SELECTION OF SIMULATION TOOLS FOR IMPROVING SUPPLY CHAIN PERFORMANCE

Mr. Chris Owen
PricewaterhouseCoopers LLP
19 Cornwall St
Birmingham B3 2DT
christopher.d.owen@uk.pwc.com

Dr. Doug Love
Dr. Pavel Albores
Aston Business School
Aston University
Aston Triangle
Birmingham B4 7ET
d.m.love@aston.ac.uk, p.albores@aston.ac.uk

ABSTRACT:
The performance of the supply chain is a key source of competitive advantage for the firm. Supply chains are becoming ever more complex due to factors such as globalisation and the development of supply networks. Modelling the supply chain is an essential step in the improvement process, and simulation is found to be a good approach in this context of high variation and dynamic behaviour. There are three main approaches to supply chain simulation; System Dynamics (SD), Discrete Event Simulation (DES) and Agent Based Modelling (ABM). At present, choice of technique owes more to custom and practice than suitability. There are no existing frameworks to assist practitioners in selecting the appropriate technique for the supply chain problem under consideration. Establishing this framework will be valuable and will be the subject of further research.

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

1. INTRODUCTION

The performance of the supply chain has become ever more important for the overall competitiveness of firms and indeed can become the focal point for performance improvement (Slone, 2004 and Harrison, 2005). The supply chain has taken over from the individual firm as the focal point of competition and it is considered that it is now supply chains which compete and not companies (Christopher, 2005). This has implications also on how firms choose to improve, moving away from a narrow cost reduction approach towards globally integrated and coordinated sourcing strategies (Trent and Monczka, 2005). In addition to this, globalisation is increasing the complexity of supply chains and it has been found that global supply chains are more difficult to manage than domestic supply chains (Meixell and Gargeya, 2005). There are a number of factors which influence this including geographical distances and different local cultures. Global supply chains also carry significant risks to performance including variability and uncertainty in exchange rates, economic and political instability and changes to the regulatory environment (Meixell and Gargeya, 2005).

Faced with the inherent and increasing complexity of the supply chain and decision making within it there is a growing need for modelling methodologies that allow firms to understand current performance and to evaluate the likely performance of alternatives (Biswas and Narahari, 2003). It is suggested that the first step in performing a supply chain study should be to determine the type of modelling approach to be used (Harrison, 2005). Modelling is also considered a key precursor to the effective integration of processes in the supply chain (Vernadat, 1996; Fleisch and Osterle, 2000).

Supply chain modelling approaches typically fall into three main areas, namely optimization, simulation and heuristics (Harrison, 2005). Although optimization has often been used, it has significant limitations, in particular; optimization has no way to handle forecast error or inaccuracy; optimization does not help when the business objectives change over time and some problems are too complex for optimization (Ingalls, 1998). Heuristics are limited in that they result in a solution with unknown quality (Harrison, 2005). Simulation has strengths as an approach in dealing with the key features of the supply chain. For example, simulation is good for modelling the impact of variation, for example, forecast error, supplier reliability and quality variance (Biswas and Narahari, 2003). Time phased and dynamic behaviour is important in supply chains. Examples of this are process delays and lead times of information and material conversion and transfer. A classical example of the consequences of these factors is the amplification of the demand signal, otherwise known as the 'Bullwhip effect', first described by Forrester (1961). Simulation has been found to be a good technique for modelling these dynamic features. Simulation has also been found to be useful in modelling business processes and their features such as abstract representation, information and physical flows, randomness and time-based effects (Ball et al, 2004). Simulation is the only approach that can holistically model the supply chain (Tang et al, 2004).

The objective of this paper is to describe the three main approaches to supply chain simulation, namely System Dynamics (SD), Discrete Event Simulation (DES) and Agent Based Modelling (ABM); to demonstrate that these techniques have different strengths and weaknesses in application, and that a framework to assist practitioners in selecting the appropriate technique would be valuable. The paper is structured as follows. The next section presents an overview of the three techniques. Section 3 discusses the literature which compares the three techniques. Section 4 discusses some of the strengths and weaknesses of the three techniques in application, demonstrates the need for a framework and leads to Section 5 which sets out the further work which will be necessary to develop the framework.

2. SD, DES AND ABM IN SUPPLY CHAIN MODELLING

2.1 System Dynamics (SD)

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, 1968). 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, 1996a), demand amplification (Ge et al, 2003; Sterman, 2000; Towill and Del Vecchio , 1994); information sharing (Ovalle and Marquez, 2003) and facility allocation (Akkermans and Voss, 1996). Towill (1996b) 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 Dellaert (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.

