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SUPPLY CHAIN DYNAMICS

Mohamed M. Naim, Stephen M. Disney & Denis R.,Towill

INTRODUCTION

There is currently a considerable pre-occupation with the impact of electronic innovations in various environments including business, commerce and manufacturing. In particular, the Internet and related information and communication technologies (ICT) have recently enabled the cost-effective dissemination of information between disparate parties in the supply chain. New supply chain strategies, such as Vendor Managed Inventory (VMI), Collaborative Planning Forecasting and Replenishment (CPFR) or Efficient Consumer Response (ECR), have begun to exploit these new communication channels (Disney, 2001), principally at the retail end of the supply chain. The impact of the ICT enabled supply chain on manufacturers and materials/component suppliers is, however, less well understood and exploited.

Advances in ICT enable a radical re-think in how products and services are marketed (Peppers & Rogers, 1998). The shift, already seen in embryonic form by companies such as Dell Computers and Domino Pizza, is from traditional mass marketing strategies towards customer-driven marketing. The former is based on identifying a set of "average" customer wants (Christopher and Towill, 2000) and "pushing" the product and services to as many people as possible who may have those wants. The latter requires an enterprise (possibly as a single entity but almost certainly a virtual one or as part of a supply chain) to establish a "1-2-1" interactive relationship with each of its customers. While the enterprise treats all its customers equally it must also prioritise its resources and efforts to its most valued customers based on each customer's lifetime value to the enterprise. With most enterprises ultimately fulfilling the needs of thousands or millions of end customers there is a need to develop efficient but flexible methods of customer interaction and product or service delivery. This is in line with contemporary thinking in Operations Management (Hill, 2000).

While ICT in the form of eBusiness is advocated as an enabler to the "1-2-1" enterprise (Peppers & Rogers, 1998), by allowing market place information to be shared by all businesses in the supply chain, there is little analytical or quantifiable evidence that it will actually improve overall performance of the enterprise in delivering customer wants. Most of the research to-date has been via empirical research studies (Holmström, 1997). It is usually proposed that passing market place information on to all businesses in the supply chain via ICT will improve performance. In fact, recent research (e.g. Hong-Minh et al., 2000) has shown, via a supply chain management game, that simply passing information on to businesses can have a detrimental effect. This is due to the fact that, as well as information transparency, there is a need to co-ordinate the separate logistics planning and control systems. Our conclusion is that such notions as VMI, ECR & CPFR are banded about with little understanding and assessment of their capabilities.

THE PROBLEM

The origins of the systems approach to generic problem solving may be traced back to the work of von Bertalanffy (in Kramer and de Smit, 1977) who proposed the General Systems Theory (GST) in 1932. GST suggest that "the whole is greater than the sum of its individual parts" and that sub-optimal solutions do not yield true total optima – this is often referred to as "gestalten".

The dangers of sub-optimisation is highlighted by what is known as Braess' Paradox (Shapiro, 2001); "If a part of a management system is re-engineered, then the odds are:

25% that the system performance is improved

50% that the system performance will not change significantly

25% that the system performance will actually get worse"

GST has generic applicability and one of its aims is to develop a unified approach that transcends disciplinary boundaries. One of the unifying principles of GST is that any system is in dynamic interaction with its environment. For systems to be efficacious and effective they must be "open" and aim to reach an equilibrium with their environment. This interactivity, resulting in feedback flows between system and environment and the delays that are inherent in any system results in dynamic behaviour.

Much of the pioneering work into aspects of supply chain dynamics was undertaken by Forrester in the late 1950's (Forrester, 1958), using a simple but representative simulation model of a production distribution supply chain. Originally developed as a detailed case study incorporating the DYNAMO simulation language, Forrester's work has been widely quoted, and misquoted in business and academic literature. Based on a series of simulation experiments, Forrester revealed a number of important behavioural features of the supply chain model that were concluded as having relevance to real world supply chains:

1. Demand in the marketplace becomes a delayed and distorted order pattern moving upstream through a supply chain
    1.1. at any one point in time, processes in various companies in the chain may be moving in different directions to each other and to the market
    1.2. supply chain designs tend to "amplify" marketplace variations. The magnitude of the variations in orders placed on the factory is greater than the variations in marketplace demand.
    1.3. supply chain designs can introduce "periodicity", or rogue seasonality which can be misinterpreted as a consequence of seasonal variations in the marketplace, rather than a property of the supply chain design.
2. Attempts to reduce poor supply chain dynamic behaviour can exacerbate the problem. Counter-intuitive behaviour often occurs because the causes of the behaviour are obscured from the decision-makers in the chain. Consequently learning opportunities are restricted.

