behaviours of a real-world system*" (North and Macal, 2007). This model represents the decision making of purchasing agents in response to the performance of a framework supplier. The estimates of the performance of the supplier and the tolerance of the purchasing agents have been estimated from the interviews and conversations with the three domain experts. However, these parameters are estimates and have not been validated with the individual OpCos. Therefore, the model cannot be quantitatively correct, i.e. it cannot precisely predict the level of leakage that will ensue from the framework deal. However, the model can be qualitatively correct in that it can be useful in understanding the likely broad range of outcomes that may ensue and the sensitivity of these outcomes to different performance levels and OpCo tolerances.

Model Calibration

In the first instance it is possible to determine whether the model as it is currently configured reproduces broadly the effect of the system in the real world. What can be observed is that each run of the model produces a different outcome for the total amount of orders placed on the framework deal. This is because the performance of the framework supplier is based on a random-normal distribution. In order to examine the performance of the system, it is necessary to perform a number of iterations of the model. Netlogo has a useful tool called BehaviorSpace. This allows the modeller to run a number of iterations of the model to see how the output varies depending on the variation of user-defined input variables. In the first place, the model is run 100 times, with all parameters left unchanged, so this will model the effect of the different random distributions. The results of this initial test are shown below:

Parameter	***Spend Leakage (£'000)***
Mean	27,187
Standard Deviation	3,559
Range	16,790
Minimum	19,340
Maximum	36,130
Count	100

Table 21 Netlogo purchasing model - result of 100 iterations - mean performance 90%

In this case, the overall level of leakage is 1 – (£27,187K / £80,000K) = 66 %.

The reported level of leakage is 60%, so the model needs to be calibrated to more closely align with this level of performance. One way to do this is to increase the proportion of orders placed with the framework supplier by increasing the performance. If the supplier performance is increased to 91% and 100 iterations run again then the results are shown below in Table 22. The overall leakage is 59% which is closer to the behaviour of the real system.

Parameter Sweeping

There are a number of input parameters to the model that could affect the output; for example, the tolerance of the individual OpCos, the mean performance of the framework supplier and the standard deviation of the framework supplier performance. In order to test the sensitivity of the model output to these input parameters a number of tests were performed. The focus of these tests was the framework supplier's performance. Since the OpCos' tolerance to the performance is a fixed quantity and is set in relation to the performance of the framework supplier, testing the sensitivity to this parameter will give a good indication of the sensitivity of the model. Two tests were performed, the first one being a test of the sensitivity of output to the mean performance of the framework supplier and the second test for the standard deviation of the performance. In each test the model was run for 100 iterations. The mean performance values were set as 85%, 87%, 90%, 93% and 95% (with a standard deviation of 5%). The standard deviation was set at 3%, 5%, 7% and 10% (with a mean performance level of 90%). The results of the two tests are shown in Table 23 and Table 24.

Parameter	*Spend Leakage (£'000)*
Mean	32,700
Standard Deviation	4,801
Range	23,930
Minimum	20,160
Maximum	44,090
Count	100

Table 22 Netlogo purchasing model – result of 100 iterations – mean performance 91%

The results of these tests show that the output of the model is highly sensitive to the framework supplier mean performance and also to the standard deviation, but to a lesser extent. What this means is that if this model were to be used to predict accurately the leakage from the deal, then it would be important to ensure that the values for these parameters were as accurate as possible in the model. In the case of this model, it cannot be used to provide accurate forecasts for leakage, but it has demonstrated that leakage will exist and that in the right circumstances leakage has the potential to be very high.

	Framework Supplier - Mean Performance Level – Spend Leakage (£'000)				
Parameter	85%	87%	90%	93%	95%
Mean	8,981	14,949	26,631	42,436	54,430
Standard Deviation	2,229	3,182	4,415	4,661	4,164
Range	11,890	16,790	22,280	25,530	26,300
Minimum	4,170	5,730	15,410	28,920	38,250
Maximum	16,060	22,520	37,690	54,410	64,820
Leakage	**89%**	**81%**	**67%**	**47%**	**32%**
Count	100	100	100	100	100

Table 23 Sensitivity of leakage to framework supplier mean performance (SD set at 5%)

	Framework Supplier - Mean Performance Standard Deviation – Spend Leakage (£'000)			
Parameter	3%	5%	7%	10%
Mean	23,312	26,995	31,138	34,011
Standard Deviation	2,849	4,757	4,242	5,178
Range	14,300	23,110	20,720	27,930
Minimum	15,460	14,600	20,930	17,700
Maximum	29,760	37,710	41,650	45,630
Leakage	**71%**	**66%**	**61%**	**57%**
Count	100	100	100	100

Table 24 Sensitivity of leakage to framework supplier performance standard deviation (mean set at 90%)

5.4.3.5 Experimentation and exploration

This final stage of the Agent Based Modelling process involves using the model to explore the different outcomes and behaviour of the agent based system. In this case study, the model has demonstrated that leakage will be a feature of framework deals and that the extent of that leakage will depend on the performance of the framework supplier. The model built in this case only addresses one category, namely non-operated plant. Even for this category it has not been possible to fully validate the model against real world data for supplier performance or for OpCo tolerance to that performance. There are a number of simplifying assumptions in the model for example, the fact that the local supplier will always be able to respond to the request should the framework supplier not be deemed suitable by the OpCo buyer. Secondly, at the moment, the supplier agents are passive, they do not react to the behaviour of the OpCo buyers. In real life, we know that the framework supplier probably would react to the decisions of the OpCo buyers, for example by improving their performance in reaction to the decision not to use them. Another simplifying assumption is that each OpCo only has one local supplier when in fact some OpCos may use more than one supplier.

There are a number of key ways in which this model could be extended. Firstly, the model for the non-operated plant could be validated in terms of the variables for OpCo tolerance and framework supplier performance. Next, the model could be extended to include the other categories. In each case the particular features of each category would need to be determined. In this way the behaviour of the total spend for the group could be investigated. A further extension would be to allow the framework supplier agent to react to the behaviour of the buying agents. In order to do this further investigation would be required to establish how the framework supplier would react.

The model in its current form is limited to one category of spend and includes a number of simplifying assumptions. The controlling variables in the model have been estimated, but not validated. Despite this, the model identifies some important policy implications for the company decision makers and how the strategic purchasing project is likely to unfold. These insights are different from those obtained by the System Dynamics approach. The key insight obtained from taking an agent based modelling approach is that the key decision maker in the current organisation is the OpCo buyer. The OpCo buyer has the discretion whether to use the group framework supplier or not. The OpCo buyer makes this decision based on the performance of the framework supplier in terms of quality, availability and delivery. The tolerance of difference OpCos to performance differs depending on their local circumstances. This results in the phenomena of 'leakage' i.e. the amount of spend that could go through the group deal but does not. The implications of this are profound. If the company wants the group project to succeed, it must tackle these issues. One option could be to reorganise procurement, and take away the decision making power from the local OpCo buyer and put it in the hands of a different part of the organisation structure. Even if this were done, the organisation will still need to address the performance issue, because the local OpCo managers on the construction sites are effectively internal customers and their needs must be considered and if possible met. This is because the competitiveness of the business overall relies on the local responsiveness and capabilities of the local OpCo. Thus, the organisation will need to understand, for each category, the characteristics of local OpCo performance requirements and the capabilities of the framework supplier. Only in this way can the group design a framework contract that will be successful. With levels of leakage approaching 60% for non-operated plant, the risk is that as the group transfers more categories onto central deals, the savings and benefits will not materialise because the spend will still be flowing to local suppliers. From a behavioural perspective, this model suggests that any attempt to centralise spend should focus on how the key individuals make decisions and how to influence them to make the right decisions. This may involve considering how the individuals are incentivised and rewarded as well.

5.4.4 Reflections on differences in modelling approach

This case study has been modelled using both SD and an ABM approach. In comparing the approaches, different policy insights have been developed. The comparison of the approaches will be in relation to the propositions developed earlier in the thesis.

Proposition 1 (P1): Discrete methods of simulation can be useful in investigating strategic problem types in the supply chain domain.

This case study has demonstrated that the agent based approach can yield very powerful insights into a strategic problem. Indeed, in this case it could be argued that the agent based approach has provided a more insightful and perhaps more accurate model of the problem than the SD model. The identification of the key decision makers in the system and the dynamics of their decision making process has proved critical to understanding how the system actually operates. This means that management can see more clearly how the new centralised procurement policy is likely to fail or at least be sub-optimal, unless these local decision making processes are understood. This insight was missing from the SD model. The SD model focused more on a top down strategic understanding of how the system works. Unless you specifically take an agent based perspective to identify the key decision makers, there is a risk that you think you understand the dynamics of the system but in fact you have ignored a key aspect of how it functions. Thus, in the case of this case study, this proposition is supported.

Proposition 2 (P2): Discrete methods of simulation can represent supply chain feedback effects in models.

In this model, the agent based model does contain feedback in that the action of the purchasing agent is changed by the performance of the framework supplier. The effect of this performance is not transparent to the model user, rather it is built into the logic of the Netlogo program and the functionality of the individual agent. In this case study this proposition is supported.

Proposition 3 (P3): System Dynamics can model supply chain problem types at the operational end of the spectrum as well as the strategic.
This case study addresses a strategic problem type and so this proposition is not applicable.

Proposition 4 (P4): The nature and role of decision makers in the problem may influence the selection of simulation technique.
This is an interesting proposition in relation to this case study. It has become evident that in this particular real world system there are key decision makers in the organisation at the OpCo level. As a result of this, the agent base modelling approach has been particularly useful as a method of modelling the problem. However, how can the modeller know in advance if this is the case? It seems that in many human systems, there are individuals making key decisions upon which the operation of the system depends. It is difficult to imagine a system in a supply chain context where this is not the case. As a result, it appears that identifying and modelling key decision makers is likely to be a key step regardless of the modelling paradigm or approach being used. It seems clear that the agent based approach lends itself well to this because the representation of the individual decision maker is natural for ABM. Thus this case study seems not to support this proposition but rather a different proposition that is: the identification of key decision makers and the modelling of their decision making process is a key step for successful modelling.

Proposition 5 (P5): The purpose of the modelling (exploratory, problem solving or explanatory) may influence the selection of simulation technique.
In this case study the modelling has primarily been about understanding and exploring how this complex system works. The models explain how the system operates at present and have some predictive power to estimate how the system might behave in other circumstances. Neither model could be said to be primarily about problem solving per se although both models offer insights which could be used by policy makers to develop more effective solutions and so could be considered to be problem solving to a limited degree. In the form developed here, it is arguable whether the SD version can be said to be mainly explanatory or the ABM model mainly exploratory. These are fairly fine distinctions. However, it does seem to be fair to say that if the purpose of the modelling is exploratory or explanatory then SD or ABM may be more suitable modelling approaches

5.5 Coffee pot case study

5.5.1 Introduction to modelling approach

In relation to this research, the coffee pot case study (Taylor et al., 2008) is classified as a 'typification' in that although it does not represent a real supply chain it nonetheless represents a class of supply chain problem types that are important and meaningful to supply chain practitioners. The research question that the researchers in this paper are attempting to explore is "*How much work in process, in-transit stock and finished goods to have on hand to support sales at a desired service level.*" In order to explore this research question, they explore various scenarios in an experimental manner, building models using discrete event simulation. In exploring these scenarios, they investigate the influence of a number of important supply chain concepts such as where to locate manufacturing, different methods of shipping (air and sea), low or high cost and efficient or responsive manufacturing. They investigate the impact of these variables on key performance factors such as customer service level, overall cost and level of inventory in the system. The authors use a discrete event programming package called SIMNET II to build their model (Taha, 1992).

In this case study the first model to be developed is a discrete event model in Simul8 (Simul8, 2012). This approach is chosen to develop a discrete model first and to provide a baseline for comparison. The model is then attempted to be built in SD using Vensim. This provides a good 'back-to-back' comparison and a good test for a number of the case study propositions.

5.5.2 Description of the Discrete Event Model

5.5.2.1 Introduction

A high level description of the modelling process was described in Figure 16. The description of the coffee pot model will use these four phases as a framework . Before starting the description of the modelling process, it is important to describe the background to the case itself and the problem characteristics. The full details of the problem is contained in Taylor et al. (2008), the purpose of this introduction is to summarise the key problem attributes and salient points.

5.5.2.2 Problem characteristics

The product and production environment in this case study is the manufacture and distribution of a coffee maker, specifically the Mr. Coffee Expert model. Detailed data on the problem are provided and are summarised in Table 25. The case concerns three main experimental variables, namely location, capacity and shipment method. It is assumed that the market for the coffee pots is in high income regions such as North America and Europe. The production location can be either low or high cost. The producing firms in the model are considered to be either efficient or responsive. An efficient producing firm has capacity constrained and in this case demand represents 90% of this capacity. A responsive producer has an auxiliary facility which can instantly produce any demand which the efficient factory cannot produce. The auxiliary facility may be located in either a high or low cost region. If the responsive auxiliary factory is used then a cost increase of 10% is incurred. The investigation progresses by investigating a number of scenarios. In each scenario, the goal of the supply chain is to deliver customer service of at least 95%. This is measured as the customer being able to receive their orders from finished stock in the market destination. If the stock is not available the delivery is considered to not be on time. Thus customer service in this context is effectively a measure of stock availability. In terms of shipment method, if coffee pots need to be transported between low and high cost regions they are either moved by sea in containers or carried as air freight. In this case, the reorder mechanism used is the reorder point and the economic order quantity (EOQ). When finished goods stock fall below the reorder level, this triggers an order for the EOQ. This reorder point is used in the model as a user defined variable which can be adjusted to achieve the desired customer service level. The overall cost and inventory of each scenario can be measured and compared with a benchmark service level as the comparator.

Aspect	Parameter	Value
Demand	Annual Demand	1,000,000 units
	Daily demand (250 days)	4,000 units
	Interarrival time of orders	5 days
	Interarrival distribution	Poisson
	Standard deviation of demand	0.33 of mean
Service	Customer service level	95%
Production	Assembly time	9.6 minutes per unit
	Shifts	3 x 8 hours
Capacity	Efficient	Average demand is 90% of capacity
	Responsive	Capacity unlimited
Cost	Low cost production cost	$7.5 per unit
	High cost production cost	$10.85 per unit
	Holding cost	$30% of unit cost per annum
	Units per pallet	50

Shipping	Sea container capacity	1400
	Air freight capacity	100
	Air freight cost	$21.05 per unit
	Sea freight cost	$1.34 per unit
	Air freight duration	2 days
	Sea Freight duration	6 weeks
Ordering	Reorder point (user specified)	r
	Reorder quantity	EOQ
	Inventory in finished goods	R
	Initial finished goods stock	(R + r) / 2
Sales	Price	$70

Table 25 Coffee pot problem data

The case includes the comparison of 10 baseline scenarios chosen to compare the different combinations of location, capacity and shipping method. These scenarios are summarised in

Table 26.

Scenario	Description
1	Efficient manufacturing in a low-cost area with no auxiliary facility. Ship in small quantities.
2	Responsive manufacturing in a low-cost area with a low-cost auxiliary facility. Ship in small quantities.
3	Responsive manufacturing in a high-cost area with a low-cost auxiliary facility. Ship in small quantities.
4	Responsive manufacturing in a low-cost area with a high-cost auxiliary facility. Ship in small quantities.
5	Efficient manufacturing in a high-cost area with no auxiliary facility.
6	Responsive manufacturing in a high-cost area with a high-cost auxiliary facility.
7	Responsive manufacturing in a low-cost area with a high-cost auxiliary facility. Ship in large quantities.
8	Responsive manufacturing in a high-cost area with a low-cost auxiliary facility. Ship in large quantities.
9	Efficient manufacturing in a low-cost area with no auxiliary facility. Ship in large quantities.
10	Responsive manufacturing in a low-cost area with a low-cost auxiliary facility. Ship in large quantities.

