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SYSTEM DYNAMICS MODELLING IN SUPPLY CHAIN MANAGEMENT: RESEARCH REVIEW

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ABSTRACT

The use of System Dynamics Modeling in Supply Chain Management has only recently re-emerged after a lengthy slack period. Current research on System Dynamics Modelling in supply chain management focuses on inventory decision and policy development, time compression, demand amplification, supply chain design and integration, and international supply chain management. The paper first gives an overview of recent research work in these areas, followed by a discussion of research issues that have evolved, and presents a taxonomy of research and development in System Dynamics Modelling in supply chain management.

1 INTRODUCTION

System Dynamics is a computer-aided approach for analysing and solving complex problems with a focus on policy analysis and design. Initially called 'Industrial Dynamics' (Forrester 1961), the field developed from the work of Jay W. Forrester at the Massachusetts Institute of Technology. System Dynamics has its origins in control engineering and management; the approach uses a perspective based on information feedback and delays to understand the dynamic behaviour of complex physical, biological, and social systems. Forrester (1961) defines Industrial Dynamics as "… *the study of the information-feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decision and actions) interact to influence the success of the enterprise. It treats the interactions between the flows of information, money, orders, materials, personnel, and capital equipment in a company, an industry, or a national economy*".

Lane (1997) precisely summarises Forrester's approach to modelling and understanding management problems as "… *social systems should be modelled as flow rates and accumulations linked by information feedback loops involving delays and non-linear relationships. Computer simulation is then the means of inferring the time evolutionary dynamics endogenously created by such system structures. The purpose is to learn about their modes of behaviour and to design policies which improve performance*". Due to the fact that social systems contain many non-linear relationships, and therefore an analytical solution to solving model equations is not feasible, Forrester chose an experimental, or simulation, approach to be utilised in System Dynamics (Vennix 1996). However, the essential viewpoint taken by System Dynamics is that feedback and delay cause the behaviour of systems, i.e. that dynamic behaviour is a consequence of system structure (Richardson and Pugh 1981).

System Dynamics has been applied to a wide range of problem domains. It includes work in corporate planning and policy design (Forrester 1961; Lyneis 1980), economic behaviour (Sterman et al. 1983), public management and policy (Homer and St. Clair 1991), biological and medical modelling (Hansen and Bie 1987), energy and the environment (Ford and Lorber 1977), theory development in the natural and social sciences (Dill 1997), dynamic decision making (Sterman 1989), complex non-linear dynamics (Mosekilde et al. 1991), software engineering (Abdel-Hamid 1984), and supply chain management (Towill 1996a; Barlas and Aksogan 1997; Akkermans et al. 1999).

The application of System Dynamics Modelling to Supply Chain Management has its roots in Industrial Dynamics (Forrester 1958, 1961). A model of a production-distribution system, the 'Forrester Model', is described in terms of 6 interacting flow systems, namely the flows of information, materials, orders, money, manpower, and capital equipment. Based on the development and use of a System Dynamics simulation model, Forrester describes, analyses, and explains issues evolving around supply chain management. It is important to point out that many current research issues in supply chain management have already been pointed out, or even scrutinised by Forrester in 1961, including demand amplification, inventory swings, the effect of advertising policies on production variations, de-centralised control, or the impact of the use of information technology on the management process.

Since Forrester, who essentially viewed a supply chain as part of an industrial system and in terms of policy design, researchers have covered issues ranging from inventory management to integrating global supply chains. However, "*the use of industrial dynamics modelling of real-life supply chains has only recently re-emerged from the shadows after a lengthy gestation period*" (Towill 1996a). In recent years, there has been a shift of focus in supply chain management towards a more integrated approach. "*Integrated Supply Chain Management is a process-oriented, integrated approach to procuring, producing, and delivering products and services to customers. ... Integrated Supply Chain Management covers the management of material, information, and funds flows*" (Metz 1998). Stevens (1989) describes a supply chain as "*a system whose constituent parts include material suppliers, production facilities, distribution services and customers linked together via the feed-forward flow of materials and the feedback flow of information*".

This paper presents a taxonomy of research and development on System Dynamics Modelling in supply chain management. Recent research is divided into three groups: (1) research concerned with contributing to theory-building; (2) research using System Dynamics Modelling to solve a problem; and (3) research work on improving the modelling approach.

2 THE BIRTH OF SYSTEM DYNAMICS MODELLING IN SUPPLY CHAIN MANAGEMENT

The first published work in System Dynamics Modelling related to supply chain management is found in 'Industrial Dynamics: A major breakthrough for decision makers' (Forrester 1958). Forrester (1961) expands on his basic model through further and more detailed analysis, and establishes a link between the use of the model and management education. Figure 1 shows the classic supply chain model that was used by Forrester in his simulation experiments.