2.2 Discrete Event Simulation (DES)

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. Cavalieri and Terzi (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, 2004).

2.3 Agent Based Modelling (ABM)

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 (Schieritz and Milling, 2003; Borshchev and Fillipov, 2004). 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. 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).

3. SELECTING THE SIMULATION APPROACH

When faced with a supply chain simulation challenge, then, the modeller has three modelling approaches to choose from, or indeed may decide to use a hybrid approach combining two or more of the techniques. At present, it would appear that the choice of which modelling 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). The significant investment in learning a particular modelling paradigm means that it is rarer to find modellers who are skilled in more than one approach. As a consequence, there appears to have been little dialogue between the various schools of thought and little comparison work done. There are frameworks for selecting simulation systems but not techniques, the assumption being that the modeller will be from one 'school' or the other. In addition to this, the pattern of use of the techniques suggests that there is not a framework for technique selection other than custom and practice. Modellers will choose the technique they apply based either on their own background and experience or on what has become the accepted norm. Moreover, the structure of academic groups and conferences is focused on technique, not problem domain. Therefore, this tends to focus on one of the three approaches, rather than on the comparison and selection of the most appropriate tool for the problem being tackled.

There have been a few studies which compare SD with DES (Brailsford and Hilton, 2000; Morecroft and Robinson, 2005; Sweeter, 1999) as well as a number which compare ABM with SD (Parunak et al, 1998; Rahmandad, 2004; Scholl, 2001; Schieritz and Milling, 2003). There are some studies which have compared all three approaches (Borshchev and Fillipov, 2004; Lorenz and Jost, 2006). Tako and Robinson (2006) set out an interesting approach to empirically compare SD and DES in the supply chain domain in terms of model building, modelling philosophy, applications and use. Their aim is to test empirically whether differences identified in the literature are confirmed in practice. Their focus is on the application of the tool i.e. how it is applied, and how differences emerge at this stage. This differs from the focus of the research described here which is more on the application domain i.e. how do the techniques compare in terms of their relative strengths and weaknesses in helping to address a given supply chain challenge. In relation to this, it should be noted that there is no detailed analysis from first principles of these techniques, so as to identify their relative strengths and weaknesses. In relation to the theoretical analysis, Lorenz and Jost (2006) point the direction in their work comparing all three techniques, but in their conclusion they admit "…it must be admitted that there is still a way to go in order to provide the wanted orientation framework that can be applied by modelling practitioners independently".

4. THE NEED FOR A FRAMEWORK

The three techniques have different strengths and weaknesses in application. They are not the same in the way that they model the problem nor indeed in the way they are used by practitioners. One technique may be more suitable or effective in modelling a particular aspect of the supply chain than another. The problem at present is that, because there is no guide for selection, an inappropriate choice can be made and thus the modelling process can be less effective, potentially ineffective or misleading. The following examples are areas where there are differences in the way that the three techniques model a particular aspect of the supply chain and demonstrate that in some cases one technique seems to be more suitable than the others.

4.1 Modelling Strategic Decision Making

The three approaches are not equally suited to the modelling of strategic decision making in the supply chain context. System Dynamics is an established approach in this area and there has been extensive work on the use of SD as a tool for facilitating management decision making through management games and 'management flight simulators' (Sterman, 1992). Rabelo et al (2005) consider that when it comes to the strategic and aggregate levels then SD has some distinct advantages over DES. They argue that DES is a data hungry technique. This is not a problem for modelling manufacturing activities where the data exists, but is much more of a problem when trying to model business level decisions where data may not exist or only as rough estimates and approximations. This makes DES inappropriate for investigating many business decisions or the interactions between business and production branches of the enterprise (Rabelo et al, 2005). Baines and Harrison (1999) consider that the qualitative and continuous nature of many top management parameters, also creates challenges to the use of DES at these levels. Agent Based Modelling shows some promise in this area, due to its inherent ability to model rules at the agent level.

4.2 Aptly Modelling the Processes

Another good example of where the approaches differ is in the modelling of supply chain processes.

4.2.1 Modelling the Detail

DES has some inherent strengths in this area because individual entities and detailed processes can be represented. Discrete event simulation is able to represent detailed transactions (Ball et al, 2004). SD is more limited in this respect as building more detailed models of processes and in particular representing individual transactions is extremely difficult and this technique is therefore appropriate to more abstract analysis (Ball et al, 2004).