Table 26 Coffee pot problem scenarios (Taylor et al., 2008)

5.5.2.3 Conceptual model building

According to Pidd (2004a) conceptual modelling is where the modeller "*tries to capture the essential features of the system that is being modelled*". Also it is pointed out that "*in small scale studies, such a conceptual model may not exist in any objective form other than in the mind of the* *analyst since modern software, especially the use of Visual Interactive Modelling Systems (VIMS) mean that the conceptualisation can occur whilst developing the model at a computer screen*”. This case is sufficiently well specified and detailed so the modeller can proceed with model development straight into the Simul8 package without the need for an interim conceptual development stage. However, what was found to be useful in building the model was to develop simple ‘proof of concept’ models that could be developed and tested in isolation before being incorporated in the full model. Examples of these concerned modelling the re-order point mechanism, the shipping of transit stock and the customer service measure of performance. In this sense, conceptual modelling progressed in a phased manner as each of the key concepts within the case were modelled individually before being incorporated within the full model.

5.5.2.4 Computer implementation

The development of the computer implementation of this model progressed initially though the development of proof of concept models. These proof of concept models were then combined together to model one of the simpler scenarios. Models of the other scenarios were developed by modifying and extending this simple base scenario.

The coffee pot case involves certain keep concepts that need to be modelled. These are the re-order point mechanism, the different shipping methods, the use of an auxiliary factory, the measurement of certain key variables including customer service, cost and inventory. This section will briefly describe how these different concepts were modelled before being embedded within the overall model of the system.

Re-order point mechanism and transit stock

The re-order point mechanism requires that once inventory falls below a target re-order point level (r), then a replenishment order is released of size EOQ (economic order quantity). To model this in the Simul8 package the modeller must use the visual logic functionality built into the software. In a simple example model customer orders are arriving with a fixed inter arrival time at the rate of 10 per day. The initial value of finished stock is 200 units. When the stock in the pipeline falls below 50 units an order for 50 units is issued to the factory, thus in this example the re-order point is 50 units and the reorder quantity is also 50 units. The units are produced in a factory with a cycle time of 10 minutes and then transported in a transit stock with a transit time of 4 days. Simul8 visual logic allows the user to specify a logical test to apply on the exit of entities from a store. In this case a test is applied to check whether the stock in the pipeline has fallen below 50 units, if it has then 50 work items are added to the manufacturing orders store. It is important that the test is made on the pipeline rather than just the finished goods stock, otherwise multiple orders for replenishment will be released. This simple system is simulated for 3 months and the results of the behaviour of the finished goods as well as the overall model structure are shown in Figure 63. The model demonstrates the re-order point mechanism as well as the shipping of goods through a transit stock where the duration of the transit time can be varied. The logical test in the visual logic of the finished goods stock is as follows:

VL SECTION: Finished Good Stock On Exit Logic

'Obeyed just after a work item exits the storage bin but before it begins travelling to the next object

IF [Manufacturing Orders.Count Contents+Transit.Count Contents+Finished Good Stock.Count Contents] < 50

Add Multiple Work Items To Queue Main Work Item Type , Manufacturing Orders , 50

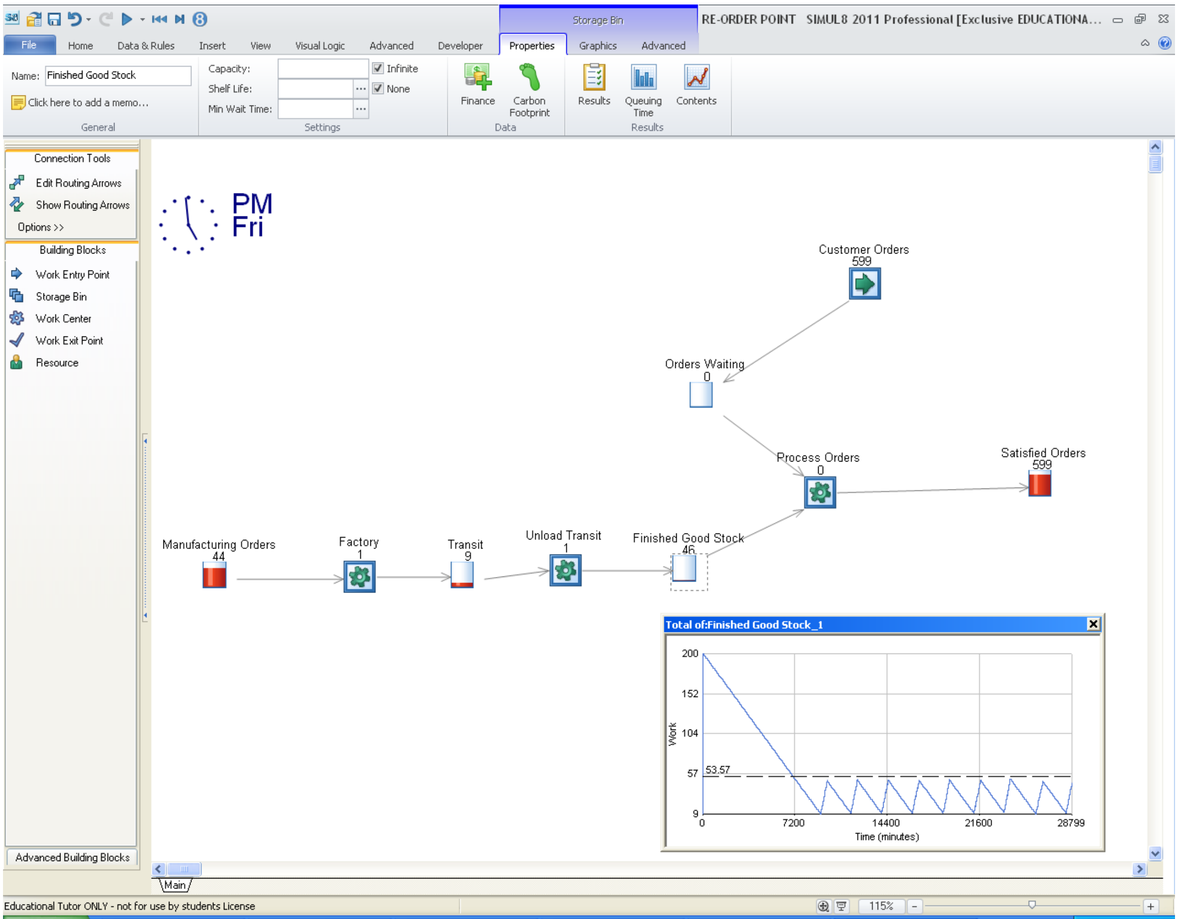

Figure 63 Re-order point proof of concept

The use of the auxiliary factory

In the case there are two capacity situations, there is an efficient factory situation where the demand constitutes 90% of the capacity of the factory and a responsive situation where an auxiliary factory can be ‘switched on’ as required to meet demand in which case capacity is effectively unconstrained. For the efficient factory situation, the model can be built in Simul8 by setting the manufacturing cycle time to a value that means that the demand equates to 90% of the capacity. This can be calculated using the data given in the case. To simulate the responsive case, additional factories, represented by workcentres can easily be added to the model.

Measuring customer service, inventory and cost

In this case on time delivery effectively means that the stock is available as soon as the customer requires it from finished stock thus customer service equates to stock availability. In order to measure this, orders are time stamped on arrival in the ‘customer orders arrive’ entry point. They are then time stamped again in the ‘process orders’ workstation. If the stock is available in finished goods, then there will be no delay between order arrival and order processing. In order to measure this, visual logic within the ‘process orders’ workstation is used to count the number of on time and late orders. This code is shown below :

VL SECTION: Process Orders On Exit Logic

```
 IF Exit Time-Arrival Time  >  0
   SET late_counter  =  late_counter+1
 ELSE
   SET on_time_counter  =  on_time_counter+1
 SET Service Level  =  on_time_counter/[on_time_counter+late_counter]
```

In this way, the measure of customer service is maintained and measured in the model. Simul8 allows for model parameters to be specified as KPIs. In this manner, the average total amount of inventory in the system can easily be monitored by identifying and specifying the relevant quantities. In terms of costing, Simul8 allows for the financial cost of each activity to be specified, as a capital cost, a cost per unit or a cost per minute. In this way, the total cost of each scenario can be easily built into the model and calculated. This bottom up approach of model development was used to prove out each of the model characteristics before building up individual models of the various scenarios was completed.

5.5.2.5 Validation and experimentation

Models of four scenarios were completed i.e. scenarios 1, 2, 6 and 9. Models 1 and 2 were completed initially and then models 6 and 9 were also developed because these are identified in Taylor et al. (2008) as being ‘*especially interesting and very different scenarios*’. In order to calibrate the scenarios, each model was run 5 times using the Simul8 trial function. This is because an individual result cannot be considered reliable and multiple replications are required in order to test different random number seeds. In each case the warm up time of the model was 1 month with a results collection period of 12 months. In each case the reorder point and reorder quantity had to be adjusted in order to achieve the 95% customer service level. The four scenarios each produced similar results to those reported in the paper in terms of their relative costs and inventory positions. Scenarios 1 and 2 are significantly more costly, mainly due to the high cost of shipping the product by air. Scenarios 2 and 6 are found to have the lowest overall levels of inventory since these are responsive scenarios whereas scenarios 1 and 9 are efficient scenarios. The detailed models for each scenario are contained on the accompanying CD in the 'coffee pot models' folder.

The results of the four scenarios are shown in Figure 64.

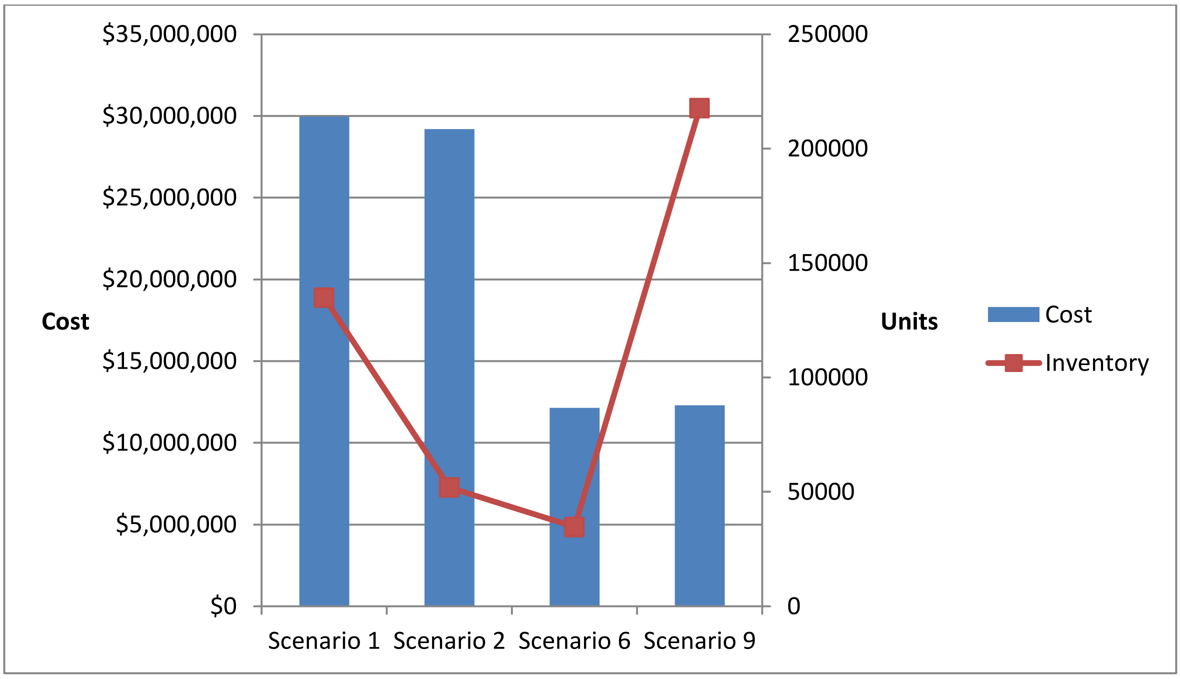

Figure 64 Results of coffee pot discrete event simulation

5.5.3 Description of the SD model

Discrete event simulation is a suitable approach for modelling the coffee pot problem, and the choice of this method by the original authors is perhaps unsurprising. What is perhaps more interesting is to attempt to use the System Dynamics approach to model this problem.

5.5.3.1 Model building – attempts to build the model from first principles

Initial attempts to build an SD model of this case involved trying to build the model from first principles. The model is built up initially based on one of the simpler scenarios i.e. scenario 6. The schematic of this model with associated causal loop diagrams is shown in Figure 65. To begin with, the first step is to model the customer demand. Given the characteristics of the demand, the demand signal is modelled within Vensim as a random normal distribution with those given characteristics. Customer orders are satisfied from finished goods. However, since there may be a situation of stock running out, it is necessary to have an order backlog part of the model. The speed with which the backlog can be cleared is related to the target delivery delay, this speed is known as the desired shipment rate. The desired shipment rate influences the release to customer rate, but this is constrained by the maximum shipment rate, which is itself constrained by the availability of finished goods. The performance of the factory is essentially driven by trying to maintain a target inventory. This target level informs the inventory adjustment which compares the current pipeline stock against the target level. The target production rate adds together the inventory adjustment rate and the desired shipment rate. The production rate is calculated as the target production rate constrained by available capacity. The shipment rate is the production rate delayed by the transit time.

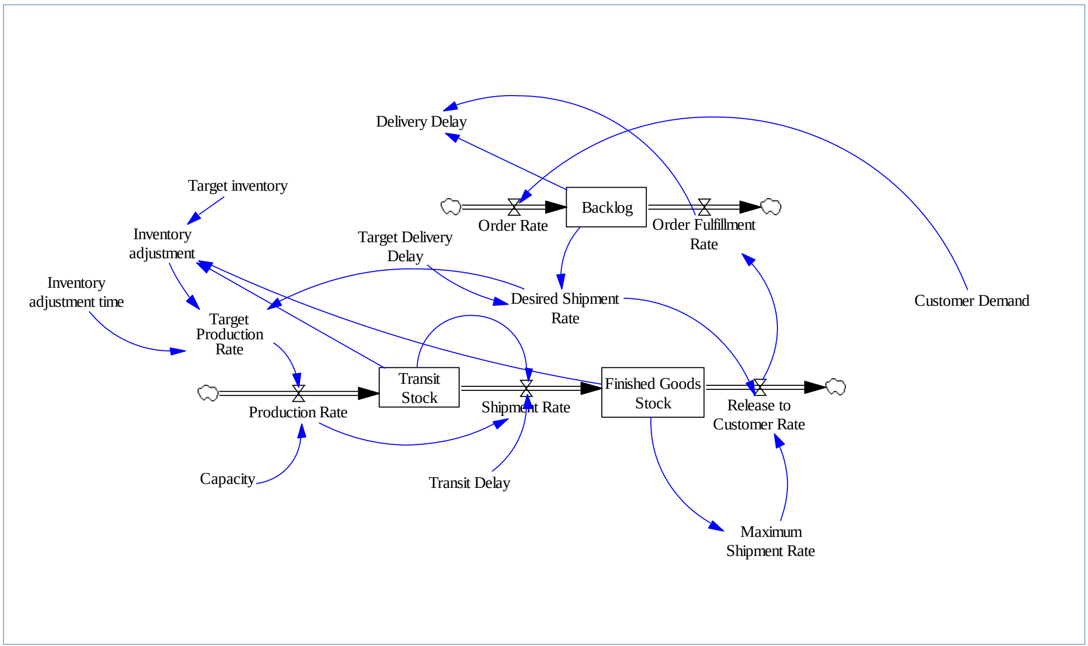

Figure 65 First principles SD model of coffee pot problem

The problem with this model becomes immediately apparent when trying to calibrate it to the customer service level required in the case study. The model must be calibrated to deliver a customer service level of 95%. This means that 95% of the time, the orders must be satisfied from finished goods. In the current model the finished goods cannot fall to zero. There is no equivalent to customer service in the SD model. The closest candidate as a measure is perhaps the delivery delay measure, but this is not the same concept. Unfortunately, at this point it was concluded that this problem could not be modelled using the SD approach. Having lost confidence in this 'first principles' approach to building the model, the author then decided to take the tried and tested

SD model of the supply chain developed by Sterman (2000) to see whether this could be adapted to suit this problem case.