Point 1 above has historically been termed "The Law of Industrial Dynamics" (Burbidge, 1984) but the same phenomenon has more recently has been described as "bullwhip" (Lee et al. 1997a and b). Bullwhip is an important measure as it is symptomatic of a poorly performing supply chain (Jones and Simons, 2000). Bullwhip is a surrogate measure of production adaptation costs (Stalk and Hout, 1990) and implies the inclusion of "just-in-case" stock holding to buffer against uncertainties. Evidence in many forms suggests that the "bullwhip" effect and Forrester's empirical conclusions are highly applicable to the vast majority of supply chains. Typical are the results observed in a global mechanical precision products supply chain (McCulen and Towill, 2001). The ability to recognise the "bullwhip" effect, its impact on business and supply chain performance and ways to eliminate or cope with it have been a key issue in a number of current management paradigms including

- Time compression (Stalk & Hout, 1990)
- Lean Thinking (Womack & Jones, 1996)
- Mass customisation (Pine, 1993)
- Supply chain management (Houlihan, 1987)
- Agile production (Kidd, 1994)

An example of the "bullwhip" effect in just one echelon of a real-world automotive supply chain is given in Figure 1. This shows customer demand coming into a business and the resulting supplier orders. The ratio in variance between the supplier order and customer demand is 2:1! Point 2 above forms a critical research agenda for this chapter as we determine whether the application of ICT in the supply chain may lead to counter intuitive behaviour, hence what are our research priorities and to what extent innovative research platforms have to be developed.

Figure 1. Sample bullwhip curve

WHAT WE KNOW: CURRENT STATE OF KNOWLEDGE

There is a 40+ year history embedded in the theories of systems thinking and cybernetics. Research on improving the dynamic behaviour of individual manufacturing businesses and supply chains is well known. Most recent research may be categorised as

- ♦ ***Management games***; such as the Beer Game that was originally developed at MIT at the end of the 1950's, (Sterman, 1989) are useful tools to illustrate the benefits of different supply chain strategies. Games are limited in the sense that generally nothing can be rigorously proved from the game in itself. But they do provide a valuable source of experiential evidence and are a good learning device. Other authors have since extended or computerised the Beer Game including van Ackere et al (1993), Kaminsky and Simchi-Levi (1998), Lambrecht and Dejonckheere (1999a and b).

- ***Empirical studies***; a number of authors have investigated the impact of ICT on the supply chain including Holmström (1998), Fransoo and Wouters (2000), Kaipia, et al., (2000). However, this type of contribution looks at quantifying the improvement performance of a known strategy after its implementation; that is, there is no predictive element and the focus of the research is to identify best practices. Unfortunately, it is not always possible to compare ICT implementation strategies directly due to the varying nature of the environments in which they have been implemented.

- ***Statistical analysis;*** this type of contribution typically provides statistical insights about the impact of demand properties such as standard deviation and auto-correlation, and supply chain properties such as lead-times and information paths on inventory costs and the bullwhip effect, or demand amplification. Statistical methods are often used to quantify performance of real situations. These methods however, fail to show how to reduce or eliminate the detrimental dynamic effects, such as "bullwhip", and insights into the causes and effects of system structure on performance are rarely obtained in depth from the technique. Recent significant contributions of this type include Lee et al. (2000), Chen et al. (2000) and Chen et al. (2000).

- ***Simulation and system dynamics;*** was advocated by Forrester (1961) as a method of investigating the dynamical effects in large non-linear systems as a means of avoiding resorting to complicated mathematical control theory based models (Edghill and Towill, 1989). Simulation approaches alone suffer from being cumbersome, time consuming and only provide limited insight (Popplewell and Bonney, 1987), but they do have the advantage of being able to model non-linearity's whilst avoiding complicated mathematics. Previous work using simulation is very prolific and includes (but is by no means limited to) Forrester (1961), and Coyle (1982), who studied traditional supply chain structures, Cachon and Fisher (1997) and Waller et al. (1999) who studied VMI.