There is a downstream flow of material from the factory via the factory warehouse, the distributor and the retailer to the customer. Orders (information flow) flow upstream, and there is a delay associated with each echelon in the chain, representing, for instance, the production lead-time or delays for administrative tasks such as order processing. Researchers since have coined the expression of the 'Forrester Supply Chain' or Forrester Model, which essentially is a simple four-level supply chain (consisting of factory, a warehouse, a distributor and a retailer).

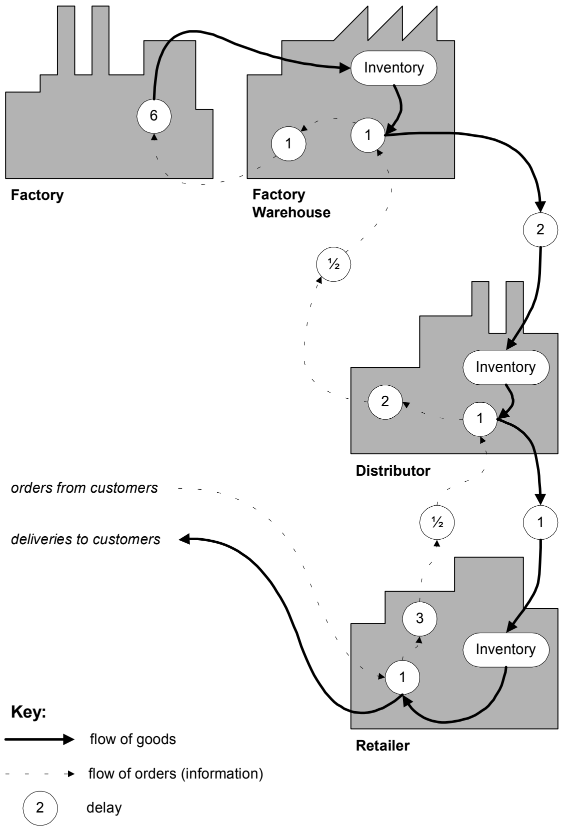

Figure 1: The Forrester Supply Chain. Source: Forrester (1961)

Using the Forrester Model as an example, Forrester (1961) describes the modelling process used in modelling continuous processes, whilst clearly emphasising the importance of information feedback to the System Dynamics method. Pointing out that the first step in a System Dynamics study is the problem identification and the formulation of questions to be answered, he illustrates the stages of model conceptualisation, model parameterisation, and model testing through various experiments. Forrester (1958) disapproves of the approach taken by operations research (OR) in the 1950's, where OR methods are applied to isolated company problems. He suggests that the success of industrial companies depends on the interaction between the flows of information, materials, orders, money, manpower, and capital equipment (Forrester 1961), and states that the understanding and control of these flows is the main task of management.

The Forrester Model received much criticism over the years, which served as a basis for applying and extending Forrester's research further. Despite its simplicity, the Forrester Model yielded important insights into supply chain dynamics. Demand amplification, a fundamental problem in supply chains, has only recently been recognise to the full extend of the problem (Towill 1996b). Forrester accidentally established the ground rules for effective supply chain design, when he "… *showed that medium-period demand amplification was a system dynamics phenomenon which could be tackled by reducing and eliminating delays and the proper design of feedback loops*" (Towill 1996b).

3 A TAXONOMY OF RESEARCH AND DEVELOPMENT ON SYSTEM DYNAMICS MODELLING IN SUPPLY CHAIN MANAGEMENT

This section presents a simple taxonomy of research and development in System Dynamics Modelling in supply chain management. Table 1 shows a grouping of Research, Practice, and how Research is put into Practice.

Table 1: A Taxonomy of Research and Development on System Dynamics Modelling in Supply Chain Management

Category Research Areas	*Research:* Modelling for Theory Building	*Practice:* Modelling for Problem Solving	*Putting Research into Practice:* Improving the Modelling Approach
Inventory Management	(b)	(b),(c)	
Demand Amplification	(b)	(b)	
Supply Chain Re-Engineering		(a),(b),(c)	(a),(b),(c)
Supply Chain Design	(a)	(a),(b),(c)	(a),(b),(c)
International SCM	(a)	(a),(b),(c)	(a),(b),(c),(d)

Key to Table 1: Techniques and Methods applied

(a) Causal Loop Diagramming
(b) Continuous simulation
(c) OR techniques
(d) Discrete simulation

Recent research is divided into three groups: (1) research concerned with contributing to theory-building; (2) research using System Dynamics Modelling for problem-solving; and (3) research work on improving the modelling approach. The following sections present a review of research, on which the above taxonomy is based on, detailing research area, issues investigated and techniques used.