5.5.3.2 Model building – attempts to build the model by adapting the supply chain model

The advantage of adapting the existing supply chain model is that this model is proven and thus can be confidently adopted as a working model of a supply chain. Again, one of the simplest scenarios, scenario 6 is adopted as the start point for the modelling. The model for this scenario is shown in Figure 66. Again, there is a problem with this model in that it does not allow for the calculation of customer service on the basis of finished goods inventory. This means that the model cannot be calibrated for different levels of customer service and thus cannot be used to answer the questions posed in this case.

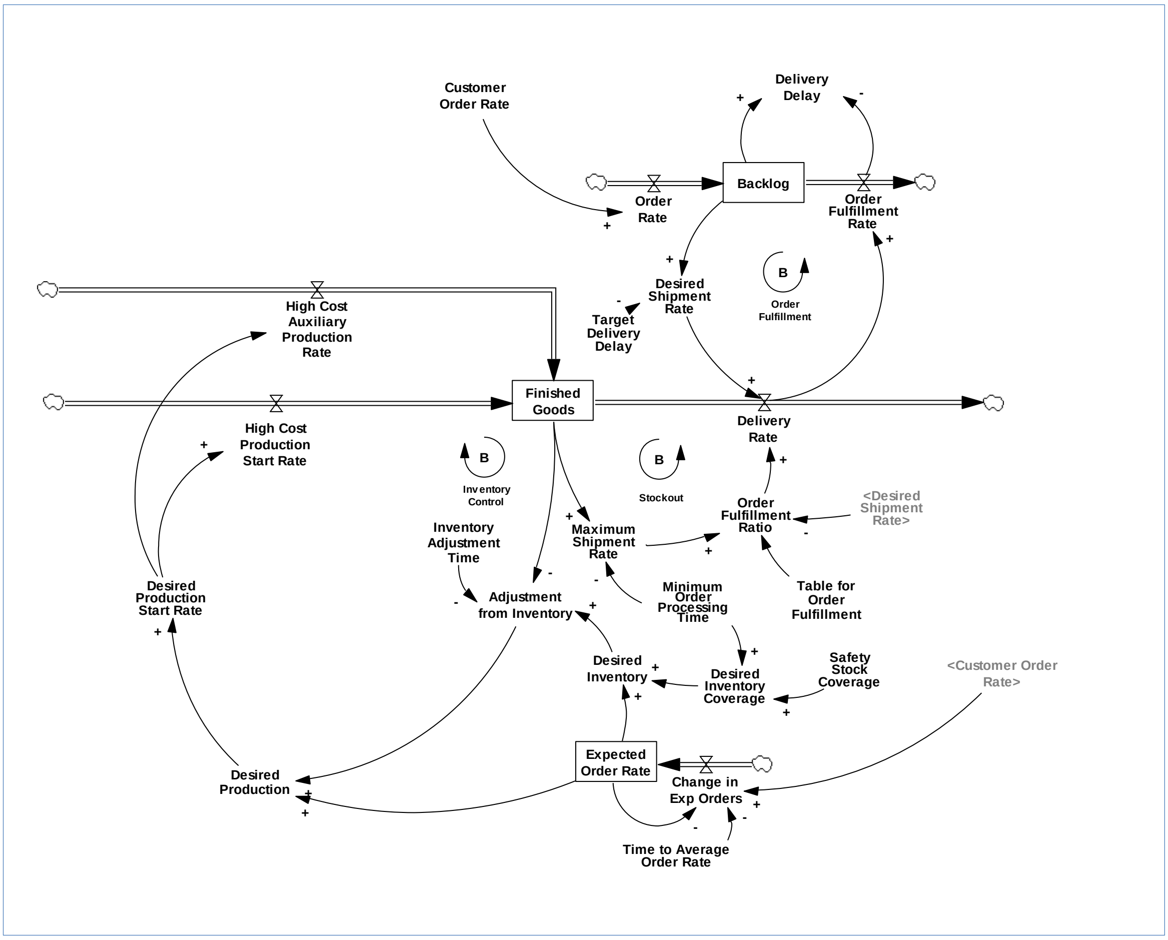

Figure 66 Adapted SD model of scenario 6

5.5.3.3 Discussion of difficulties in model building

This researcher has been unable to model this problem using SD. Specifically, the main measure of performance of the model i.e. customer service (or stock availability) is an inherently discrete measure. The SD model contains other parameters such as average delivery delay, but these measures are continuous and averages over time. Thus it has not been possible to produce a model which can be calibrated in terms of a given level of customer service (in this case 95%) to determine the requisite inventory levels and costs for different scenarios. At this point, this researcher had to consider alternative explanations for this finding. Is the problem with SD or is the problem with this researcher's knowledge and proficiency with the approach? Initially, advice was sought from this researcher's supervisors, to check whether something obvious was being missed. However, it soon became apparent that this was not the case and that there are real constraints in trying to use SD to model this type of problem. It should also be pointed out that this problem concerns only one product type, whereas in many real supply chain problems, the requirement would be to model multiple line items. This further reinforces the limitations of SD in this area.

In order to test this finding it was decided to post a question to the open discussion forum of the SD Society. In this way, it might be possible to test whether the community of SD expert modellers could see a way of modelling this problem or whether this was considered to be not possible. The details of this discussion are contained in Appendix 2 and are also a matter of public record (Owen, 2012). The initial question posed by this researcher lays out the problem and the fact that it has proven to be impossible to model the problem in its current form using SD. The responses to the post are interesting and revealing. Robert Eberlein's response points out that the way that inventory problems are tackled differs for operational research (OR) and SD. He states "*The focus in SD is on the implications of the different actions and responses with the expectation that actions in one area will have consequences to that same area both locally and globally. Trying to capture the global response is what is generally the focus*." He admits that there are limits to the applicability of SD when he states "…*tracking any one individually is not of much interest. Thus it is tough to do things like determine exact cycle times*..". Interestingly he points out that just being able to model something using SD software does not make it SD when he says "*All that said, there is a pretty good chance you can figure out a way to handle the cases you mention using the same software that people doing system dynamics work use. That is not saying that it would be necessarily be system dynamics*". Leonard Malczynski suggests that hybrid modelling may be the way forward when he states "*I do believe in hybrid or extra-methodological (outside of SD) modeling and do not fault the methodology of system dynamics if my problem is not tractable using it*. *SD tools however often permit mixed methodology modelling*". Most interesting for this author was the response from Jay Forrester, the founding father of System Dynamics. He notes that this was an issue considered in the early days of SD when he says "*Owen raises a question* *that arose frequently in the early days of system dynamics, but in the last many years I have not often heard of people with this concern*". His focus then shifts though to point out that the key point is the viewpoint that one must take as the modeller. He states " *In constructing a system dynamics model one must first decide whose viewpoint one should take. For the purpose of changing inventory levels one does not want the viewpoint of the deliveryman who may be berated for a late delivery. Instead one wants to use the viewpoint of the manager who might change the policies governing the system; I doubt that such a person is interested in each individual item. The issues raised by Owen are not how to make a system dynamics model replicate an unsuitable methodology but rather to consider what methodology is appropriate for the problem at hand*". This suggests that the SD approach is not concerned with monitoring the movement of individual orders, and this supports the earlier comment by Robert Eberlein. However, it does raise the potential challenge to SD that if the modeller is interested in the individual item, then SD may not be able to model the problem concerned. Finally, at the end of the discussion Robert Eberlein states "*It is not always the nature of the enquiry so much as the nature of the enquirer that results in the choice of a modeling method*" which is an interesting perspective.

This interesting exchange with some of the most eminent members of the SD community seems to validate the claim that there are certain problem types for which SD is not suitable. The responses suggest that the perspective of SD is more strategic, managerial and not focused on the behaviour of individual entities. This does mean that there are practical limits to the application of SD to certain problem types and this has significant implications for practitioners and those modelling and investigating supply chain problems in practice.

5.5.4 Reflections on differences in modelling approach

This case has been successfully modelled using discrete event simulation, however it has been found to be not possible to model it with SD. The researcher has tested this finding with the SD community and found evidence to support this conclusion. In this section the findings of this case will be considered in relation to the case study propositions.

Proposition 1 (P1): Discrete methods of simulation can be useful in investigating strategic problem types in the supply chain domain.

The coffee pot problem could be considered to have strategic aspects to it in terms of the definition being used in this research from Chopra and Meindl (2007). The case considers supply chain configuration, location and capacity decisions and modes of transportation. It has been demonstrated that discrete event simulation can be very effective in modelling this problem and thus investigating a strategic problem type.

Proposition 2 (P2): Discrete methods of simulation can represent supply chain feedback effects in models.
The coffee pot case involves information feedback and feedforward in that the reorder point mechanism is triggered from comparing the supply line with the reorder point level. Information in one part of the system is used to make decisions elsewhere in the system. Once again this has demonstrated that feedback can be very effectively built into discrete models of systems.

Proposition 3 (P3): System Dynamics can model supply chain problem types at the operational end of the spectrum as well as the strategic.
This case demonstrates that SD cannot be used to model this problem. This means that there are important problems that cannot be investigated successfully using SD. The response of the SD community in a discussion forum on this was effectively to suggest that the important problems in this area do not involve the tracking of individual orders. However, it may be that in the increasingly competitive world, the misplacement of a single order could have serious consequences for businesses. It may be that these problems cannot be dismissed this easily.

Proposition 4 (P4): The nature and role of decision makers in the problem may influence the selection of simulation technique.
In this case, the major strategic decisions in terms of location, factory type and shipping method are already taken in the sense of defining certain scenarios. The dynamic decisions taken during the execution of the orders are simply mechanistic and are ordering decisions being made in response to a reorder level. These decisions are effectively and successfully modelled in the discrete event model. The discrete event simulation method seems to be a good fit for the problem being modelled. With the problem in this configuration it is difficult to see how agent based methods would be more successful. However, if the strategic decisions were modelled dynamically, agent based modelling might be a powerful approach in this case. This would mean that agents could vary location, factory type and shipping method in order to achieve an optimum performance.

Proposition 5 (P5): The purpose of the modelling (exploratory, problem solving or explanatory) may influence the selection of simulation technique.

The main purpose in this case is essentially problem solving in type. The aim is to find the answer to the research question which concerns cost and inventory levels for a given service level in defined scenarios. The discrete event simulation method is found to be a good match for this purpose. SD has found to be unsuccessful in modelling this case and so limits have been identified for its applicability in this area of problem.

5.6 Summary

This chapter has explained the choice of the case studies in relation to the research questions and the propositions. Each case has been individually described and the findings have been explored in some detail within each case. The next chapter will develop the findings by taking a cross case perspective.

Chapter 6 Discussion

6.1 Introduction

Individual case analysis provides insights in relation to the propositions as has been shown. However, cross case analysis provides a further vehicle to furnish findings which are not necessarily evident at the single case level. Secondly and importantly, the cross case analysis provides a method to improve the robustness and validity of the theory building. A summary of the findings of the individual cases is shown in Table 27. The approach to cross case analysis will be to take the five propositions in turn and discuss them in relation to the cases. This analysis will form the basis of developing theory to explain what has been observed in the cases. In addition, for each proposition, further literature will be examined to test whether the findings are supported or contradicted.

6.2 Cross Case Analysis

The following sections contain the cross case analysis for each of the key propositions.

6.2.1 The value of the cases

Each of the cases have provided individual and complementary insights. The purchasing case provides a real life empirical example of organisational and process change in a contemporary business setting. The case has demonstrated some of the differences between applying a top down SD approach to a bottom up agent based method. In a different, but complementary way the coffee pot problem which is more a logistics and customer service modelling challenge has identified some of the potential weaknesses with the SD approach at the operational level. Both these cases provide evidence o f the potential for discrete modelling approaches at the strategic level. The Bullwhip case and the SD archetypes provide further evidence that discrete methods can represent feedback effects, and also that these methods are useful in investigating strategic problems. The value of the cases has been in providing further insights into the practical aspects of model building. Although the theoretical analysis may have pointed in a certain direction, the practice of model building is a key part of developing the deeper appreciation of the modelling approaches strengths and limitations.

6.2.2 Cross case analysis – Proposition 1

Proposition 1 concerns the application of discrete simulation methods to strategic problem types. The working definition for strategic supply chain problems that has been used throughout this research are given by Chopra and Meindl (2007) and Simchi-Levi et al. (2003) and were summarised in Table 1. The cases provide a good coverage of what can be considered strategic problem types in the supply chain domain. It is clear from the cases that discrete methods are at least as effective as SD in modelling these problems. In addition, in the purchasing case study an additional finding was that the agent based method revealed decision making going on at the operational level which had a significant influence over the performance of the system that had not been surfaced by the SD approach and this suggests a potential weakness in the SD methodology. Thus the case for the use of DES and ABM in modelling strategic problems seems strong. One difference between discrete methods and SD which emerged during the research concerns the transparency of models or the degree to which decision making is clear to users of the model. With SD, causal loop diagrams provide a vehicle for having effective dialogue with a team or with clients. In the case of discrete methods, the workings of the model are largely hidden in the code of the agents or the model elements. However, there are mechanisms for making decision making more visible in discrete approaches such as mapping decision state charts in ABM. These could be used with teams or clients to ensure that the decision making process is captured accurately. Also, with DES, the use of Visual Interactive Modelling Systems (VIMS) enables models to be built that are intuitive and where the function is clear to the client. It may be that the reason discrete methods have not been used as much as SD for policy and strategy development in the past is to do with custom and practice rather than method suitability.

There is some evidence in the literature that discrete methods could be more useful in modelling strategic problem types. An example of this is the whole hospital model proposed by Gunal and Pidd (2009). In this paper, the authors describe how the British National Health Service has been given various overarching waiting time targets by policy makers and politicians. These waiting times concern a number of areas, but one example given is the 18 week Referral to Treatment (RTT) target. Reviewing the literature, the authors maintain that simulation has been used in the hospital sector, but has mainly been used in discrete areas of the hospital to tackle fairly operational problems. Simulation has not been used to model the whole hospital or to inform policy. The authors go on to describe their development of the District General Hospital Performance Simulation Model (DGHPSim) which is a holistic discrete event simulation model of a general hospital. The authors demonstrate how the model can be used to model the complex interplay of factors to achieve overall results. Of particular interest is that they find that the successful reduction of patient waiting time relies on the implementation of a number of policies which together achieve the desired effect. This shows the importance of modelling holistically and considering the interaction of all the factors. Another example of using discrete event simulation to model healthcare policy is the modelling of the spread of ocular hypertension and glaucoma described by van Gestel et al. (2010).They mention that the use of discrete event simulation in health economic decision analysis has been growing in recent years. They report that the approach can be used successfully to model treatment strategies to evaluate their effectiveness.

They do acknowledge certain constraints of discrete event modelling which may prove to be barriers to adoption. For example, they suggest that it is important to achieve model transparency so that the structures and workings of the model are clear to stakeholders so they trust the outcomes. This can be difficult due to the flexibility in DES approaches and the lack of a standard approach. Other challenges with DES mentioned include simulation time, time to build the models, data collection and the degree of experience needed by the modeller. However, they argue there are potential solutions to these problems, for example the use of model visualisation techniques to improve model transparency and improved computing speeds to improve model run times.

An interesting example given by Rauner et al. (2005) concerns the use of DES to model the spread of HIV/AIDS in developing countries. DES is chosen over SD because it is more suitable for modelling the transmission mechanism which is mother to baby. This requires that individual mother-baby pairs are defined which is impossible for SD but possible for DES in this case (support for Proposition 3). The model is found to be very effective for modelling the impact of different practices and policies on transmission rates. These papers demonstrate that there seems to be an increasing interest in the use of discrete methods for modelling strategic problems in healthcare. There are challenges, but the benefits of the approach seem to outweigh these and ideas are being generated on how to meet these challenges.

Returning to the supply chain, an interesting and recent contribution to the debate is Tako and Robinson (2012) who compare the use of SD and DES in the logistics and supply chain context. The authors perform a literature review on articles published in peer reviewed literature between 1996 and 2006 which use these modelling approaches in these contexts are reviewed.
They classify the approach in terms of the type of problem being investigated and in particular the position of that problem in relation to a spectrum from strategic to operational.