- ***Continuous control theory techniques;*** for production and inventory control was first recognised by the Nobel Prize for Economics Winner in 1978 (for his work on organisational dynamics), Herbert Simon. Simon (1952) described how to use linear deterministic control theory for production and inventory control. This was transformed into "good practice" format by Towill (1982). Axsäter (1985) presents a useful review paper of early work, summarising the advantages and limitations of the field. He concludes that control theory "illustrates extremely well dynamical effects and feedback", but cannot incorporate sequencing and lot-sizing issues. Grubbström (1996) and other colleagues at Linköping Institute of Technology have been applying the Laplace transform and economic techniques such as Net Present Value to MRP systems. Continuous control theory suffers from the fact that some scheduling and ordering scenarios are inherently discrete and the continuous representation of discrete time delays is mathematically complicated.

- ***Discrete control theory;*** is a very powerful way of investigating sampled data systems (i.e. a scheduling and ordering systems and computer system which are inherently discrete). Vassian (1955), inspired by Simon's work in the continuous domain, studied a production-scheduling algorithm using discrete control theory. DeWinter (1966), in possibly only one of only two contributions that consider novel supply chain structures, looks at a form of centralised inventory control used in naval supply chains. Deziel and Eilon (1967) describe a significant application. Burns and Sivazlian (1978) consider a four level traditional supply chain using z-transforms. Bonney and Popplewell (1988) have investigated MRP systems. Dejonckheere, et al., (2000a) have been using z-transforms and Fourier transforms to investigate the bullwhip performance of common forecasting mechanisms within common control structures. Disney (2001) has been using discrete control theory to investigate Vendor Managed Inventory supply chains. The disadvantages of discrete control theory is that the mathematics often involves lengthy and tedious algebraic manipulation.

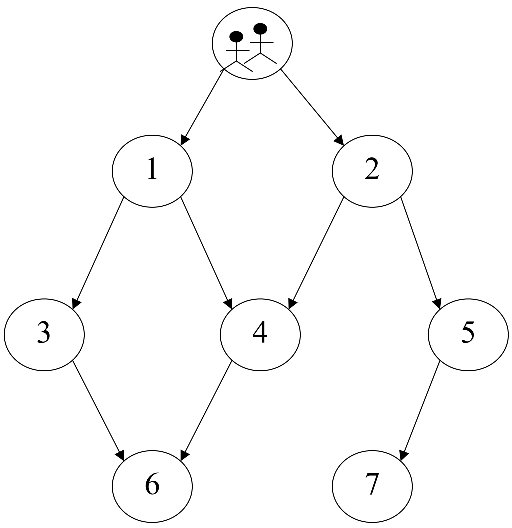
- ***Classical OR/management science***; at about the same time as the seminal work of Simon (1952) and Vassian (1955) this separate but parallel strand of research established a dynamic programming approach to the inventory control problem. Arrow (2002) gives a recap of the genesis of the search for the "optimal inventory policy". While not actually investigating structural dynamics this approach aims to establish optimal policies for inventory control. Inherent in this approach is the assumption that there are an infinite number of possible policies and it tries to identify the best one for a given set of assumptions. For example, the assumptions may be concerned with the cost structure, demand pattern, lead-times and planning horizons. An objective function has to be defined and it is usually based on inventory holding and shortage costs. Key works in the field include Karlin (1960), Scarf (1960), Veinott (1965) and Johnson and Thompson (1975). Such an approach rarely considers the generation of order upstream from the point of inventory control and therefore may be regarded as a sub-optimal approach. Towill et al. (2003) have undertaken a detailed comparison of the control theory and OR approach to Decision Support System (DSS) design for managing supply chain dynamics.
- ***The hybrid approach;*** Naim & Towill (1994) brought together the separate elements above into a contingency based methodology. Control theory models coupled with simulation (such as, Disney, et al., 1997) and statistical methods (Griffiths et al, 1993) has enabled a systematic approach (such as, Evans et al, 1998) to understanding the linear, time invariant and the non-linear, time varying dynamic behaviour of production and inventory control systems (Cheema, 1994). Solutions have been similarly proposed to improved customer service levels and increased stock turns through action-based research (Lewis, 1997). The analytical studies have also been related to empirical survey findings. Berry et al. (1998) applied this approach to model the delivery performance of a healthcare vendor with an active catalogue of 6000 products covering "A", "B", and "C" classified items.