3.1 Modelling for Theory-Building

Modelling that falls into this category mainly is conducted for the purpose of improving the understanding of a system through theory-building.

3.1.1 International Supply Chain Management

Akkermans's research is a typical example of work in the use of System Dynamics Modelling in international supply chain management (Akkermans et al. 1999). Reflecting a shift in emphasis in supply chain management in recent years, Akkermans, Bogerd and Vos (1999) address the more complex issue of international supply chain management (ISCM).

Based on a workshop with experts in ISCM, they propose a new theory of 'virtuous and vicious cycles' in international supply chain management, by establishing an "*exploratory causal models of goals, barriers, and enablers on the road towards effective International Supply Chain Management*" (Akkermans et al. 1999). They define supply chain management as: (1) involving multiple echelons, processes, and organisational functions; (2) displaying a clear focus on co-ordination and/or integration; (3) aiming for a simultaneous increase in customer service and profitability. Current success factors include top management commitment, cross-functional teams with feedback between management and staff, and the use of new information systems. However, until to date no causal model exists, which explains the interrelationship between these factors and performance improvement in the supply chain.

In order to develop a causal model, a Delphi-study (Vennix 1996) is carried out, involving about 30 ISCM experts from various industries. A workshop based around the 'Participative Business Modelling' approach (Akkermans 1995) is then used to address the questions of: (a) the main goals for implementing ISCM; (b) the obstacles and enablers; and (c) the interrelationship between these factors. Several obstacles (roadblocks) are identified, including local optimisation and functional silos, insufficient communication throughout the supply chain, and lack of top management support. On the other hand, the implementation of sophisticated information technology systems, the promoting of cross functional careers, the pressure from customers demanding ISCM services, and the use of best practices established by innovative companies are seen as enablers 'on the road towards ISCM'. Akkermans, Bogerd and Vos (1999) propose a causal model describing their theory of the interrelations of key success factors in international supply chain management.

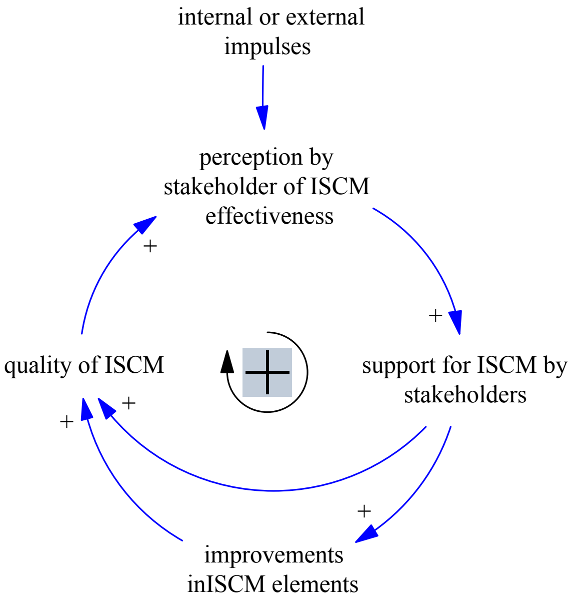

Figure 2: Virtuous and Vicious Cycles in ISCM. Source: Akkermans et al. (1999)

They show that the core dynamics are straightforward; all participating companies seem to be caught in a reinforcing loop of either success of failure. Furthermore, Akkermans, Bogerd and Vos (1999) point out that the same mechanisms form either a virtuous or vicious cycle, and are fairly generic across industries.

3.1.2 Decision-Making in Stock Management

Sterman (1989) proposes that misperceptions of feedback account for poor performance in dynamic decision-making, as the decision processes are based on an anchoring and adjustment heuristic. Feedback is defined as not only outcome feedback, but also changes in the environment or condition of choice, which are caused by past action. Such multiple feedbacks are the norm in real problems of choice.

Sterman (1989) presents a generic model of a stock management system as shown in Figure 3, which forms the basic structure in an environment for a decision-making experiment. This generic stock management structure is applicable to many different scenarios, including raw material ordering, production control, or at a macroeconomic level, the control of the stock of money. The model consists of two parts, the physical stock and flow structure of the system, and the decision rules used to control the system.