The overall conclusion is very interesting in that they find no evidence to support the hypothesis that DES is used more at the operational/tactical end of the spectrum with SD at the strategic end. They admit that this contravenes the received wisdom in this area. This finding offers support to proposition 1 because it seems evident that discrete event simulation is being used to model strategic problems as much as SD.

The use of ABM to model strategic problem types is perhaps more accepted that DES. Two examples from the literature confirm that researchers are using ABM to model strategic issues in the supply chain domain. Albino et al. (2007) use ABM to model the benefits of cooperation between firms in industrial districts. The authors select what they call the multi-agent system (MAS) approach because the problem involves multiple autonomous firms choosing to collaborate. This matches well to the characteristics of MAS i.e. multiple semi-autonomous agents able to communicate through messages. Akanle and Zhang (2008) use a multi-agent system (MAS) again to model the dynamics of supply chain configuration. The configuration is not dynamic for every customer order but is determined for a period of time based on customer buying criteria and resource availability.

These examples together with the examples from the DES literature provide strong support for the proposition that discrete methods of simulation can be effectively used to model strategic problem types in the supply chain domain.

6.2.3 Cross case analysis – Proposition 2

Proposition 2 concerns the modelling of feedback using discrete methods. In all the cases feedback has been successfully modelled using a discrete approach. Feedback essentially means taking information from one part of the system and using it elsewhere in the system, usually to inform action. SD has been identified in the literature review as being strong on modelling systems which have feedback as a key characteristic. However, it may be that SD has become associated with the concept of feedback because that is what it has become famous for since the original work by Forrester. Also, the way that SD makes the feedback of information so visible in causal loop diagrams serves to reinforce this association. In reality, though, many systems involve the transfer of information around them and it is difficult to see how modellers can distinguish systems with a high degree of feedback from those that have a low level of feedback. Surely what is required is a method of modelling that can faithfully represent the system?

Discrete methods can clearly model feedback and so the existence or not of feedback should not be a criteria upon which to base the choice of simulation method. It might be useful if feedback could be more visible in discrete methods and more easily built into models. Currently, the feedback of information is hidden within the model coding and not as visible to the model user or customer as it is in SD. What this means is that it may be easier to model feedback in SD because the method itself encourages the modeller to be thinking in terms of what information influences decision making.

In the case of ABM, in some cases the feedback is an inherent quality of the system itself rather than information. For example, in the agent exponential growth model, the reason the model grows exponentially is driven by the number of agents in the system at a given point in time are reproducing. This number is a feature of the system, not an abstract number that is sourced from another part of the model. In conclusion, the presence of feedback in a system should not be a determining factor in method choice. However, it is recognised that SD makes the modelling of feedback more visible than discrete methods. In terms of the literature, Sarimveis et al. (2008) provide a detailed review of the application of control theory concepts to problems in the supply chain domain. Regarding DES, Coyle (1985) suggests that the point of view taken in discrete event systems is of an open system in which the output has a negligible effect on the input. The case studies have provided an opportunity to explore how feedback can be modelled using both DES and ABM and have demonstrated that discrete methods of simulation can very effectively model the feedback or feed forward of information. An example of a discrete event simulation model embodying feedback of information is described by Mujtaba (1994). The authors set themselves the challenge of modelling a complex manufacturing enterprise (Hewlett Packard). Their methodology includes the modelling of the feedback of information in the system. In the context of the Bullwhip problem, Kimbrough et al. (2002) investigate whether computer agents can develop successful strategies to manage inventory.

They discover that, using genetic algorithms, computer agents can outperform undergraduate and MBA students in the decision making processes of the game. A related stream of research concerns efforts to manage or mitigate the impact of the Bullwhip effect through strategies such as information sharing. They discover that, using genetic algorithms, computer agents can outperform undergraduate and MBA students in the decision making processes of the game.

	Case Study 1 – Bullwhip and SD Archetypes	Case Study 2 - Purchasing	Case Study 3 – Coffee Pot Problem
Proposition 1 - Discrete methods of simulation can be useful in investigating strategic problem types in the supply chain domain.	**Supported** The Bullwhip case clearly demonstrates that discrete methods, and in this case Agent Based Modelling (ABM) can be used effectively to investigate a strategic problem type.	**Supported** The purchasing case clearly demonstrates that ABM can be used very effectively to investigate a strategic problem type. In fact, it could be argued that it identified key decision making in the system which was not identified by the SD approach.	**Supported** Discrete Event Simulation (DES) is found to be very effective in investigating this supply chain problem which spans strategic to operational issues.
Proposition 2 - Discrete methods of simulation can represent supply chain feedback effects in models.	**Supported** Both the Bullwhip case and the SD archetypes demonstrated that discrete methods can represent feedback effects in models.	**Supported** The agent based model does incorporate feedback effects.	**Supported** This case demonstrates that both feedback and feed forward of information can be effectively modelled by DES.
Proposition 3 - System Dynamics can model supply chain problem types at the operational end of the spectrum as well as the strategic.	Not applicable	**Contradicted** This case provides some evidence that the System Dynamics approach may be vulnerable to omitting key decision makers at the operational level.	**Contradicted** This case demonstrates that SD cannot model classes of supply chain problem where discrete behaviour or measures are important.
Proposition 4 - The nature and role of decision makers in the problem may influence the selection of simulation technique.	**Supported** ABM is found to be very effective at locating the decision making process in a given agent. This means that the representation of decision making by individuals is perhaps more accurate and easier to model than in SD, where the decision making process is detached from the individuals in the system.	**Supported** This case demonstrates that ABM can be very effective in identifying the key decision makers in systems. It also provides some evidence that the SD approach may contain risks that it ignores key decision makers embedded in the system.	**Supported** DES seems to be suited to problems where decision making is quite mechanistic. If more complex decision making processes are required, ABM may be needed.
Proposition 5 - The purpose of the modelling (exploratory , problem solving or explanatory) may influence the selection of simulation technique.	**Supported** Both SD and ABM are found to be useful in exploratory and explanatory modes. The transparency of SD models may lend the approach to a more interactive process than ABM.	**Supported** Both SD and ABM appear to be well suited to exploratory or explanatory modelling.	**Supported** DES seems well suited to a problem solving approach.

Table 27 Summary of case study findings

A related stream of research concerns efforts to manage or mitigate the impact of the Bullwhip effect through strategies such as information sharing. Zhang and Zhang (2007) use discrete event simulation to investigate information sharing in a supply chain and in particular the impact of missing out intermediate tiers, as for example Dell has done with their direct marketing to the customer. They develop a model using a simulation tool GPSS/World based on the software General Purpose Simulation System. On the basis of the cases and the supporting literature, it seems clear that feedback can be modelled using discrete event methods. This is not to say that discrete methods can provide all the control theory analytical tools, but that in terms of feedback this is possible. It should also be recognised that the method of representing feedback in SD on model diagrams means that feedback effects may be more transparent to the modeller and their client. Moreover, the SD methodology itself may provide more focus on identifying and mapping sources and causes of feedback than discrete methods.

6.2.4 Cross case analysis – Proposition 3

Proposition 3 concerns the use of SD to model operational problems. Two of the cases have shed particular light on this area in different ways. The Coffee Pot case demonstrates that there are practical limits to the applicability of SD in certain situations in the supply chain domain. These situations are when the system behaviour of interest concerns a discrete measure of performance, such as on time delivery, or when the investigation requires the modelling of discrete entities, resources or processes. On the other hand, the purchasing case has identified a potential risk that System Dynamics may ignore important decision making processes in the operational layer. Regarding the first problem, the author posted a question on the System Dynamics Discussion forum (Owen, 2012). The response of the SD community to this challenge was to suggest that the important problems are different and that the problem would be framed differently for an SD approach (see Appendix). It is valid to say that SD is not suited to certain problem types, but it is not valid surely to argue that the problem is not the right problem to be investigating. The problem may be of considerable interest to the client or organisation concerned and it may have discrete characteristics that mean that SD is not a suitable method for this particular situation. It is not for the modeller to say whether the problem is worth solving. How does the modeller determine if a problem is in this category? The suggestion is that if the focus of the study is on the discrete performance or behaviour, then the problem is in this category. There are many other supply chain problems that would be classified as such and for which SD would not be suitable. In this event, the modeller has two choices, either build the model using a discrete approach, or use a hybrid model encompassing SD and a discrete method. Using a hybrid method may come at the additional cost of having to learn two methodologies and potentially having to build an interface between the two systems. It may be possible to use a multi-paradigm package such as Anylogic (Anylogic, 2012) to build the model. But the challenge remains why not build the model using a discrete approach overall? The SD approach must offer some additional advantages to outweigh the costs of using two methods. Given the conclusions to Proposition 1, that discrete methods can be used effectively to model strategic problems, there may be an argument for using the discrete approach alone in modelling supply chain problems that span both strategic and operational aspects.

On the other hand, Tako and Robinson (2012) identify some evidence which appears to support the claim that SD can be used to model operational problems. For example, they cite Han et al. (2005) who use SD to model an earthmoving process as part of a construction problem. The process being modelled could be argued to be an operational problem since it concerns optimising the cost of an earthmoving process involving loaders and trucks transporting earth to a planned site. However, on closer scrutiny the problem can be modelled using SD since it does not have discrete characteristics. For example, the earth is continuous substance. The number of loaders and/or trucks is always a quantity greater than one. The authors admit "*Owing to the SD model's continuous and aggregational nature, it is difficult to address the specifics of a particular resource. For example, when using SD, it is difficult to address what kind of activity the truck with identification number 3, is doing. Such a distinction of a particular resource will be the main challenge for SD models to be applied at an operational level*". Thus this example, although demonstrating that SD can be used to model some operational problems, nonetheless identifies the constraints to such an application. The other example cited is Oyarbide et al. (2003) who investigate the use of SD to model an assembly line. The authors conclude that there are three levels of problem in manufacturing system design which they describe as coarse, intermediate and detailed evaluation. They recommend using 'brain power' for the coarse level, DES for the detailed level and suggest the most suitable level for SD is in the intermediate evaluation level. The point out that "*SD forces the user to view a manufacturing system at a relatively aggregated level of detail*". Again, the use of SD is constrained to a level above the detailed operational layer. Demirel (2006) explores the use of both SD and ABM to model a supply chain system. The investigation involves building models of the same system using SD and ABM and testing the impact of various factors on system behaviour including supplier inventory position, price, phantom orders and customer loyalty. In each case the finding is that whilst ABM can embody these factors into the model, SD cannot. In each case the response of the model changes when this factor is incorporated into the agent's behaviour. This leads the author to the conclusion that "*system dynamics may miss the dynamics at more detailed level resulting from the emerging* *heterogeneity among individual agent behaviours in these cases. There are also cases where SD cannot capture the dynamics generated by ABM, even at an aggregate level*". However, in the SD model the suppliers are all modelled as aggregated stocks. What is not explored is the option of modelling different co-flows to model different cohorts of suppliers. This is an option in SD and although it is limited, it may allow the SD model adequate disaggregation to model the phenomena identified. What is certain is that at a certain point SD will not be able to model the discrete behaviour of the system (as per Proposition 3), but the question is whether the phenomena can be adequately represented in an aggregate form.

This constraint on SD is also described in Riddalls et al. (2000) who suggest that what they call discrete event dynamic systems (DEDS) may have emerged due to the limitations of differential equation approaches. They give the example of the inability of SD to model something as simple as customers queue swapping in a supermarket or variable service speed.

On the surface the literature may appear to be contradictory, some authors claiming that SD can be used to model operational problems and others saying that it cannot. This is due to inconsistencies in the term operational. Some problems that are considered operational, such as the earth moving problem described above can indeed be successfully modelled using SD. Others, such as the supermarket queue and the coffee pot problem cannot. More specifically, what can be stated is that SD cannot model problems where the performance measure or the behaviour of discrete entities, resources or processes is the focus of interest.

Regarding the second challenge, the risk of key decision making being overlooked is acknowledged by Lyneis (1999) who gives several examples in the context of strategy where models have been found to be incorrect on further examination in the detail. He describes this process of model validation as 'calibration' and says that "*the initial formulation of a problem and the formulation of the structure of a simulation model are based on managers' "mental models*. *These models are rarely complete or one hundred per cent correct*." His suggestion is that careful calibration of the models will lead to the identification and elimination of errors. However, the concern is that the starting point for the development of SD models is a top down development of a dynamic hypothesis. This surely makes the process vulnerable to the discovery of an error in the detailed operational layer of an organisation or system. On the other hand, the start point for the ABM approach is to identify the important decision makers (agents) in the system. This does not privilege the senior managers' view of the organisation, but seeks to identify the decision makers wherever they may be in the organisation and seeks to build the model around these agents and how they make such decisions.

6.2.5 Cross case analysis – Proposition 4

Proposition 4 suggests that the nature and role of decision makers in the problem may influence the choice of simulation technique. The three cases have embodied different aspects of decision making in the supply chain domain. What has become apparent in the cases is that decision making is modelled in different ways by the three techniques. This is summarised in Table 28.

Approach	How are decisions modelled?
System Dynamics	• Decisions are modelled as visible causal loops • Decisions are not conceptually linked to individual people but are abstracted
Agent Based Modelling	• Decisions are modelled within the agent state chart and are invisible during the model run, but can be examined • Decisions are clearly linked to individuals
Discrete Event Simulation	• Decisions are built into the model code and are thus invisible, but the logic can be examined by the modeller • Location of the logic will depend on the world view (event, activity, process or object-orientation)

Table 28 Approaches to modelling decisions

What this means is that rather than necessarily informing the choice of approach, each approach has limitations when it comes to modelling decision making. System Dynamics models decisions visibly, but it is difficult to see the connection between the model and the individual decision maker. SD models will often incorporate factors or tables that do not link directly to an individual but more a phenomena, for example the table for order fulfilment in the SD Bullwhip model. Agent based modelling as a methodology is closer to modelling the individual decision making process. This is because the approach explicitly requires that the key agents, or decision makers, are identified early in the modelling process. The decision making processes are explicitly linked to these individuals in the agent state chart. However, the ABM approach makes the decision making process less visible than SD in that the state charts are hidden within the individual agents. DES models traditionally embody the decision making within the logic of the individual resources and workstations. The decision making process in this case is both hidden and not linked to the individual decision makers. Thus each approach has strengths and weaknesses. In terms of modelling where the decision making process is a key area of investigation, it seems that SD and ABM may provide more clarity and focus than DES.

Proposition 4 suggests that the nature and role of decision makers in the system will influence the selection of simulation approach. The case studies have demonstrated that all three approaches have challenges when modelling decision making, either to do with the difficulty in aligning decision making processes represented in the model with individuals in the real system or to do with the transparency of the decision making process in the model. In the literature, Mönch et al. (2011) set out the challenges of modelling supply chains using discrete simulation approaches, which they refer to as discrete event logistics systems (DELS). The authors set the scene by proposing that the difficulty of modelling these systems is 'magnified enormously' due to four factors, namely: the scale and scope of global supply networks; the dynamic behaviour of these networks; the broad range of information and communication systems in use and finally, the high density of decisions in these systems. They go on to describe a range of challenges to modelling, some of which are listed below:

- multiple levels of abstraction
- no unified DELS language
- incomplete knowledge of policies to be modelled
- modelling mixed discrete / continuous phenomena
- human decision making
- model development time

The authors conclude that current modelling efforts fall short suggesting there is "*the inability to model large-scaled, real-world supply chains in a timely, cost-effective way*".

Van Der Zee and Van Der Vorst (2005) explore the role of modelling and simulation in supporting decision making in the supply chain domain. They suggest that the communicative role of models requires a level of 'model transparency and completeness'. They argue that current methods of simulation focus too much on the physical, transactional nature of supply chains and not enough on the decision making and control aspects. In particular, they suggest that certain aspects of the supply chain should be made explicit, such as: actors, roles, control policies and procedures, timing and execution of decisions. They find current methods lacking in that they make such features 'hidden' and dispersed through the model. The use of intelligent agents is seen as a positive development since there is a more natural association between the agents and the real life managers and decision makers in the real system. The authors propose a software independent agent based modelling framework as a way forward. In terms of human decision making, both Dubiel and Tsimhoni (2005) and Siebers and Aickelin (2011) point out the limitations of DES in modelling human behaviour and use an agent based approach to develop their models as a hybrid within a DES framework.