An example of this is given by Bilczo et al (2003) who are modelling and investigating the Boeing supply chain. Their overall objective was to better plan their supply chain so as to improve the supply of specific raw material alloys which seem to go through periods of severe shortage, thus disrupting aircraft production. SD is initially used to model the supply chain, and insights are achieved on the causes of demand amplification. A specific example of this is the delay in suppliers increasing their capacity in response to demand increases, due to the costly need for capital investment. Suppliers wait until they are sure the demand increase is for real. What they found as the investigation unfolded, was that the insight they needed was in understanding the lowest levels of the supply chain, the processing houses and machine shops. For this purpose they found DES to be a more suitable tool.

4.2.2 Discrete Versus Continuous

As Lee and Kim (2002) point out, the nature of the supply chain system is neither completely discrete nor continuous and both aspects must be considered together in developing a supply chain model. They also suggest that the supply chain activities can be considered to exist in three levels, namely operational, tactical and strategic. They propose that a purely DES model will have the following problems :

- Reflecting the continuous nature of the process is not possible;
- Representing the interaction that occurs among those levels is not possible;
- There is too much simplification for small scaled models.

This implies that when modelling supply chain problems the practitioner may need to apply different techniques to different areas of the supply chain system. This suggests the need for a framework in matching the technique to the area of analysis.

Their solution to this is to propose a hybrid model which uses continuous modelling and discrete modelling together to suit the characteristics of the aspect being modelled.

4.2.3 Modelling Variation and Dynamic Behaviour

It has already been established (1.4) that simulation is an approach that is suited to modelling sources of variation as well as the dynamic aspects of the supply chain. With DES, variation in inputs to the system can be modelled as different distributions which can approximate the behaviour of the real world. Other sources of variation can be modelled in the logic of the individual entities and processes. With SD, randomness in inputs can be modelled as noise to the continuous inputs. With ABM, randomness can be programmed into the logic of the individual agents. These differences in the way that the variation is represented in the three approaches may well mean that they are more or less suited to modelling specific types of variation and stochastic behaviour. SD has traditionally been strong in modelling dynamic behaviour because of its strong links to control theory and the use of feedback loops as a fundamental feature of the approach. As has been described in section 2.1, SD has been used to study classical dynamic effects such as demand amplification. SD thus has strengths in this area which may not be present in the other two approaches.

4.3 A Framework for Simulation Tool Selection

Building simulation models is expensive because it requires a significant investment in time, and scarce skills. This has led to interest in developing reusable model elements (Albores, 2007; Swaminathan, 1998) in order to reduce costs and improve model building efficiency. Without doubt, because of the issues outlined above, it is possible to use the wrong modelling approach to model a supply chain problem. For example, Lee et al (2002) found that when DES was used alone to model a supply chain, excess levels of inventory were recommended when compared with a combined continuous and discrete model, although they do not go into a detailed explanation as to why. This demonstrates the risks of using an inappropriate approach. Therefore, we need a framework to assist supply chain practitioners in matching problem types with modelling approaches. This would improve the success rate of modelling projects and improve the return on investment for businesses using these techniques.

5. SUGGESTED FRAMEWORK

Development of a framework will require investigating both the problem types that practitioners are trying to solve, along with the features of the technique they are using to analyse them. This matching of problem type to the feature of the technique will form the core of the work. The approach to developing this framework is described in the following sections. In addition, the initial structure of the analysis of the techniques is presented, along with some examples of how they might be classified.

5.1 Identification of a Taxonomy of Supply Chain Problem Types

Through a review of the literature, a taxonomy of supply chain problem types will be identified. Additional research in the practitioner community will be carried out to add depth and triangulate the findings of the literature review. This will create the problem types which can be analysed using these simulation approaches.

5.2 Theoretical Analysis of the Three Techniques

A key aspect of the research, and an area which has not been examined rigorously to date, is to perform a theoretical analysis of the techniques. The purpose of the review will be to identify the features of the three techniques in relation to key fundamental simulation concepts. This analysis will provide guidance as to how the different techniques are likely to perform in relation to each other.

So far the following simulation aspects have been defined (see Table 1 below). To illustrate how this comparison will work, five of the aspects are explored in more detail in Table 2.

5.3 Development of a Framework

The purpose of the framework will be to create a linkage between the supply chain problem types and the relative utility of the simulation approaches being used. This will be achieved through identifying and mapping the relationship between the problem types, the features of these problem types, and the types of simulation challenges they present. These features will then be linked to the fundamental theoretical aspects of the tools, and this will be used to assist in the selection of the appropriate approach to modelling that particular problem. The utility of the approach will be defined, and will be a combination of factors including ease of model building (speed and cost), ability of the technique to model the problem characteristics (informed by the theoretical work), speed of model running and ease in interpreting model results.