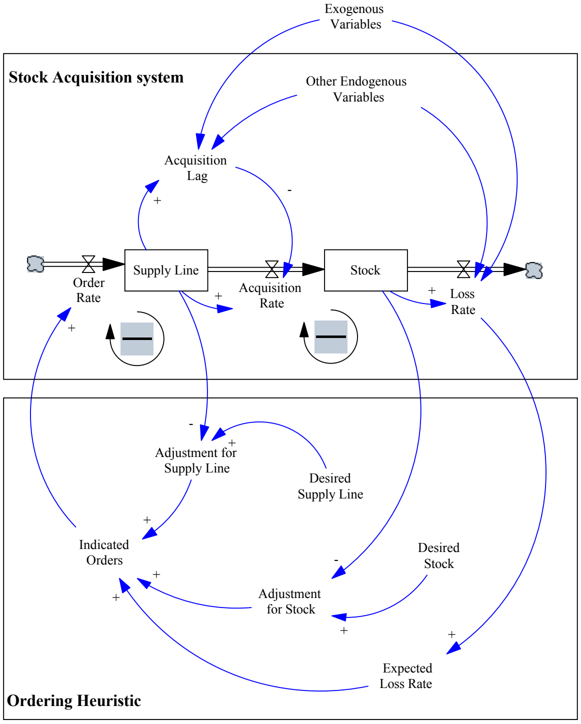

Figure 3: Generic Stock Management System. Source: Sterman (1989)

Sterman (1989) states that "*in most realistic stock management situations the complexity of the feedbacks among the variables precludes the determination of the optimal strategy*", and proposes an order decision model based on a locally rational heuristics. An anchoring and adjustment policy is characterised by a mental simulation process, where an unknown quantity is estimated through recalling a known reference point (called the anchor), and then adjusting it according to other factors.

Sterman (1989) then uses the 'Beer Game' (Sterman 1984) to conduct an experiment on managing a simulated industrial production and distribution system. The Beer Game presents a multi-echelon production distribution system, containing multiple actors, non-linearities, feedbacks and time delays throughout the supply line. The players are advised to minimise costs by managing their inventories under uncertain demand and unknown delivery lags. During the course of a simulation run, the system exhibits oscillations – the decision rules applied do not take account of long time lags between placing an order and receiving the goods.

Sterman (1989) suggests that the decision-making process is dominated by locally rational heuristics, in form of an anchoring and adjustment policy. This is due to the complexity of the system and time pressure, under which decisions are taken. Further factors to include in this hypothesis of decision-making are the availability, timeliness and perceived accuracy of information regarding the supply line.

3.2 Modelling for Problem-Solving

This approach is primarily concerned with the application of System Dynamics Modelling to solve a problem in supply chain management. Issues investigated range from ordering policies and inventory management to supply chain design.

3.2.1 Inventory Management

Typical of research on the development of inventory management policies is the work of Barlas and Aksogan (1997). Increasingly competitive markets have lead to the development of Quick Response systems, aiming to allow faster response to market demand changes whilst maintaining lower inventory levels.

Barlas and Aksogan (1997) use a case study in the apparel industry to develop a System Dynamics simulation model of a typical retail supply chain, in this case a three-echelon chain consisting of manufacturer, wholesaler, retailer and end customer. The purpose of their simulation exercise is to develop inventory policies that increase the retailer's revenue and at the same time reduce costs; another objective of the research is to study the implications of different diversification strategies.

Using a commercially available SD modelling environment, they develop a simulation model of the apparel supply chain. The model represents the physical structure of the system and also incorporates ordering and production decision rules. Data obtained from a major cloth manufacturer is then used for parameter estimation for the System Dynamics model. When the SD modelling environment is not capable of using certain algorithms, for instance the calculation of expected stockouts based on given values for SKU, demand and supply, a C program is used to perform the required calculations. Data collection takes place in form of interviews with managers from the customer service, logistics and sales department as well as the representative of a retail store. Following a traditional SD modelling approach (Richardson and Pugh 1981), the model is then validated using data from the apparel case study.

Numerous simulation runs are carried out, testing different ordering and production policies under various inventory levels and demand patterns. Barlas and Aksogan (1997) find that order policies as used in continuous systems are not adequate for partially discrete, partially continuous inventory systems. The outcome of the modelling efforts then leads to the proposition of new ordering policies for partially continuous, partially discrete inventory system, which are robust in terms of fluctuations in demand.

3.2.2 Demand Amplification

The work of Anderson, Fine and Parker (1997) is typical of research on demand amplification in supply chains. Although cyclic demand fluctuation in market driven economies is a widely researched issue and well understood, upstream demand amplification in an industrial supply chain is less tacit.

Using the machine tool industry as a case study, Anderson, Fine and Parker (1997) explore the implication of demand amplification on lead-time, inventory, production, productivity, and workforce. Capital equipment firms are exposed to particularly large variances in demand, because a small change in end-product demand creates dramatic changes in the demand for the capital equipment required to manufacture those products.