Thus it seems that both from the case studies and the literature, current methods of simulation do not provide an adequate set of tools for modelling the decision making processes in the supply chain domain. The challenges are significant, but the approaches in their current form do not seem to be suited to those challenges and some significant development may be required to bring them to a position where they can be effective.

6.2.6 Cross case analysis – Proposition 5

Proposition 5 suggests that the purpose of the analysis may influence the selection of approach. Two of the cases (Bullwhip and Purchasing cases) are more explorative and explanatory in nature. The coffee pot case is both explanatory and problem solving. These cases have thus not really challenged the received wisdom in this area because these are largely the ways in which the approaches have been seen to be used in the past (Lorenz, 2006). The extension of DES into a more explanatory mode in the coffee pot case is perhaps an interesting area worthy of further exploration. The finding that SD is unsuitable for operational problem types perhaps shows a potential weakness for SD in problem solving, but this is in relation to a particular class of problems i.e. discrete problems. It is perhaps too simplistic to associate one approach to modelling with the overarching purpose of the investigation. The different approaches may be suitable for all three modes of investigation. The way in which the approach is used is to some extent in the hands of the modeller. Although traditionally, an approach may have been used mainly in one mode e.g. ABM used mainly in exploratory mode, this may not mean that it cannot be used effectively in another mode.

The case studies have served to test the propositions formulated from the literature review and theoretical analysis. However, the purchasing case has provided evidence for a further conclusion. The purchasing case demonstrated that the SD approach may have a potential weakness in that it may not surface key decision making processes lower down in an organisation, for example at the operational level. This is because the approach is a top down approach. In the purchasing case a dynamic hypothesis was developed which seemed plausible to the central team involved in the project. This is because the central team had partial information and access to what was going on lower down in the organisation. The agent based methodology, conversely, required early in the process the explicit identification of the key decision makers in the system. This drove this researcher to seek out a deeper understanding of the system and to identify key decision making processes that meant that the dynamic hypothesis generated by the SD approach might overstate the potential success of the endeavour. It could be said that this is an isolated incident or that this is to do with the fact that the SD methodology was not properly implemented. However, the SD approach inherently drives a different mentality. The starting point is to develop a high level working dynamic hypothesis to explain the workings of the system. Once this high level structure has been defined and has been understood by the team at the centre, it may become received wisdom. This is not to say that in every case teams using the SD approach will make this error, but rather that the methodology may lend itself to being vulnerable to this risk. This risk could be an example of a Type III error i.e. the error of solving the wrong problem (Balci, 1994).

Previous propositions have considered the suitability of the approach in relation to the nature of the problem being modelled. This proposition is related to the nature of the inquiry itself, in other words, why are we modelling? Consideration of why we are modelling means thinking about the philosophical position of the modeller and the client. At the positivist end of the spectrum, the purpose may be more focused on 'hard' problem solving, where there is a clearly defined problem and a narrow set of potential solutions. In this research, the coffee pot problem could fall into this space. However, problems may be strategic, messy and unstructured and call for more 'soft' methods such as problem structuring (Rosenhead and Mingers, 2001) and soft systems methodology (Checkland, 1999). The purchasing case study and the Bullwhip case may fall more into this category. Lane (2000) explores the purpose of modelling in relation to DES and SD and suggests that each approach may be suited to a certain problem space in relation to three types of complexity, namely organisational, dynamic and detail (Figure 18). He explains that attempting to build too much detail into an SD model may be problematic in that trying to "*make a model all things to all people in this way can lead to its being understood by few and hence less organisationally effective*…." He also describes the varied way in which SD is used to explore different areas of society from its initial foundations to broader interactive SD which involves high levels of client participation and response in model building. There is some consensus in the literature that if the model purpose is to investigate policy and strategy, high levels of interactivity and transparency may be required from the simulation approach if it is to be successful (Lane, 2000 ; Pidd, 2003 ; Mönch et al., 2011).

In terms of coffee pot case, the use of DES as an approach has not yielded new insights in relation to this proposition because it is already known that DES is useful in this area. The finding that SD cannot model certain discrete problems places limits on the usefulness of SD in relation to this problem space. The more interesting area is the two more strategic cases and the use of ABM to model them. In the purchasing case, the use of the ABM approach surfaced important decision making at the operational level not identified by the SD approach. The use of agents to model the Bullwhip case illustrates the ease of matching decision makers in the real world to agents in the model. Thus the agent based approach seems to have been useful in the more exploratory mode. However, current approaches to ABM may be restricted in this exploratory mode if they do not meet the requirements of transparency and interactivity identified above.

Each of the approaches could potentially be used to support philosophical enquiry at both ends of a spectrum from positivist to intepretist. What is key is the attitude and approach of the modeller to the problem and the people who work in the system concerned. Secondly, the nature of the approach itself may either support or hinder the modeller’s efforts.

6.3 Discussion

The previous sections have explored the case study findings and the enfolding literature drawing out and in some cases, refining the conclusions. This section will consider the implications of these findings for the key customers of this research, namely supply chain practitioners. The research will also be critically reviewed in terms of its strength and weaknesses and limitations. Finally, a consideration of generalizability will be undertaken.

6.3.1 Implications for supply chain practitioners

Supply chain practitioners are interested in investigating and solving problems in the real world. There will be practical constraints such as the modelling experience of the modeller, access to data and decision makers, budgetary constraints in terms of time and money. It is not possible to provide a definitive selection matrix which links all types of supply chain problems to modelling approaches. However, this research provides more clarity on the suitability of these three approaches to different supply chain problem types. It has shown that, in some cases, the scope of application of the approaches may be wider than previously assumed. Thus a practitioner trained and experienced in one of the discrete approaches may be able to investigate more strategic problems, for example. Conversely, a System Dynamics practitioner is constrained from investigating certain type of more detailed discrete problems. In some cases, any of the approaches could be used to investigate a given problem situation. Nonetheless, it is also true that certain problems are perhaps more easily or efficiently modelled using one of the techniques.

Lorenz (2006) proposed a framework for matching the approach to the problem through aligning purpose, object and methodology, although they admitted that this was an initial view and further research was needed. In the context of the supply chain domain, this research has extended and provided more clarity and resolution to these questions. The findings can be summarised in relation to an amended version of this framework as shown in Table 29. Practitioners can consider the characteristics of the problem they are investigating and identify which approach best fits their situation. From a pragmatic perspective, if more than one approach is suited to the problem, and the practitioner is already more experienced with one of the approaches, then this could guide their choice.

6.3.2 Use of hybrid approaches

In some cases, the problem concerned may cover a wide scope and more than one approach might be considered necessary to model the problem. As has been covered previously in Section 2.4, some researchers have built hybrid models in these circumstances. This is a reasonable way forward, however, this does come at some cost to the modeller in having to learn more than one approach, and potentially having to build an interface between them.

		Approach		
Aspect		**System Dynamics**	**Discrete Event Simulation**	**Agent Based Modelling**
Purpose of the enquiry		Exploration and explanation of dynamic relationships Interactive investigation of policies with client	Problem solving Optimisation Can be used for exploration and explanation, but transparency and client involvement become key	Exploration Understanding of agent behaviours Investigation of unexpected consequences
Characteristics of the problem	Problem Level – Strategic	Policy investigation and evaluations	Can be used at the strategic level but transparency of models and involvement of clients becomes key	Useful when understanding of individual 'agent' behaviours are the focus of enquiry. Can be used at the strategic level but transparency of models and involvement of clients becomes key
	Problem Level – Operational	May be vulnerable to missing important decision making at this level Cannot be used for certain discrete problems at this level	Process level investigation into inventory levels, customer service, physical logistics	Investigation into behaviour of individual 'agent' behaviours at the operational level.
	Discreteness of measures, entities, resources, process is important	Aggregation of measures , entities, resources and processes is acceptable	Discrete measures or behaviour of discrete entities, resources and processes is an important aspect of the problem	Discrete measures or behaviour of discrete entities, resources and processes is an important aspect of the problem
	Decision making process	Not important to link decision process in the model directly to decision makers in the real world	Not important to link decision process in the model directly to decision makers in the	Important to link decision process in the model directly to decision makers in the

			real world	real world
	Physical Space	Not important to the problem	May be important to the problem	May be important to the problem
Key characteristics of the approach	Perspective	Top down, development of dynamic hypothesis	Process perspective (material and information flows)	Agent perspective (essentially bottom up)
	Feedback	Modelled explicitly	Can be modelled but is hidden	Can be modelled but is hidden

Table 29 Matching the approach to the problem

The findings of this research suggest that discrete methods may be useful in the strategic domain, for example, so the modeller should consider using an overall discrete modelling approach as well as an SD/discrete hybrid.

6.3.3 Limitations of the research

This section will out to reflect on this research process, to identify its strengths and weaknesses and the limitations that may apply to any findings, conclusions and insights. This will then lead to a consideration of the degree to which the findings can be generalised.

One of the key strengths of this research has been the 'back-to-back' modelling of supply chain problems using more than one simulation approach. This was identified as one of the key weaknesses in the previous comparison literature and was identified by a number of researchers as a key area for further research (Ozgun and Barlas, 2009 ; Demirel, 2006). Only through this detailed modelling can effective comparisons be made that allow the debate to move beyond the received wisdom of the previous debate. Linked to this, a further strength was that the researcher was neutral in terms of the three paradigms, in that he was initially a novice with each of the approaches. Although this was very challenging, and required a steep learning curve, in fact this researcher was able to develop a degree of competence and confidence with all three of the main paradigms during the course of the research. Many previous comparisons have involved researchers who are strong with one approach, but less confident with the other, thus limiting the potential for them to compare different techniques. The modelling of a real supply chain problem in a real company gave this researcher a very rich source of data and experience within which to test out some of the ideas and practices. This access to a real case was a defining aspect to this research and has perhaps led to some key findings, particularly in relation to System Dynamics. Finally, a key strength for this research has been the extensive experience that this researcher has of being a practitioner and consultant in the supply chain domain. This has meant that this researcher has been grounded in the reality and demands of the domain rather than purely focused on the technicalities of the simulation approaches.

On the other hand, this research has used a limited number of cases for the analysis. One practical case has been used and two ‘typifications’ or secondary cases. More cases would clearly lead to a higher level of confidence in the generalizability of the findings. Nonetheless, as has been stated previously, a small number of cases may lead to analytic rather than statistical generalisation. The cases have focused on a subset of supply chain problem types. Although quite extensive, the problem types do not address all the many and varied types of supply chain problems that the practitioner may encounter. In particular, in relation to the SCOR model, the cases do not cover the Make-to-order (MTO) or Engineer-to-order (ETO) situations, and do not cover the wide range of issues in the Delivery process area. Another potential limitation has been that the modelling has been carried out by this researcher. This means that there is some risk of bias, since this researcher may have conscious or unconscious preferences or attitudes that are leading to the focusing on certain issues and the biasing of results. This risk would be mitigated if the modelling had been performed by a wider range of modellers. Unfortunately, this was not practical. It would also have worked against the associated strength identified of the researcher being paradigm neutral, since most modellers will be biased towards one approach or another. Another limitation of the research is the fact that only one practical real life case was investigated. More real life cases would lead to more confidence in the findings.

6.3.4 Generalisability

The extent to which the findings from case study research can be generalised relies upon the rigour of the research i.e. can we be confident that a different researcher would have arrived at the same results, and external validity i.e. to what extent will these findings apply in other similar circumstances (Yin, 2003). In order to ensure rigour, this research has followed a case study protocol to ensure consistency. In addition, the simulation approach has followed closely the accepted methodology as described in relevant texts. This has increased the probability that a different researcher following this approach would have found the same results. In terms of external validity, two key aspects of research design have been important. Firstly, the use of multiple cases and embedded units of analysis increases the validity of the findings. Secondly, the use of ‘typifications’ such as the coffee pot case and the Bullwhip case are themselves typical problem types that apply in a variety of supply chain settings. In that sense, the ‘typifications’ themselves a representative of a wider set of problems than an individual practical case. The inclusion of a practical real life cases study, ensures that the domain of enquiry extends beyond the academic and into the real world. These steps, together with the review of the enfolding literature have ensured that these findings and insights can be generalised to the use of these simulation approaches within the supply chain domain. However, at this point, these findings could not be said to hold true for all problem domains outside the supply chain.

6.4 Conclusion

Chapter 6 has refined the propositions in the light of cross-case analysis and a review of the enfolding literature. Chapter 7 will set out the key findings of the work, the contributions and recommendations for further work.

Chapter 7 Conclusions, contribution and further work

7.1 Introduction

It has been established that the supply chain is a complex and dynamic environment, and that many firms compete on the basis of their performance in this area. Simulation is a method suited to problem solving in this challenging context, but practitioners need support in selecting the most appropriate method for their situation. This research has set out to investigate this area to provide more rigour to support this decision making process. Historical views seem based more on custom and practice rather than a rigorous, empirical comparison. For this reason, this research reviewed the approaches from first principles and examined their history and development. This led to a more refined set of propositions based on the original claims identified in the literature. These propositions were then examined by modelling a selection of supply chain problems 'back-to-back' using both a continuous and a discrete approach. The case study method was followed with a clear protocol and the use of clear methodology for simulation has ensured rigour in the research process. This holistic comparison of the three main approaches, SD, DES and ABM has not been conducted before in the supply chain domain. This section will set out the key conclusions of this work and the contributions to both theory and practice. The approach taken will be to firstly return to the research questions to describe how these have been addressed. The nature of the contribution to both theory and practice will then be outlined. A reflection on the research process itself will be conducted and the chapter will conclude with recommendations for further research.

7.2 Review of research questions

The research was initially driven by broad research questions which were aimed to understand the role of simulation in the supply chain context and then to compare the relative strengths and weaknesses of the main approaches. The overall purpose was to provide guidance for supply chain practitioners in selecting the most appropriate method for their particular problem and situation. The overall methodology took these research questions and through a detailed literature review and theoretical analysis, distilled out a set of more precise propositions. These propositions provided the basis upon which to conduct the case study research. The case study approach has led to conclusions and findings, and provided the basis for the development of a framework to guide practitioners in the selection of the appropriate simulation approach.

Research questions 1,2 and 3 concerned identifying the different methods of simulation used in the supply chain domain and a consideration of their theoretical foundations and how this might inform their suitability for modelling different problems.

RQ1: What are the main methods of simulation used to improve supply chain performance?

The literature review identified that the three main methods of simulation used in the supply chain domain are System Dynamics (SD), Discrete Event Simulation (DES) and Agent Based Modelling (ABM). This question was explored in some detail in Chapter 2.

RQ2: What are the theoretical building blocks and assumptions that lie behind these techniques?

Theoretical analysis examined the origins and fundamental building blocks of these techniques. The details of this analysis are contained in Chapter 4. Although it is recognised that all three of the approaches can be considered paradigms, there are two main simulation world views, namely continuous and discrete.

RQ3: How does this illuminate the supply chain problem types for which certain techniques might be better suited than others?

From a theoretical perspective the received wisdom was challenged. A number of propositions were developed which emerged from the challenge to the received wisdom. These are restated here for convenience and are also in Section 4.5.1.

Proposition 1 (P1): Discrete methods of simulation can be useful in investigating strategic problem types in the supply chain domain;

Proposition 2 (P2): Discrete methods of simulation can represent supply chain feedback effects in models;

Proposition 3 (P3): System Dynamics can model supply chain problem types at the operational end of the spectrum as well as the strategic;

Proposition 4 (P4): The nature and role of decision makers in the problem may influence the selection of simulation technique;

Proposition 5 (P5): The purpose of the modelling (exploratory, problem solving or explanatory) may influence the selection of simulation technique.

In some cases, such as physical space, suitability of the approaches can be proven from first principles. However, in a number of cases, a review from first principles challenged the received wisdom. For example, there seemed to be no real reason why discrete methods could not be used to model strategic problem types; there seemed to be no reason why discrete methods cannot model feedback and there could be more scope for applying SD to operational problem types.