There is little explicit analytical evidence of the impact of ICT on supply chain dynamics. In fact, counter intuitive behaviour has resulted from our playing of the Beer Game. For example transparency of market place demand transmitted along the supply chain can easily have an overall detrimental effect if no holistic strategy is in place (Hong-Minh et al, 2000). It would clearly be impossible to examine all the above approaches in this chapter. What we will do is to develop some of the concepts regarding supply chain dynamics based on key published material that help to define a framework for future research.

SUPPLY CHAINS & COMPLEXITY

In the 1960's Mark Gardner and Ross Ashby (in research undertaken in what is now Cardiff University) were concerned with the general behaviour of large dynamical systems (Gardner & Ashby, 1970). "Large" was arbitrarily defined with examples given as airport traffic congestion due to 10^2 aeroplanes, group activities involving 10^4 people and the human brain with 10^6 neurones. Via simulation Gardner and Ashby made a significant contribution to our understanding of the behaviour of complex systems. This resulted from the careful design and subsequent analysis of a set of experiments based on the number of variables in a system and the way in which these variables interact.

Figure 2 shows a possible configuration for a traditional supply network where communication proceeds in just one path from the market-place up-stream to the suppliers. Each numbered node represents both an operation in the network plus the end consumers, here seen as an aggregate market place node. Gardner and Ashby undertook a number of experiments in which the number of nodes and the number of connections actually used were varied. The latter, representing information flows in the supply network, were selected at random both in number and sign. By repeating the experiments many times the probability of stable operation of the network was established. This showed the existence of "switching lines" between stable and chaotic behaviour and contains a stark message for anyone concerned with the design and operation of supply chains.



<u>Traditional supply chain</u>
n = 8 nodes including market place
N = maximum number of connection = 23
X = number of connections actually used = 8
C = systems connectance = X/N = 35%

Figure 2 Possible complexity in a traditional network

Figure 3 shows a summary of the simulation results as depicted by Towill (1997). The axes of the graph are the probability of stable behaviour of the system and the "system connectance", which is the percentage of the system nodes randomly connected to each other. Two important phenomena are manifestly evident.

1. As the number of nodes increases the probability of a stable operation decreases dramatically.
2. As the system connectance increases the network swiftly crosses the switching line and enters the unstable operations region.

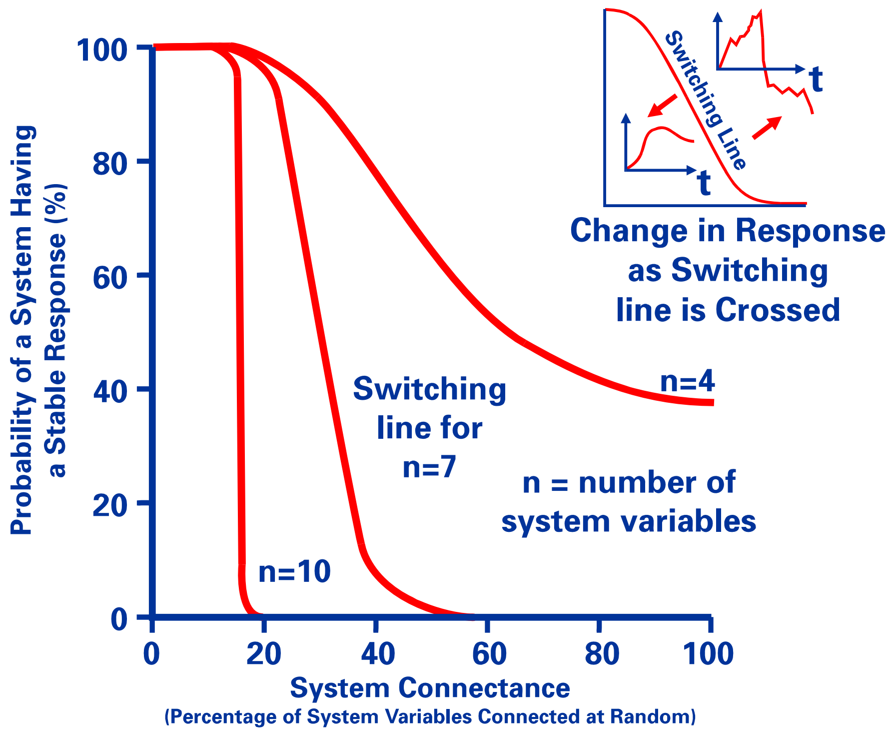
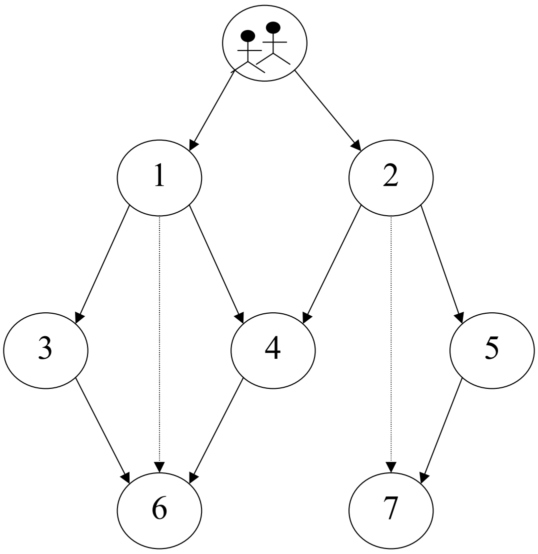