Anderson, Fine and Parker's (1997) approach uses a System Dynamics model to explain demand amplification along capital equipment supply chains, and to test various strategies that could improve the functioning of the industry. The System Dynamics Modelling methodology allows them to incorporate typical features of the capital equipment industries, such as feedback loops, delays and non-linearities. Although a discrete representation is more realistic for some parts of the model, continuous formulations are chosen for time and stocks, and found to be not too distorting; the essential dynamics of the industry are well demonstrated. Anderson, Fine and Parker (1997) develop a model of the machine tool industry, consisting of three firms: a product maker, a machine maker, and a product parts supplier. Each firm in the model is represented by a simplified version of the 'standard system dynamics firm model' (Lyneis 1980). Some factors, including order cancellations, pricing policies, and national vs. international market share, are not incorporated in the model, but this does not have a negative impact on model accuracy in relation to the problems investigated. Next, they compare simulated with actual data, using statistical data as the input order rate to the model. Size and timing of the simulated time-series is shown to reflect the aggregate industry behaviour relatively accurately, as shown with goodness-of-fit tests based on the R^2 and the Theil inequality statistics. Policy development then is conducted based on four hypotheses, which are derived from interviews at manufacturing and machine tool companies.

Anderson, Fine and Parker (1997) demonstrate that: (1) the (observed and simulated) extreme amplification is primarily due to the machine tool industry production capacity in conjunction with the 'investment accelerator' effect; (2) the machine maker's employee productivity decreases with increasing volatility; (3) shorter production lead-time reduces supplier backlogs; and (4) smoothing machine maker employment policies and product maker order policies can improve machine maker operations. They also identify the machine tool customers' order forecast rules as an important leverage point for reducing volatility, which could be improved through closer collaboration between customers and suppliers in the machine tool industry.

3.2.3 Supply Chain Re-Engineering

Towill's (1996b) work represents research on supply chain re-design. He states that rapid, effective and efficient response to changes in the market is one of the main challenges in modern supply chains. Time compression therefore is an answer to these challenges. Towill (1996b) proposes that time compression strategies based on simulation allow to predict supply chain performance improvements.

By means of using the Forrester Model (Forrester 1961) as a framework for improving systems performance, he provides a ranking of supply chain re-engineering strategies. A performance metric as proposed by Johansson et al. (1993) is used for supply chain benchmarking.

$$PI = \left[\frac{quality * customer\_service\_level}{total\_\cos t * lead\_time} \right] \tag{1}$$

Equation (1) displays this performance metric, consisting of four components. Each of these components may be adjusted by adding a relative weighting, allowing for adaptation to different preferences. According to Towill (1996b), the cycle time compression paradigm suggests that reduced lead-times will also positively influence the other three components. While lead-time has a critical effect on the stability of a supply chain, the key benefits of time compressing are improved demand forecasting, quicker defect detection, quicker to market and also a forward shift of decoupling points towards the customer.

Based on the simulation results, Towill (1996b) then proposes the use of re-engineering strategies as follows: (1) reduction in all lead-times (material-, information- and cash-flows); (2) elimination of time delays in decision points; (3) provision of marked information to all upstream decision makers.

Based on the case of the shipbuilding industry in Indonesia, Cakravastia and Diawati (1999) describe a System Dynamics model that allows locating potential bottlenecks, and prognosticating the logistic performance in that particular industry. They define logistic performance though three key indicators, namely product quality, cost, and delivery time. Traditionally, the focus of attention was directed towards controlling the physical and information flow. However, a literature review identified that the negligence towards the importance of the financial flow is causing major problems, and hence is reducing the logistic performance. Cakravastia and Diawati (1999) propose that therefore a System Dynamics model should incorporate the physical flow, the information flow and the financial flow. Firstly, the general structure of shipbuilding industries is captured in a flow diagram; the flow of inventory in the chain is pointed out as well as the information flow. They then provide a causal diagram of the corresponding financial flow, along with a causal diagram showing the material flow. Based on this initial analysis, a System Dynamics simulation model is constructed. The model portrays the time behaviour of key indicators, including orders, work in progress, deliveries, delivery delays, total sales and net profit. Finally, Cakravastia and Diawati (1999) propose the further use of the developed model, with regards to assessing the logistic performance and also the design of logistic policies.

3.2.4 Supply Chain Design

Globalisation presents a new challenge in the allocation of facilities in multi-national companies. Location-specific variables may change frequently and thus make allocation decisions more complex. Besides profitability, other aspects such as quality and lead-time have to be taken into consideration. Most traditional methods fail to address dynamic issues, creating a need for new approaches. Vos and Akkermans (1996) use a combination of Vos' method and System Dynamics Modelling to develop 'ex ante' models to support managerial decision-making.