Questions 4,5 and 6 concerned comparing the strengths and weaknesses of the different techniques. From a methodology perspective, this was driven through the case study research.

RQ4: What are the relative strengths and weaknesses of different techniques in simulating certain supply chain problem types?

RQ5: What experiments can be done to test and compare alternative approaches?

The case studies were selected to allow the testing of the key propositions. Each case provided some evidence to support or contradict the proposition. A review of enfolding literature served to refine the conclusions and findings. The overall findings are summarised in Table 30.

Original Statement of Proposition	Other Comments
Proposition 1 (P1): Discrete methods of simulation can be useful in investigating strategic problem types in the supply chain domain.	Supported both by case study findings and enfolding literature review.
Proposition 2 (P2): Discrete methods of simulation can represent supply chain feedback effects in models.	Supported both by case study findings and enfolding literature review.
Proposition 3 (P3): System Dynamics can model supply chain problem types at the operational end of the spectrum as well as the strategic.	Rejection of the original proposition supported by case study findings and refined by enfolding literature review.
Proposition 4 (P4): The nature and role of decision makers in the problem may influence the selection of simulation technique.	Decision making is modelled differently by all three approaches. Each approach has limitations.
Proposition 5 (P5): The purpose of the modelling (exploratory, problem solving, explanatory) may influence the selection of simulation technique.	Some insights into the potential uses for all three approaches in all different modes of enquiry depending on the philosophical stance of the modeller and the client.

Table 30 Summary of findings

RQ6: How can these conclusions be used to generate recommendations for practitioners on how they should deploy these tools in achieving their supply chain objectives?

Recommendations for practitioners are shown in Table 29. For practitioners, the challenge is to match the purpose of the modelling activity and the characteristics of the problem to the approach.

7.3 Contribution

The previous section has revisited the research questions and described the findings and conclusions in relation to them. This section will describe the nature of the contribution in relation to knowledge and practice.

7.3.1 Contribution to knowledge

A number of contributions have been made to the knowledge in this area.

7.3.1.1 Holistic cross-paradigm comparison of continuous and discrete simulation approaches in the supply chain domain

This research has conducted the first holistic cross-paradigm comparison of continuous and discrete approaches the supply chain domain. The determination to approach each case from the perspective of System Dynamics and one of the discrete approaches has led to new findings and insights. The comparison has clarified limitations of SD in relation to modelling operational problem types as well as risks with its application to strategic modelling. Further insights have been achieved in terms of implications of the overall modelling philosophy on the way the problem is approached and modelled. The independence of this researcher towards the paradigms is another unusual feature of this work. Usually, researchers are more familiar with one of the approaches than the others, thus potentially biasing any comparison work.

7.3.1.2 'Back to Back' modelling of supply chain problems using a continuous and discrete approach

Modelling the same problem using different simulation techniques has rarely been done in the past. This back to back modelling has provided more precision to the nature of the advantages or disadvantages of the approaches than has previously been the case. In particular, the careful following of the relevant methodology has ensured that the conclusions drawn have been to do with the inherent differences of the modelling approaches rather than 'the way' the modelling has been conducted.

7.3.1.3 Application of discrete approaches to modelling strategic supply chain problem types

In all the cases, discrete methods were used to model strategic problem types. It is clear from these cases that discrete methods provide an effective method for investigating strategic problem types. Moreover, in the case of the purchasing case, the agent based approach provided additional insights to the SD method. The review of enfolding literature supports the notion that there is further potential for discrete methods in the strategic problem domain.

7.3.2 Contribution to practice

In a number of areas, the findings of this research inform the practice of applying simulation in the supply chain context. This is both in terms of additional risks and limitations to the applicability of the approaches and alternatively, the potential for them to be applied in new ways or in new areas.

7.3.2.1 Development of an initial framework for selection of approach

A framework (Table 29) linking model purpose, problem characteristics and approach, a refinement and extension of the model proposed by Lorenz (2006) has been developed. The framework is a refinement, in that it contains only those characteristics which are found to be real differentiators between the approaches based on the empirical work which has been undertaken. It is an extension because there is additional clarity in a number of areas, for example, more clarity concerning the limits and risks of System Dynamics; more clarity on the modelling of feedback; insights into the potential role of discrete methods in modelling strategic problems and the modelling of decision making processes.

7.3.2.2 Identification of the limits of the application of SD to discrete problem types in the supply chain domain

It is very important to understand the potential limits of the application of SD to supply chain problems. This research has shown that there are hard limits to the application of SD in the supply chain domain. This is of significant importance to the practitioner, because it means there are problems which SD cannot help to solve. The response of the SD community, as has been discussed, has been to imply that problems that cannot be solved or illuminated with SD must therefore be trivial. This is perhaps an understandable reaction from the perspective of a particular paradigm. However, the coffee pot problem is a typical inventory and customer service problem often encountered in the supply chain domain, and thus this is an important limitation of SD. The boundary of the application of SD is where the phenomenon of interest is discrete, whether that is the measure of performance (on time delivery, for example) or the behaviour of resources, processes and entities. This boundary of applicability is also of interest to hybrid modellers who may wish to use SD to model the strategic/policy side of the problem and a discrete approach to model the operational detail.

7.3.2.3 Risks of applying SD to strategic problem types in the supply chain domain

The purchasing case study has suggested that in modelling a strategic problem, there is the risk that important decisions being taken in the operational layer will be missed and as a result incorrect assumptions will be made concerning the behaviour of the system. The system dynamics community have recognised the existence of this risk and have developed methods to try to mitigate it, for example using calibration. However, this risk is an inherent feature of the method itself being top down and based on developing a structural explanation for the dynamic behaviour of the system of study. On the other hand, the ABM method, which starts with the identification of the key decision makers in the system, does not suffer from this risk. This is an important potential risk of the use of SD in modelling any system.

7.3.2.4 Modelling of feedback using discrete methods (including SD archetypes)

This research has demonstrated that information and material feedback can be modelled using discrete methods. The modelling of SD archetypes shows that technically, any model constructed in SD can be replicated using discrete methods. This moves the debate from whether feedback can be modelled using discrete methods (it can) to whether SD provides a better approach for modelling feedback. Feedback is a concept central to the SD method. As such, feedback is modelled explicitly and visibly in SD models through causal loop diagrams, balancing and reinforcing loops. To this extent, in terms of visibility, SD is perhaps clearer to the client than discrete methods. This finding suggests that perhaps the modelling of feedback in discrete methods could be made more explicit.

7.3.2.5 Modelling of decision making in the supply chain domain

This research has shown that each of the three approaches models decision making differently, and that all of the methods have limitations. ABM provides perhaps the most natural faithful representation of the decision makers in the real world to the model. However, the transparency of the decision making process is perhaps better in SD. Decisions and decision making is largely hidden in DES. All three methods could perhaps be improved in terms of the way that they model decision making processes.

7.3.3 Findings

Finally, in some areas further insights have been achieved, which although not contributions are nonetheless significant.

7.3.3.1 Modelling purpose

An insight provided by this research is that all three approaches can be used to support different modes of enquiry. It is perhaps not helpful to constrain a particular approach to a particular mode, for example, DES to problem solving. The mode of enquiry being adopted by the modeller and/or client is not necessarily linked to the approach to be taken in simulating the system.

7.4 Further research

There are a number of areas which merit further research based on these findings. This section will outline these proposed areas.

7.4.1 Further development of the framework

This research has involved a limited number of cases of problem types in the supply chain domain. These findings should be tested and extended by applying the ‘back-to-back’ modelling approach to a wider set of supply chain problems. In particular, in relation to the SCOR model, further testing of models in the Make-to-order and Engineer-to-order areas could be done in order to extend the understanding of the issues in these areas. Further modelling of the wide range of processes in the Delivery (D) area of the model would also be beneficial. Some examples of additional areas for investigation could be: e-sourcing, contracting, supplier selection and supplier quality assurance. Extending the research in this way could lead to a comprehensive framework linking supply chain problem type to guidance on modelling approach selection.

7.4.2 Other problem domains

This research has been conducted in the supply chain domain. It would be interesting to test and extend these findings in other domains where simulation is used extensively, for example manufacturing and healthcare. May of the findings may be applicable outside the supply chain domain.

7.4.3 Making feedback clearer in discrete modelling methods

Although feedback can be modelled using discrete methods, it is not as explicit as it is in SD. It would be interesting to explore whether the feedback processes could be made more transparent and explicit to model users and clients.

7.4.4 Further back-to-back testing of SD in strategy and policy domain

Research is required to achieve further confidence in the finding that SD may be vulnerable to missing important decision making in the operational layer. This could be accomplished with more 'back-to-back' modelling of cases with SD and ABM. In addition, to avoid researcher bias, it would be interesting to have the same case modelled by two different teams, perhaps each team expert in their own field.

7.4.5 Modelling decision making

Further research is needed into the way that decisions are modelled in all three approaches. The purpose of this research could be to develop further clarity on how the decision making process can be made more transparent and faithful in the model. This is required to increase model transparency and client involvement.

7.4.6 Modelling purpose

Further research is required into the link between the purpose of the modelling enquiry and the modelling approach. Can all three approaches be used to support any mode of enquiry as has been suggested by this research? Is one approach more suited to a particular mode of enquiry, or is the mode of enquiry independent of the approach? These are questions that could be the focus in this area.

7.5 Reflection on the research process

The process of doing Doctoral research is educational and formative. As well as the actual research project itself, the researcher learns how to conduct research. This researcher also believes that critical to this process is the ability to be a reflective practitioner (Schön, 1983). Reflection is at the heart of learning. This section will outline some reflections on the DBA process and the learning process. The nature of the reflective process means that I will be writing this section in the first person.

7.5.1 The DBA process

Studying for a Doctorate part time is undoubtedly challenging. Data on completion rates suggest that as few as 53% of students who embarked on a part time Doctorate had completed ten years after they started (HEFCE, 2010). I embarked on the DBA in October 2004 and so submission in July 2012 means an overall duration of 7 years and 10 months, i.e. almost 8 years. However, it has been pointed out to me that the 'average' duration for a PhD is probably closer to 4 years rather than 3 years and so 8 years part time is perhaps a respectable time frame! This researcher found the challenge of combining a career as a consultant with postgraduate study and a family very demanding and, at times, unachievable. The most challenging aspect was that at times the research and the career were going in different directions and the demands were competing rather than mutually supporting. With the benefit of hindsight, it might have been preferable if the two could have been more aligned. This might have meant modifying the research to more closely align with the workplace i.e. to have performed the research on the work that was being undertaken at a given time. However, a disadvantage of this is that the research is more vulnerable to changes in one's professional circumstances, and perhaps would be less theoretically robust. In fact, when the research and the professional work did align, in the purchasing case, some of very interesting findings emerged. I would have preferred if possible to have conducted more research into modelling practical real life situations. Access is always a challenge for researchers, but I feel going forward, that I would place more emphasis and effort in gaining access to real life situations. This is because I believe that the real insights and theory building occur when the theory is tested against the empirical evidence. This is particularly the case with the modelling of complex socio-technical systems, such as supply chains. Thus, even if I could not have achieved a better alignment between career and research, I would have sought out more real life supply chain cases to model through some other avenue if necessary.

7.5.2 The learning process

Learning how to conduct research requires to an extent 'un-learning' many of the attitudes of business and consultancy. What I mean is that what constitutes knowledge in academia requires a more rigorous set of conditions that is perhaps is the case in business. Initially, in my case, this led to scepticism and perhaps a lack of confidence in holding an opinion. However, once a degree of familiarity with the literature and the field has been achieved, slowly and surely a level of confidence starts to develop. I think this confidence, when justified, is important and this is an area I need to develop i.e. having the confidence to stand by an opinion when that opinion has been earned through rigorous research.

Another lesson learned has been the importance of writing as a way to clarify and formulate ideas. Only during the writing up process did some of the concepts and findings crystallise and become sufficiently focused. In retrospect, I believe that the overall duration of the project might have been speeded up if I had perhaps written a paper mid-way through the process. This might have clarified concepts and prevented the process from stalling.

7.5.3 Conclusion

This section has outlined some reflections on the DBA research process and the learning that has occurred. Overall, I believe that the process of completing a DBA has been enormously rewarding and enriching. It has led to a career change and enabled me to follow a personal passion.

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Appendix 1 - Cases Mapped on to SCOR level 3 Processes

Level 1	Level 2	Level 3	Level 3 Description	Purchasing Case	Coffee Pot Case	Bullwhip Case
Plan	P1 Plan Supply Chain	P1.1 Identify, Prioritize, and Aggregate Supply Chain Requirements	The process of identifying, aggregating, and prioritizing, all sources of demand for the integrated supply chain of a product or service at the appropriate level, horizon and interval.	YES	YES	YES
Plan	P1 Plan Supply Chain	P1.2 Identify, Assess, and Aggregate Supply Chain Resources	The process of identifying, prioritizing, and aggregating, as a whole with constituent parts, all sources of supply that are required and add value in the supply chain of a product or service at the appropriate level, horizon and interval.	YES	YES	NO
Plan	P1 Plan Supply Chain	P1.3 Balance Supply Chain Resources with Supply Chain Requirements	The process of identifying and measuring the gaps and imbalances between demand and resources in order to determine how to best resolve the variances through marketing, pricing, packaging, warehousing, outsource plans or some other action that will optimize service, flexibility, costs, assets, (or other supply chain inconsistencies) in an iterative and collaborative environment.	NO	NO	NO
Plan	P1 Plan Supply Chain	P1.4 Establish Supply Chain Pl	The process of developing a time-phased course of action that commits supply-chain resources to meet supply-chain requirements. The establishment and communication of courses of action over the appropriate time-defined (long-term, annual, monthly, weekly) planning horizon and interval, representing a projected appropriation of supply-chain resources to meet supply-chain requirements.	YES	YES	NO
Plan	P2 Plan Source	P2.1 Identify, Prioritize, and Aggregate Product Requirements	The process of identifying, prioritizing, and considering, as a whole with constituent parts, all sources of demand for a product or service in the supply chain.	YES	YES	YES
Plan	P2 Plan Source	P2.2 Identify, Assess, And Aggregate Product Resources	The process of identifying, evaluating, and considering, as a whole with constituent parts, all material and other resources used to add value in the supply chain for a product or services.	YES	YES	NO
Plan	P2 Plan Source	P2.3 Balance Product Resources with Product Requirements	The process of developing a time-phased course of action that commits resources to meet requirements.	YES	YES	NO
Plan	P2 Plan Source	P2.4 Establish Sourcing Plans	The establishment of courses of action over specified time periods that represent a projected appropriation of supply resources to meet sourcing plan requirements.	YES	YES	NO
Plan	P3 Plan Make	P3.1 Identify, Prioritize, and Aggregate Production Requirements	The process of identifying, prioritizing, and considering as a whole with constituent parts, all sources of demand in the creation of a product or service.	NO	YES	YES
Plan	P3 Plan Make	P3.2 Identify, Assess, and Aggregate Production Resources	The process of identifying, evaluating, and considering, as a whole with constituent parts, all things that add value in the creation of a product or performance of a service.	NO	YES	YES
Plan	P3 Plan Make	P3.3 Balance Production Resources with Production Requirements	The process of developing a time-phased course of action that commits creation and operation resources to meet creation and operation requirements.	NO	YES	YES
Plan	P3 Plan Make	P3.4 Establish Production P	The establishment of courses of action over specified time periods that represent a projected appropriation of supply resources to meet production and operating plan requirements.	NO	YES	YES
Plan	P4 Plan Deliver	P4.1 Identify, Prioritize, and Aggregate Delivery Requirements	The process of identifying, prioritizing, and considering, as a whole with constituent parts, all sources of demand in the delivery of a product or service.	NO	YES	YES
Plan	P4 Plan Deliver	P4.2 Identify, Assess, and Aggregate Delivery Resources and Capabilities	The process of identifying, evaluating, and considering, as a whole with constituent parts, all things that add value in the delivery of a product or service.	NO	YES	YES
Plan	P4 Plan Deliver	P4.3 Balance Delivery Resources and Capabilities with Delivery Requirements	The process of developing a time-phased course of action that commits delivery resources to meet delivery requirements.	NO	YES	YES
Plan	P4 Plan Deliver	P4.4 Establish Delivery Plans	The establishment of courses of action over specified time periods that represent a projected appropriation of delivery resources to meet delivery requirements.	NO	YES	YES
Plan	P5 Plan Return	P5.1 Assess, and Aggregate Return Requirements	The process of identifying, evaluating, and considering, as a whole with constituent parts, all sources of demand for the return of a product.	NO	NO	NO
Plan	P5 Plan Return	P5.2 Identify, Assess, and Aggregate Return Resources	The process of identifying, evaluating, and consideration for all resources that add value to, execute, or constrain the processes for the return of a product.	NO	NO	NO
Plan	P5 Plan Return	P5.3 Balance Return Resources with Return Requirements	The process of developing courses of action that make feasible the commitment the appropriate return resources and or assets to satisfy return requirements.	NO	NO	NO
Plan	P5 Plan Return	P5.4 Establish and Communicate Return Plans	The establishment and communication of courses of action over specified time periods that represent a projected appropriation of required return resources and or assets to meet return process requirements.	NO	NO	NO
Source	S1 Source Stocked Product	S1.1 Schedule Product Deliveries	Scheduling and managing the execution of the individual deliveries of product against an existing contract or purchase order. The requirements for product releases are determined based on the detailed sourcing plan or other types of product pull signals.	NO	YES	YES
Source	S1 Source Stocked Product	S1.2 Receive Product	The process and associated activities of receiving product to contract requirements.	NO	YES	YES
Source	S1 Source Stocked Product	S1.3 Verify Product	The process and actions required determining product conformance to requirements and criteria.	NO	YES	YES
Source	S1 Source Stocked Product	S1.4 Transfer Product	The transfer of accepted product to the appropriate stocking location within the supply chain. This includes all of the activities associated with repackaging, staging, transferring and stocking product. For service this is the transfer or application of service to the final customer or end user.	NO	YES	YES
Source	S1 Source Stocked Product	S1.5 Authorize Supplier Payment	The process of authorizing payments and paying suppliers for product or services. This process includes invoice collection, invoice matching and the issuance of checks.	NO	YES	YES