5.4 Experimental Design

It is anticipated that there may be areas where the three approaches demonstrate clear strengths and weaknesses compared to each other in relation to modelling certain problem types. However, there may also be areas where their relative utility is unclear. In these cases, experiments will be designed to test the findings through modelling the same problem type using the different approaches to establish whether this can be clarified empirically. These experiments will provide further insights on the use of the tools in practice.

5.5 Testing the Framework with Practitioners

The purpose of this phase will be to test the framework with simulation modelling practitioners both in the business and academic communities. This will involve selecting supply chain improvement or analysis opportunities and using the framework to see how effective it is in application. Feedback will be sought on how useful the framework is and how it might be improved.

6. CONCLUSION

In this paper, it has been demonstrated that simulation is well suited to improving supply chain performance. The literature on the three main approaches has been reviewed and it has been proposed that a framework for assisting practitioners in selecting the appropriate techniques for their challenge would be valuable, since they have different strengths and weaknesses in the supply chain domain. The approach to developing this framework has been outlined. The key finding so far is that there is no framework in existence which matches the simulation approach, and its theoretical underpinnings, with the supply chain problem under consideration.

Table 1 – Simulation Aspects

Aspect	Description
Model Elements	What are the basic building blocks used to represent the system?
Individual Entities	How are individual entities represented?
Treatment of Time	How is time represented in the model?
System Structure	How is the system structure represented in the model?
Spatial Relationships	How are distances between individual entities represented?
Delays	How are delays modelled?
Feedback	Can feedback be shown in the model and if so how?
Decision Making	How is decision making modelled?
Randomness and Uncertainty	How is randomness of inputs and processes represented?
State Changes	What is the approach to modelling state changes?
Human Agents	How are human agents represented and modelled?
Adaptation	How does the technique model the process of adaptation?
Mathematical Formulation	What is the underlying mathematics and logic of the technique?

Table 2 – Initial Comparison of Simulation Techniques

Modelling Aspect	System Dynamics	Discrete Event	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.
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. **ABM -** this is a strength of ABM. Individual agent behaviour can be influenced by spatial relationship.

Modelling Aspect	System Dynamics	Discrete Event	Agent Based Modelling	Modelling Implications
Delays	Modelled and central to model behaviour	Modelled for entities	Modelled as part of statechart	**SD -** delays are treated as being the same for all entities in the flow, so again SD assumes homogenous behaviour on the part of system entities. So SD will be suited to systems where this assumption holds true. **DES -** The delay experienced can be varied dependant on the individual characteristics of the entity. So if it is important for some reason to model very different entity delays, DES would be more suitable than SD. **ABM -** The delay experienced by the agent can be modelled as a function of the decision logic of the agent in interaction with other agents in the system. So if the level of detail or granularity needed to be understood is key, then ABM will be suitable.
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?

Identifying aspects and the initial modelling implications have been informed by Brailsford and Hilton (2000), Borshchev and Fillipov (2004), Lane (2000), Law and Kelton (2000), Lorenz and Jost (2006), Morecroft and Robinson (2005), Pidd (2004) and Schieritz and Milling (2003).

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AUTHOR BIOGRAPHIES

CHRIS OWEN is a Consultant with PwC and a DBA student in the Operations and Information Management Group at Aston Business School. He holds an MBA from Aston Business School and a BEng in Manufacturing Engineering from Brunel University. He started his career as a manufacturing systems engineer with Lucas Engineering and Systems, designing and implementing manufacturing cells. He has also managed manufacturing and assembly operations in a leading UK aerospace business. His current research focuses on the use of simulation techniques in the supply chain.

PAVEL ALBORES is a Lecturer in Operations Management at Aston Business School. He has acted as consultant in the areas of manufacturing simulation for a number of organisations and on the analysis of emergency response to terrorist attacks for the Fire Service and the Office of the Deputy Prime Minister in the UK. His current research interests are Simulation, Business Processes, Supply Chains and Networked Organizations, and Modelling and Simulation of Emergency Response. He is also a visiting lecturer at the University of Basilicata, Italy

DOUG LOVE held an appointment as a lecturer in manufacturing engineering at Aston before moving to the university's Business School in 1995. He has a B.Sc. in mechanical engineering from U.M.I.S.T., a Ph.D. from Aston and is a Chartered Engineer and a member of the manufacturing division of the UK Institution of Engineering and Technology. He worked as a production engineer on the early development of group technology cells and later held senior managerial positions in production control and manufacturing management. His research interests reflect the early interest in cellular manufacturing, being mainly focussed on the development of computerized tools and techniques to support the design and operation of manufacturing systems including a number of data-driven and enterprise simulation systems. He is a member of the Operations and Information Management Division at Aston Business School.