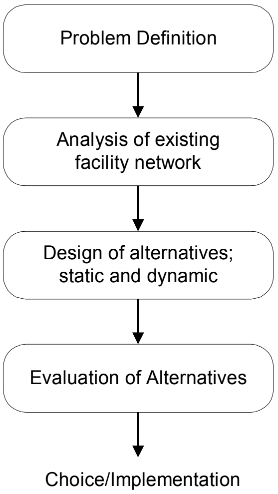

Figure 4: Vos' extended Design Method. Source: Vos (1997)

Vos' original method is based on three principles: (1) the identification and design phase of strategic decision-making; (2) the active participation of decision-makers; and (3) an integral chain approach as the underlying conceptual model. It is enhanced by the use of System Dynamics modelling to overcome the restrictions imposed by the static nature of the original method.

Vos and Akkermans (1996) apply this framework in the case of a European company considering expansion to

Asia. Starting with a static analysis in form of a production function comparison, they assess the cost benefit of an Asian plant. As a next step, a System Dynamics Model is developed and a sensitivity analysis is carried out. Results show low sensitivity regarding changes in personnel and fixed costs, however, demand fluctuations have a great impact on financial performance. Vos and Akkermans (1996) state that this 'dynamic allocation method' provides valuable insights to participating managers. Facilitation-oriented approaches combined with System Dynamics Modelling allow for the incorporation of 'soft' variables, such as employee skills or motivation, and at the same time overcome the restrictions of traditional static approaches.

3.3 Improving the Modelling Approach

Research within this class is seeking to make a methodological contribution by extending and improving the application of System Dynamics Modelling to supply chain management. Current research shows a wide range of different methods. Some approaches target the application of the simulation tool to the application domain, for instance, the combination of SD with Operational Research and Management Science approaches. Other work is concerned with the combination of Group Decision Support (GDS) with System Dynamics Modelling, as Akkermans (1995) demonstrates with 'Participative Business Modelling'.

3.3.1 Integrated System Dynamics Framework

Based on the case of a two-echelon steel industry supply chain, Hafeez et al. (1996) demonstrate the application of 'systems engineering' to supply chains and describe an integrated system dynamics framework, with the aim of giving an example to 'good total systems design'. The modelling exercise deals with the design of a supply chain with respect to moving more rapidly towards a minimum reasonable inventory, whereby the chain exhibits capacity constraints, breakdowns and material supply lead-time bottlenecks. Hafeez et al. (1996) describe the complex combination of 'man' and 'machine' as one of the major problems in modelling supply chains. By using an integrated system dynamics framework (Naim and Towill 1994), they make an effort to take into consideration the complex details associated with modelling attitudinal, organisational and technological issues.

Having simulated and analysed several different scenarios based on a real-world steel supply chain case, Hafeez et al. (1996) propose that the developed model may be viewed as a 'Management Information System' and suggest that the generalised integrated system dynamics framework should be tested regarding its effectiveness in various (other) market sectors.

Figure 5 below shows a flowchart representation of the 'Cardiff Framework for Supply Chain Design', which is described by Naim and Towill (1994) in detail.

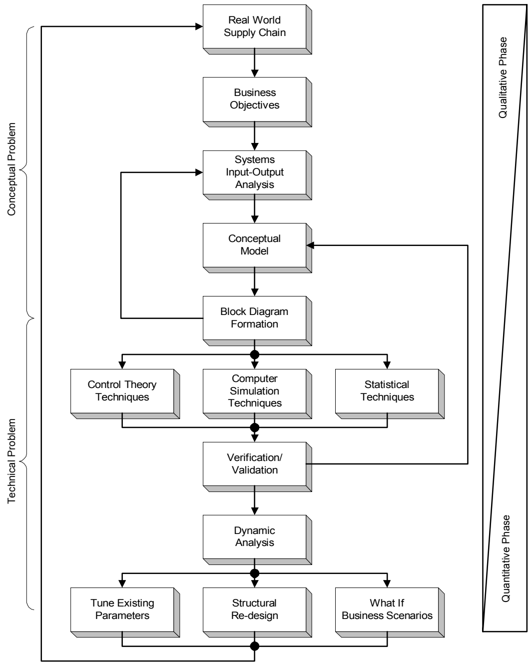

Figure 5: The Cardiff Framework for Supply Chain Design. Source: Naim and Towill (1994)

The framework is specifically designed to allow for a holistic approach to modelling supply chains, through decomposition of the supply chain into distinct autonomous business units. After going through overlapping phases of qualitative and quantitative analysis, the partial models then are combined to represent the complete supply chain. The qualitative phase is concerned with the acquisition of intuitive and conceptual knowledge sufficiently comprehensive to understand the structure and operation of the supply chain. Input-output analysis, conceptual modelling and block diagramming form part of this phase, which is aiming to deal with the conceptual problem. When dealing with more technical problems during the quantitative phase, the development and analysis of mathematical and simulation models become the focus of the approach. Naim and Towill (1994) conclude that the combination of a 'hard' systems approach with a 'soft' systems analysis allows for a structured approach to supply chain design.