Level 1	Level 2	Level 3	Level 3 Description	Purchasing Case	Coffee Pot Case	Bullwhip Case
Source	S2 Source Make-to-order Product	S2.1 Schedule Product Deliveri	Scheduling and managing the execution of the individual deliveries of product against the contract. The requirements for product deliveries are determined based on the detailed sourcing plan. This includes all aspects of managing the contract schedule including prototypes, qualifications or service deployment.	NO	NO	NO
Source	S2 Source Make-to-order Product	S2.2 Receive Product	The process and associated activities of receiving product to contract requirements.	NO	NO	NO
Source	S2 Source Make-to-order Product	S2.3 Verify Product	The process and actions required determining product conformance to requirements and criteria.	NO	NO	NO
Source	S2 Source Make-to-order Product	S2.4 Transfer Product	The transfer of accepted product to the appropriate stocking location within the supply chain. This includes all of the activities associated with repackaging, staging, transferring, and stocking product and or application of service.	NO	NO	NO
Source	S2 Source Make-to-order Product	S2.5 Authorize Supplier Payme	The process of authorizing payments and paying suppliers for product or services. This process includes invoice collection, invoice matching and the issuance of checks.	NO	NO	NO
Source	S3 Source Engineer-to-order Product	S3.1 Identify Sources of Supply	The identification and qualification of potential suppliers capable of designing and delivering product that will meet all of the required product specifications.	NO	NO	NO
Source	S3 Source Engineer-to-order Product	S3.2 Select Final Supplier(s) ar	The identification of the final supplier(s) based on the evaluation of RFQs, supplier qualifications and the generation of a contract defining the costs and terms and conditions of product availability.	NO	NO	NO
Source	S3 Source Engineer-to-order Product	S3.3 Schedule Product Deliveri	Scheduling and managing the execution of the individual deliveries of product against the contract. The requirements for product deliveries are determined based on the detailed sourcing plan. This includes all aspects of managing the contract schedule including prototypes and qualifications.	NO	NO	NO
Source	S3 Source Engineer-to-order Product	S3.4 Receive Product	The process and associated activities of receiving product to contract requirements.	NO	NO	NO
Source	S3 Source Engineer-to-order Product	S3.5 Verify Product	The process and actions required determining product conformance to requirements and criteria.	NO	NO	NO
Source	S3 Source Engineer-to-order Product	S3.6 Transfer Product	The transfer of accepted product to the appropriate stocking location within the supply chain. This includes all of the activities associated with repackaging, staging, transferring, and stocking product.	NO	NO	NO
Source	S3 Source Engineer-to-order Product	S3.7 Authorize Supplier Payme	The process of authorizing payments and paying suppliers for product or services. This process includes invoice collection, invoice matching and the issuance of checks.	NO	NO	NO
Make	M1 Make-to-stock	M1.1 Schedule Production Acti	Given plans for the production of specific parts, products, or formulations in specified quantities and planned availability of required sourced products, the scheduling of the operations to be performed in accordance with these plans. Scheduling includes sequencing, and, depending on the factory layout, any standards for setup and run. In general, intermediate production activities are coordinated prior to the scheduling of the operations to be performed in producing a finished product.	NO	YES	YES
Make	M1 Make-to-stock	M1.2 Issue Material	The selection and physical movement of sourced/in-process product (e.g., raw materials, fabricated components, subassemblies, required ingredients or intermediate formulations) from a stocking location (e.g., stockroom, a location on the production floor, a supplier) to a specific point of use location. Issuing product includes the corresponding system transaction. The Bill of Materials/routing information or recipe/production instructions will determine the products to be issued to support the production operation(s).	NO	YES	YES
Make	M1 Make-to-stock	M1.3 Produce and Test	The series of activities performed upon sourced/in-process product to convert it from the raw or semi-finished state to a state of completion and greater value. The processes associated with the validation of product performance to ensure conformance to defined specifications and requirements.	NO	YES	YES
Make	M1 Make-to-stock	M1.4 Package	The series of activities that containerize completed products for storage or sale to end-users. Within certain industries, packaging may include cleaning or sterilization.	NO	NO	NO
Make	M1 Make-to-stock	M1.5 Stage Product	The movement of packaged products into a temporary holding location to await movement to a finished goods location. Products that are made to order may remain in the holding location to await shipment per the associated customer order. The movement to finished goods is part of the Deliver process.	NO	NO	NO
Make	M1 Make-to-stock	M1.6 Release Product to Delive	Activities associated with post-production documentation, testing, or certification required prior to delivery of finished product to customer. Examples include assembly of batch records for regulatory agencies, laboratory tests for potency or purity, creating certificate of analysis, and sign-off by the quality organization.	NO	NO	NO

Level 1	Level 2	Level 3	Level 3 Description	Purchasing Case	Coffee Pot Case	Bullwhip Case
Make	M2 Make-to-order	M2.1 Schedule Production Acti	Given plans for the production of specific parts, products, or formulations in specified quantities and planned availability of required sourced products, the scheduling of the operations to be performed in accordance with these plans. Scheduling includes sequencing, and, depending on the factory layout, any standards for setup and run. In general, intermediate production activities are coordinated prior to the scheduling of the operations to be performed in producing a finished product.	NO	NO	NO
Make	M2 Make-to-order	M2.2 Issue Sourced/In-Process	The selection and physical movement of sourced/in-process product (e.g.,raw materials, fabricated components, subassemblies, required ingredients or intermediate formulations) from a stocking location (e.g., stockroom, a location on the production floor, a supplier) to a specific point of use location. Issuing product includes the corresponding system transaction. The Bill of Materials/routing information or recipe/production instructions will determine the products to be issued to support the production operation(s).	NO	NO	NO
Make	M2 Make-to-order	M2.3 Produce and Test	The series of activities performed upon sourced/in-process product to convert it from the raw or semi-finished state to a state of completion and greater value. The processes associated with the validation of product performance to ensure conformance to defined specifications and requirements.	NO	NO	NO
Make	M2 Make-to-order	M2.4 Package	The series of activities that containerize completed products for storage or sale to end-users. Within certain industries, packaging may include cleaning or sterilization.	NO	NO	NO
Make	M2 Make-to-order	M2.5 Stage Finished Product	The movement of packaged products into a temporary holding location to await movement to a finished goods location. Products that are made to order may remain in the holding location to await shipment per the associated customer order. The movement to finished goods is part of the Deliver process.	NO	NO	NO
Make	M2 Make-to-order	M2.6 Release Finished Product	Activities associated with post-production documentation, testing, or certification required prior to delivery of finished product to customer. Examples include assembly of batch records for regulatory agencies, laboratory tests for potency or purity, creating certificate of analysis, and sign-off by the quality organization.	NO	NO	NO
Make	M3 Engineer-to-order	M3.1 Finalize Production Enginee	Engineering activities required after acceptance of order, but before product can be produced. May include generation and delivery of final drawings, specifications, formulas, part programs, etc. In general, the last step in the completion of any preliminary engineering work done as part of the quotation process.	NO	NO	NO
Make	M3 Engineer-to-order	M3.2 Schedule Production Activit	Given plans for the production of specific parts, products, or formulations in specified quantities and planned availability of required sourced products, the scheduling of the operations to be performed in accordance with these plans. Scheduling includes sequencing, and, depending on the factory layout, any standards for setup and run. In general, intermediate production activities are coordinated prior to the scheduling of the operations to be performed in producing a finished product.	NO	NO	NO
Make	M3 Engineer-to-order	M3.3 Issue Sourced/In-Process P	The selection and physical movement of sourced/in-process product (e.g., raw materials, fabricated components, subassemblies, required ingredients or intermediate formulations) from a stocking location (e.g., stockroom, a location on the production floor, a supplier) to a specific point of use location. Issuing product includes the corresponding system transaction. The Bill of Materials/routing information or recipe/production instructions will determine the products to be issued to support the production operation(s).	NO	NO	NO
Make	M3 Engineer-to-order	M3.4 Produce and Test	The series of activities performed upon sourced/in-process product to convert it from the raw or semi-finished state to a state of completion and greater value. The processes associated with the validation of product performance to ensure conformance to defined specifications and requirements.	NO	NO	NO
Make	M3 Engineer-to-order	M3.5 Package The series of activities that containerize completed products for storage	The series of activities that containerize completed products for storage or sale to end-users. Within certain industries, packaging may include cleaning or sterilization.	NO	NO	NO
Make	M3 Engineer-to-order	M3.6 Stage Finished Product	The movement of packaged products into a temporary holding location to await movement to a finished goods location. Products that are made to order may remain in the holding location to await shipment per the associated customer order. The movement to finished goods is part of the Deliver process.	NO	NO	NO
Make	M3 Engineer-to-order	M3.7 Release Product to Deliver	Activities associated with post-production documentation, testing, or certification required prior to delivery of finished product to customer. Examples include assembly of batch records for regulatory agencies, laboratory tests for potency or purity, creating certificate of analysis, and sign-off by the quality organization.	NO	NO	NO

Level 1	Level 2	Level 3	Level 3 Description	Purchasing Case	Coffee Pot Case	Bullwhip Case
Deliver	D1 Deliver Stocked Product	D1.1 Process Inquiry & Quote	Receive and respond to general customer inquiries and requests for quotes.	NO	YES	YES
Deliver	D1 Deliver Stocked Product	D1.2 Receive, Enter & Validate	Receive orders from the customer and enter them into a company's order processing system. Orders can be received through phone, fax, or electronic media. "Technically" examine orders to ensure an orderable configuration and provide accurate price. Check the customer's credit. Optionally accept payment.	NO	NO	NO
Deliver	D1 Deliver Stocked Product	D1.3 Reserve Inventory & Deter	Inventory and/or planned capacity (both on hand and scheduled) is identified and reserved for specific orders and a delivery date is committed and scheduled.	NO	NO	NO
Deliver	D1 Deliver Stocked Product	D1.4 Consolidate Orders	The process of analyzing orders to determine the groupings that result in least cost/best service fulfilment and transportation.	NO	NO	NO
Deliver	D1 Deliver Stocked Product	D1.5 Build Loads	Transportation modes are selected and efficient loads are built.	NO	YES	NO
Deliver	D1 Deliver Stocked Product	D1.6 Route Shipments	Loads are consolidated and routed by mode, lane and location.	NO	YES	NO
Deliver	D1 Deliver Stocked Product	D1.7 Select Carriers & Rate Sh	Specific carriers are selected by lowest cost per route and shipments are rated and tendered.	NO	YES	NO
Deliver	D1 Deliver Stocked Product	D1.8 Receive Product from Sou	The activities such as receiving product, verifying, recording product receipt, determining put-away location, putting away and recording location that a company performs at its own warehouses. May include quality inspection.	NO	NO	NO
Deliver	D1 Deliver Stocked Product	D1.9 Pick Product	The series of activities including retrieving orders to pick, determining inventory availability, building the pick wave, picking the product, recording the pick and delivering product to shipping in response to an order.	NO	NO	NO
Deliver	D1 Deliver Stocked Product	D1.10 Pack Product	The activities such as sorting / combining the products, packing / kitting the products, paste labels, barcodes etc. and delivering the products to the shipping area for loading.	NO	NO	NO
Deliver	D1 Deliver Stocked Product	D1.11 Load Vehicle & Generate	The series of tasks including placing/loading product onto modes of transportation and generating the documentation necessary to meet internal, customer, carrier and government needs..	NO	NO	NO
Deliver	D1 Deliver Stocked	D1.12 Ship Product	The process of shipping the product to the customer site.	NO	YES	YES
Deliver	D1 Deliver Stocked Product	D1.13 Receive & Verify Product	The process of receiving the shipment by the customer site (either at customer site or at shipping area in case of self-collection) and verifying that the order was shipped complete and that the product meets delivery terms.	NO	NO	NO
Deliver	D1 Deliver Stocked Product	D1.14 Install Product	When necessary, the process of preparing, testing and installing the product at the customer site. The product is fully functional upon completion.	NO	NO	NO
Deliver	D1 Deliver Stocked Product	D1.15 Invoice	A signal is sent to the financial organization that the order has been shipped and that the billing process should begin and payment be received or be closed out if payment has already been received. Payment is received from the customer within the payment terms of the invoice.	NO	NO	NO

Level 1	Level 2	Level 3	Level 3 Description	Purchasing Case	Coffee Pot Case	Bullwhip Case
Deliver	D2 Deliver Make-to-order Product	D2.1 Process Inquiry & Quote	Receive and respond to general customer inquiries and requests for quotes.	NO	NO	NO
Deliver	D2 Deliver Make-to-order Product	D2.2 Receive, Configure, Enter	Receive orders from the customer and enter them into a company's order processing system. Orders can be received through phone, fax, or through electronic media. Configure your product to the customer's specific needs, based on standard available parts or options. "Technically" examine order to ensure an orderable configuration and provide accurate price. Check the customer's credit. Optionally accept payment.	NO	NO	NO
Deliver	D2 Deliver Make-to-order Product	D2.3 Reserve Resources & Det	Inventory and/or planned capacity is identified and reserved for specific orders, and a delivery date is committed and scheduled.	NO	NO	NO
Deliver	D2 Deliver Make-to-order Product	D2.4 Consolidate Orders	The process of analyzing orders to determine the groupings that result in least cost/best service fulfilment and transportation.	NO	NO	NO
Deliver	D2 Deliver Make-to-order Product	D2.5 Build Loads	Transportation modes are selected and efficient loads are built.	NO	NO	NO
Deliver	D2 Deliver Make-to-order Product	D2.6 Route Shipments	Loads are consolidated and routed by mode, lane and location.	NO	NO	NO
Deliver	D2 Deliver Make-to-order Product	D2.7 Select Carriers & Rate Sh	Specific carriers are selected by lowest cost per route and shipments are rated and tendered.	NO	NO	NO
Deliver	D2 Deliver Make-to-order Product	D2.8 Receive Product from Sou	The activities such as receiving product, verifying, recording product receipt, determining put-away location, putting away and recording location that a company performs at its own warehouses. May include quality inspection.	NO	NO	NO
Deliver	D2 Deliver Make-to-order Product	D2.9 Pick Product	The series of activities including retrieving orders to pick, verifying inventory availability, building the pick wave, picking the product, recording the pick and delivering product to packing area in response to an order.	NO	NO	NO
Deliver	D2 Deliver Make-to-order Product	D2.10 Pack Product	The activities such as sorting / combining the products, packing / kitting the products, paste labels, barcodes etc. and delivering the products to the shipping area for loading.	NO	NO	NO
Deliver	D2 Deliver Make-to-order Product	D2.11 Load Product & Generat	The series of tasks including placing/loading product onto modes of transportation and generating the documentation necessary to meet internal, customer, carrier and government needs..	NO	NO	NO
Deliver	D2 Deliver Make-to-order Product	D2.12 Ship Product	The process of shipping the product to the customer site.	NO	NO	NO
Deliver	D2 Deliver Make-to-order Product	D2.13 Receive & Verify Product	The process of receiving the shipment at the customer (either at customer site or at shipping area in case of self-collection) site and verifying that the order was shipped complete and that the product meets delivery terms.	NO	NO	NO
Deliver	D2 Deliver Make-to-order Product	D2.14 Install Product	When necessary, the process of preparing, testing and installing the product at the customer site. The product is fully functional upon completion.	NO	NO	NO
Deliver	D2 Deliver Make-to-order Product	D2.15 Invoice	A signal is sent to the financial organization that the order has been shipped and that the billing process should begin and payment be received or be closed out if payment has already been received. Payment is received from the customer within the payment terms of the invoice.	NO	NO	NO