3.3.2 Participative Business Modelling

Akkermans (1995) proposes an approach labelled 'Participative Business Modelling' (PBM) to address not only the technical, but also the organisational complexities inherent in the development of logistics strategies. Existing methods mainly focus on technical complexity, and although they excel in tackling these issues, often the implementation success does not live up to the expectations. This is due to low management participation and the resulting lack of commitment towards the proposed strategies.

Participative Business Modelling combines intensive management participation with rigorous analysis and extensive modelling, aiming to facilitate learning about strategic issues and therefore the gaining of insights. Starting with qualitative analysis, the method gradually leads to more formal, quantitative modelling. PBM draws from several different methods, including System Dynamics Modelling, Operational Research, Social Sciences and process consultation, and aims to combine them for a greater benefit. It contains an implicit conceptual model (or theory) on effective strategic decision-making. Figure 6 shows the conceptual research model for the PBM.

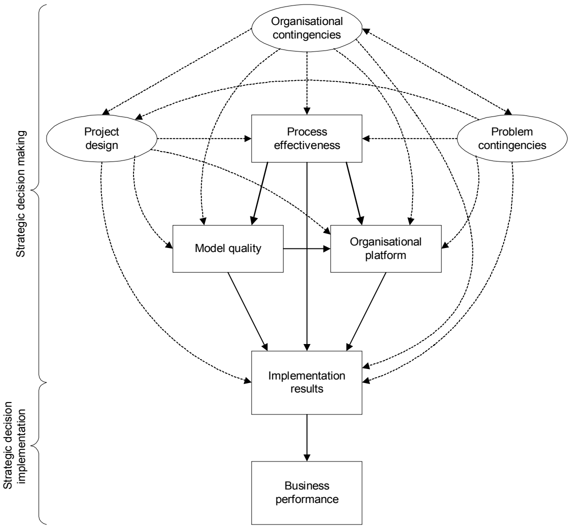

Figure 6: PBM: A Conceptual Model of Strategic Decision-Making. Source: Akkermans (1995)

Participative Business Modelling comprises of four project phases: (1) the project definition phase, using cognitive mapping; (2) the model conceptualisation phase, which is employing brainstorming, causal loop diagramming, and stock and flow diagramming; (3) the modelling formalisation phase, where System Dynamics Modelling as well as discrete event simulation may be applied; and (4) the knowledge dissemination phase, where the models are used for sensitivity and scenario analysis.

Akkermans (1995) demonstrates the application of PBM to facilitate the design of a logistics strategy through a case study, were an international company sets out to establish logistic operations in Europe. Two types of constrains are identified: Firstly, technical complexities, such as requirements for time-critical operation, marketing, financial and legal constraints, and the lack of an existing logistics structure; and secondly, organisational complexities, including low management support and geographically separated decision-makers. In applying the PBM method, Akkermans and the involved management go through four phases, starting with structured interviews. Following a modelling workshop, quantitative models are developed, before these models are finally used to understand and improve the logistics performance of the proposed system. Akkermans (1995) then provides a review of the approach used and suggests several additions, including the use of workbooks and use of discrete event simulation models.

4 CONCLUDING DISCUSSION

This paper first gave an overview of System Dynamics Modelling in general and its application to Supply Chain Management related issues. The first work in System Dynamics in relation to supply chain management goes back to Forrester (1958). He already investigated many up to date research issues. "*It is, therefore, appropriate to regard Forrester not only as the 'father' of System Dynamics, but also as the originator of many of the techniques of modern supply chain management*" (Towill 1996b).

The paper then presented a taxonomy of research and development on System Dynamics Modelling in Supply Chain Management, classifying recent research work within 3 groups: (1) Modelling for Theory-Building; (2) Modelling for Problem-Solving; (3) Improving the Modelling Approach. It laid out the research areas, and within each area the main techniques and methods applied.

Several areas for further research can be identified. A taxonomy of a particular area within System Dynamics in supply chain management could show the relations between partnerships in supply chains, problems addressed and the conditions for success or failure (Anderson et al. 1997). Theoretical models of the organisational change process towards international supply chain management should be tested regarding content and validity (Akkermans et al. 1999). And finally, the taxonomy of research and development on System Dynamics Modelling in Supply Chain Management, as presented in section 3 of this paper, suggests further research on improving the modelling approach in areas related to inventory management.

REFERENCES

Abdel-Hamid, T. K. 1984. The Dynamics of Software Development Project Management: An Integrative System Dynamics Perspective. PhD Thesis, Sloan School of Management, MIT, Cambridge (MA).

Akkermans, H. A. 1995. Developing a logistics strategy through participative business modelling. *International Journal of Operations & Production Management* 15 (11):100-112.

Akkermans, H. A., P. Bogerd, and B. Vos. 1999. Virtuous and vicious cycles on the road towards international supply chain management. *International Journal of Operations & Production Management* 19 (5/6):565-581.

Anderson, E. G., Jr., C. H. Fine, and G. G. Parker. 1997. Upstream Volatility in the Supply Chain: The machine Tool Industry as a Case Study. Austin (TX): Departament of Management, University of Texas.

Barlas, Y., and A. Aksogan. 1999. *Product Diversification and Quick Response Order Strategies in Supply Chain Management* [web page]. Bogazici University 1997 [cited 27 August 1999]. Available from http://ieiris.cc.boun.edu.tr/faculty/barlas/.

Cakravastia, A., and L. Diawati. 1999. Development Of System Dynamic Model To Diagnose The Logistic Chain Performance Of Shipbuilding Industry In Indonesia. Paper read at International System Dynamics Conference, Wellington, New Zealand.

Dill, M. 1997. Capital Investment Cycles: A System Dynamics Modelling Approach to Social Theory Development. Paper read at 15th International System Dynamics Conference: "Systems Approach to Learning and Education into the 21st Century", Istanbul, Turkey.

Ford, A., and H. W. Lorber. 1977. Methodology for the Analysis of the Impacts of Electric Power Production in the West. Paper read at Environmental Protection Agency Conference on Energy/Environment II.

Forrester, J. W. 1958. Industrial Dynamics: A Major Breakthrough for Decision Makers. *Harvard Business Review* 36 (4):37-66.

———. 1961. *Industrial Dynamics*. Portland (OR): Productivity Press.

Hafeez, K., M. Griffiths, J. Griffiths, and M. M. Naim. 1996. Systems design of a two-echelon steel industry supply chain. *International Journal of Production Economics* (45):121-130.

Hansen, J. E., and P. Bie. 1987. Distribution of body fluids, plasma protein, and sodium in dogs: a system dynamics model. *System Dynamics Review* 3 (2):116-135.

Homer, J. B., and C. L. St. Clair. 1991. A Model of HIV Transmission through Needle Sharing. A model useful in analyzing public policies, such as a needle cleaning campaign. *Interfaces* 21 (3):26-29.

Johansson, H. J., P. McHugh, A. J. Pendlebury, and W. A. Wheeler. 1993. *Business Process Re-enginering*. Chichester: Johne Wiley & Sons.

Lane, D. C. 1997. Invited Review and Reappraisal: Industrial Dynamics. *Journal of the Operational Research Society* 48:1037-1042.

Lyneis, J. M. 1980. *Corporate Planning and Policy Design: A System Dynamics Approach*. Cambridge (MA): Pugh-Roberts Associates.

Metz, P. J. 1998. Demystifying Supply Chain Management. *Supply Chain Management Review* (Winter 1998):46-55.

Mosekilde, E., E. R. Larsen, and J. D. Sterman. 1991. Coping with Complexity: Deterministic Chaos in Human Decisionmaking Behavior. In *Beyond Belief: Randomness, Prediction, and Explanation in Science*, edited by J. L. Casti and A. Karlqvist. Boston (MA): CRC Press.

Naim, M. M., and D. R. Towill. 1994. Establishing a Framework for effective Materials Logistics Management. *International Journal of Logistics Management* 5 (1):81-88.

Richardson, G. P., and A. L. Pugh, III. 1981. *Introduction to System Dynamics Modeling*. Portland (OR): Productivity Press.

Sterman, J. D. 1984. Instructions for Running the Beer Distribution Game: MIT System Dynamics Group.

———. 1989. Modeling Managerial Behavior: Misperceptions of Feedback in a Dynamic Decision Making Experiment. *Management Science* 35 (3):321-339.

Sterman, J. D., J. W. Forrester, A. K. Graham, and P. M. Senge. 1983. An Integrated Approach to the Economic Long Wave. Paper read at Long Waves, Depression, Innovation, Siena-Florence, Italy.

Stevens, G. C. 1989. Integrating the Supply Chain. *International Journal of Physical Distribution & Logistics Management* 19 (8):3-8.

Towill, D. R. 1996a. Industrial dynamics modelling of supply chains. *Logistics Information Managment* 9 (4):43-56.

———. 1996b. Time compression and supply chain management - a guided tour. *Supply Chain Management* 1 (1):15-27.

Vennix, J. A. M. 1996. *Group Model Building: Facilitating Team Learning Using System Dynamics*. Chichester: John Wiley & Sons.

Vos, B. 1997. Redesigning international manfacturing and logistics structures. *International Journal of Physical Distribution & Locistics Management* 27 (7):377-394.

Vos, B., and H. A. Akkermans. 1996. Capturing the dynamics of facility allocation. *International Journal of Operations & Production Management* 16 (11):57-70.

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