Level 1	Level 2	Level 3	Level 3 Description	Purchasing Case	Coffee Pot Case	Bullwhip Case
Deliver	D3 Deliver Engineer-to-order Product	D3.1 Obtain and Respond to RF	The process of receiving a request for proposal or request for quote, evaluating the request (estimating the schedule, developing costs estimates, establishing price), and responding to the potential customer.	NO	NO	NO
Deliver	D3 Deliver Engineer-to-order Product	D3.2 Negotiate & Receive Conti	The process of negotiating order details with customer (e.g., price, schedule, product performance) and finalizing the contract. Optionally accept payment.	NO	NO	NO
Deliver	D3 Deliver Engineer-to-order Product	D3.3 Enter Order, Commit Reso	The process of entering/finalizing the customers order, approving the planned resources (e.g., engineering, manufacturing, etc.) and officially launching the program.	NO	NO	NO
Deliver	D3 Deliver Engineer-to-order Product	D3.4 Schedule Installation	The process of evaluating the design and build schedules relative to customer requested installation date to determine installation schedule.	NO	NO	NO
Deliver	D3 Deliver Engineer-to-order Product	D3.5 Build Loads	Transportation loads are selected and efficient loads are built.	NO	NO	NO
Deliver	D3 Deliver Engineer-to-order Product	D3.6 Route Shipments	The process of consolidating and routing shipments by mode, lane, and location.	NO	NO	NO
Deliver	D3 Deliver Engineer-to-order Product	D3.7 Select Carriers and Rate S	Specific carriers are selected by lowest cost per route and shipments are rated and tendered.	NO	NO	NO
Deliver	D3 Deliver Engineer-to-order Product	D3.8 Receive Product from Sou	The activities such as receiving product, verifying, recording product receipt, determining put-away location, putting away and recording location that a company performs at its own warehouses. May include quality inspection.	NO	NO	NO
Deliver	D3 Deliver Engineer-to-order Product	D3.9 Pick Product	The series of activities including retrieving orders to pick, verifying inventory availability, building the pick wave, picking the product, recording the pick and delivering product to packing area in response to an order.	NO	NO	NO
Deliver	D3 Deliver Engineer-to-order Product	D3.10 Pack Product	The activities such as sorting / combining the products, packing / kitting the products, paste labels, barcodes etc. and delivering the products to the shipping area for loading.	NO	NO	NO
Deliver	D3 Deliver Engineer-to-order Product	D3.11 Load Product & Generate	The series of tasks including placing product onto vehicles, generating the documentation necessary to meet internal, customer, carrier and government needs.	NO	NO	NO
Deliver	D3 Deliver Engineer-to-order Product	D3.12 Ship Product	The process of shipping the product to the customer site	NO	NO	NO
Deliver	D3 Deliver Engineer-to-order Product	D3.13 Receive & Verify Product	The process of receiving the shipment (either at customer site or at shipping area in case of self-collection) and verifying that the order was shipped complete and that the product meets delivery terms.	NO	NO	NO
Deliver	D3 Deliver Engineer-to-order Product	D3.14 Install Product	When necessary, the process of preparing, testing and installing the product at the customer site. The product is fully functional upon completion.	NO	NO	NO
Deliver	D3 Deliver Engineer-to-order Product	D3.15 Invoice	A signal is sent to the financial organization that the order has been shipped and that the billing process should begin and payment be received or be closed out if payment has already been received. Payment is received from the customer within the payment terms of the invoice.	NO	NO	NO
Deliver	D4 Deliver Retail Product	D4.1 Generate Stocking Sched	The process of scheduling resources to support item-stocking requirements.	NO	NO	NO
Deliver	D4 Deliver Retail Product	D4.2 Receive Product at Store	The activities such as receiving product, verifying, recording product receipt, determining put-away location, putting away and recording location that a company performs at its own stores. May include quality inspection.	NO	NO	NO
Deliver	D4 Deliver Retail Product	D4.3 Pick Product from Backro	The process of retrieving restocking orders to pick, determining inventory availability, building a pick wave, picking item and quantity from a designated backroom warehouse location, recording the resulting inventory transaction, and delivering the product to point of stock	NO	NO	NO
Deliver	D4 Deliver Retail Product	D4.4 Stock Shelf	For restocks, the tasks associated with identifying the item location, stocking the shelf according to merchandise plans, and recording the appropriate inventory transaction. For promotional items and stock repositioning the tasks associated with shelf and point of sale preparation, stock placement, and end of sale activities.	NO	NO	NO
Deliver	D4 Deliver Retail Product	D4.5 Fill Shopping Cart	Typical set of tasks associated with product selection, storage and movement through to checkout.	NO	NO	NO
Deliver	D4 Deliver Retail Product	D4.6 Checkout	The processes and tasks associated with product checkout including scanning, method of payment, credit application and approval, service agreement, order confirmation, and/or invoice or receipt.	NO	NO	NO
Deliver	D4 Deliver Retail Product	D4.7 Deliver and/or Install	The process of preparing and installing the product at the customer site. The product is fully functional upon completion.	NO	NO	NO

Appendix 2 – System Dynamics Society Discussion Forum

System Dynamics Discussion Forum

Limitations of SD in modelling operational problems

Posted: **Thu May 10, 2012 1:57 pm**

by **Chris Owen**

As part of my doctoral research I am comparing different approaches to simulation including SD, Discrete Event Simulation (DES) and Agent Based Modelling (ABM) in modelling supply chain problems. One area I have been investigating is the limit of SD in modelling operational problem types typically modelled by discrete methods. As exemplars I have tried to replicate two models from literature. One is a model of a coffee pot supply chain described in Taylor et al (2008) and the second is a model in Pidd (2004) called Joe's Exhaust Shop. Both problems involve discrete entities, resources and processes.

In both cases I have been unable to replicate the model in SD. In the coffee pot problem, the issue is that the model relies on the ability to modify a reorder point quantity to achieve a certain customer service level. In SD I have tried to modify John Sterman's generic supply chain model, but I have run into the issue that since there is no such thing as a discrete delivery, you cannot measure on time delivery of a given customer order. You have to use a proxy measure like average delivery delay or backlog and so far I have not been able to replicate the model in such a way that I can answer the questions posed in the paper i.e. what level of inventory do you need at certain points to deliver a certain level of customer service. In the case of the exhaust parlour, I have struggled since the system has discrete resources and discrete processes. I have had some success in replicating this but overall the model becomes too complex very quickly.

I have come to the conclusion that there are hard limits to the use of SD in application on problems where discrete characteristics become important. Now I appreciate that the reaction to this might be to say that SD would/should not be used to model such problems anyway. What I am interested in doing is being more precise about where these limitations might lie. There seems to be very little literature about this, one paper I have come across is by Ozgun and Barlas (2009) who use SD to model a simple queuing system.

Now I have to accept an alternative explanation to this which is that this is because I am just not good enough at SD modelling so the limitations are with me rather than SD as a technique!

I would be interested to hear your thoughts on where the limits of SD lie and whether you think these models could be replicated in SD.

OZGUN, O. & BARLAS, Y. Discrete versus Continuous Simulation : When does it matter? 23rd International Conference on System Dynamics, 2009 Albuquerque, New Mexico.

PIDD, M. 2004 Computer Simulation in Management Science, Wiley and Sons.

DON TAYLOR, G., LOVE, D. M., WEAVER, M. W. & STONE, J. 2008. Determining inventory service support levels in multi-national companies. International Journal of Production Economics, 116, 1-11.

Re: Limitations of SD in modelling operational problems

Posted: **Fri May 11, 2012 3:27 am**

by **Magne Myrtveit**

Dear Chris,

SD modelling languages are dialects (subsets) of dataflow languages. Most SD tools limit their support to continuous data flows.

I am not sure if your two examples highlight limitations in the technology you are using, or if you are facing limitations of dataflow modelling in general.

Are you able to provide a brief formulation of the models you try to convert to an SD representation? Maybe people in this group can help you?

Best regards,
Magne

Re: Limitations of SD in modelling operational problems

Posted: **Fri May 11, 2012 8:01 am**

by **Robert Eberlein**

Hi Chris,

Your post title is a little bit odd, perhaps that was intentional. "The comparative value of SD in modeling operational problems" would be more compelling to me. I am not familiar with the case studies you mention, but let me say a few words about the different mental models for dealing with inventory issues.

The most prominent is probably the selection of an appropriate inventory level and order quantity. In some ways those of in SD drive right into this issue with the beer game where there is an inventory holding cost and a backorder cost. The two basic ingredients to any optimization problem that might look at reorder points, economic order quantity and the like. But consider at how the analysis would proceed.

OR: Assume a stochastic demand stream and supply chain properties and then minimize expected cost or a variant by designing a clever rule.

SD: Look at the implications of commonsense (or even clever) rules on the behavior of the entire supply chain.

A bit cartoonish, but hopefully my point is clear. The focus in SD is on the implications of the different actions and responses with the expectation that actions in one area will have consequences to that same area both locally and globally. Trying to capture the global response is what is generally the focus. An implication of this is that something called Inventory in a system dynamics model is likely to be composed of heterogeneous components (again the beer game does this generality a disservice). With inventories consisting of lots of different things jumbled together tracking any one individually is not of much interest. Thus it is tough to do things like determine exact cycle times - that is only possible (and meaningful) when dealing with a homogeneous collection of things.

All that said, there is a pretty good chance you can figure out a way to handle the cases you mention using the same software that people doing system dynamics work use. That is not saying that it would be necessarily be system dynamics.

I would agree that using the system dynamics method (problem statement, reference models, dynamic hypothesis, simulation) is not an effective way to do all supply chain cases. But I also think the perspective it brings to supply chain issues is extremely valuable.

Re: Limitations of SD in modelling operational problems

Posted: **Fri May 11, 2012 11:31 am**

by **Leonard Malczynski**

Chris,
In Chapter 6 of Industrial Dynamics , Jay Forrester presents a type of model structure that is "amenable to the objectives and principles outlined" (Forrester 1961). He indicates that a model should have the following characteristics:

• Be able to describe any statement of cause-effect relationships that we may wish to include.
• Be simple in mathematical nature.
• Be closely synonymous in nomenclature to industrial, economic and social terminology .
• Be extendable to large numbers of variables (thousands) without exceeding the practical limits of digital computers, and
• Be able to handle "continuous" interactions in the sense that any artificial discontinuities introduced by solution-time intervals will not affect the results. It should, however, be able to generate discontinuous changes in decisions when these are needed.

Perhaps discrete (when needed) is implied in that last bullet from Jay.
As Magne and Bob intimated, is it the problem or the tool that is the constraint?

I do believe in hybrid or extra-methodological (outside of SD) modeling and do not fault the methodology of system dynamics if my problem is not tractable using it.
SD tools however often permit mixed methodology modeling.

Regards,
Len

Re: Limitations of SD in modelling operational problems

Posted: **Fri May 11, 2012 7:50 pm**

by **Jay Forrester**

Owen raises a question that arose frequently in the early days of system dynamics, but in the last many years I have not often heard of people with this concern. The issue here should not be how to use system dynamics to represent a discrete simulation, but instead, one should address the issue of the best way to model the problem.

We are not told why one wants to know the individual separate delivery delays on unique items. A single delivery delay on one item is not a basis for management to take action about proper inventory levels. I assume that after the discrete item simulation one will average delivery delays as a basis for arriving at policy changes. In other words, the real interest is in the behavior of the product stream, not individual items.

In constructing a system dynamics model one must first decide whose viewpoint one should take. For the purpose of changing inventory levels one does not want the viewpoint of the deliveryman who may be berated for a late delivery. Instead one wants to use the viewpoint of the manager who might change the policies governing the system; I doubt that such a person is interested in each individual item.

The issues raised by Owen are not how to make a system dynamics model replicate an unsuitable methodology but rather to consider what methodology is appropriate for the problem at hand.

Re: Limitations of SD in modelling operational problems

Posted: **Mon May 14, 2012 1:50 am**

by **Onur Ozgun**

Hi Chris,
You may be interested in a master's thesis by a previous member of a research group. It uses different modeling approaches in different aggregation levels of supply chains.
http://www.ie.boun.edu.tr/facilities/sesdyn/publications/theses/MS_demirel.pdf

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Re: Limitations of SD in modelling operational problems

Posted: **Tue May 15, 2012 4:54 am**

by **Chris Owen**

Thank you for these responses, they are very insightful and helpful. I would like to check my understanding and perhaps build on a couple of points if I may.
The problems that I have tried to replicate have discrete characteristics, or at least the way they have been represented does. What I have tried to do here is a 'back to back' test of trying to model a system as conceptualised in a discrete way. If the problems had been approached from the beginning with a System Dynamics approach then the way they were conceptualised might well have been different. As Professor Forrester says, the first decision is 'whose viewpoint one should take'. It may be possible to replicate these problems in SD software but as Robert Eberlein points out 'that is not saying that it would necessarily be system dynamics'. Using a SD approach, if these discrete aspects were found to be critical then one approach is to model them in a hybrid manner as suggested by Len.
Would it be reasonable to say that at the point the problem is being framed it may be that the nature of the enquiry means that the use of a discrete modelling method is more suitable?
For me it is interesting to understand this crossover point in terms of where it might exist.
I am also comparing the techniques at the strategic end of the spectrum, for example, modelling the centralisation of purchasing in a construction firm. Here, I am finding SD very powerful because it helps to surface and visualise the decision making process. The discrete methods (ABM and DES) for me are less useful because the decision rules are hidden in the code rather than being explicit in causal loops. This may limit their value as an interactive method.
Thanks again for your responses and thanks Onur for the Masters Thesis.
Regards,
Chris.

Re: Limitations of SD in modelling operational problems

Posted: **Wed May 16, 2012 4:50 am**

by **Robert Eberlein**

Hi Chris,

>Would it be reasonable to say that at the point the problem is being framed it may be that the nature of the enquiry means that the use of a discrete modelling method is more suitable?

It is not always the nature of the enquiry so much as the nature of the enquirer that results in the choice of a modeling method. It would be very interesting to find cases that at the outset looked largely the same but for which a different analysis approach was taken. This may be difficult, since the exposition of a case presumes the history of what was done, but some weaker comparisons of similar cases would also be of interest.

All times are UTC - 5 hours

Appendix 3 – Models CD

This CD contains copies of all the models used to support this research. There is a separate folder for each case study and the models associated with that case are in the folder. In order to run or inspect the models, the following software is required:

- System Dynamics Models - Vensim (Vensim, 2012)
- Agent Based Models – Netlogo (Netlogo, 2012)
- Discrete Event Models – Simul8 (Simul8, 2012)