Figure 3: Empirical relationship between system size, connectance and stability (from Towill, 1997, based on the simulation results of Gardner & Ashby, 1970)

The implications for supply chain networks and any supporting strategy of passing on information, say via EPOS, are obvious. Figure 4 shows the same supply network of Figure 1 but with EPOS data now transferred from the first echelon (say, equivalent to the retailers in the grocery sector) through to the third echelon (say, the raw food suppliers delivering goods to the food processors). Thus, the number of connections increases to 10 and the system connectance thereby increases to 43% making the probability of stable response much lower. Hence it is clear that the supply network must be properly designed and not allowed to grow in an "ad hoc" manner. *Otherwise, using the wrong information at the wrong node in the wrong way may suddenly cause the network to become unstable and chaos reign throughout the system*.



e-enabled supply chain
n = 8 nodes including market place
N = maximum number of connection = 23
X = number of connections actually used = 10
C = systems connectance = X/N = 43%

Figure 4 Possible increased complexity in an ICT enabled network

These results concur with the seminal work of Shannon (1948) that Kramer and de Smit (1977) have embedded in other research in the field of chaos and information availability. It is important to realise that data transfer on its own is not information. Kramer and de Smit (1977) have noted that data may be transferred between a sender and a receiver but it only contains information if and when it removes uncertainty in some way. Thus, in a supply system scenario, additional data is insufficient unless the receiver knows what to do with it. It also does not help that a lack of co-ordination between the nodes in the system means that the receiver is still unaware of the consequences of their own actions. The same argument also applies to the likely actions taken by the other nodes, taken to hopefully improve their situation.

SUPPLY CHAINS AND HUMAN BEHAVIOUR

The MIT "Beer Game" (Senge, 1990) represents a four-echelon supply chain including a retailer, a wholesaler, a distributor and a factory. A flow of information (orders) goes from the retailer to the factory and a flow of product returns. The game involves different delays: two weeks delay for the order to reach the next echelon and two weeks transport delay from the inventory of an echelon to the next as shown in Figure 5. Usually the players (representing one echelon) cannot speak to each other. A customer demand is inputted at the retailer level and after having satisfied the order, the retailer must decide the quantity needed to be ordered from the wholesaler. Each echelon has to pass an order to its supplier in order to fulfil the order of its immediate customer.

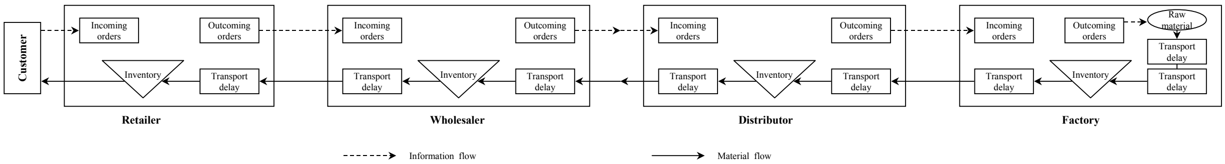


Figure 5 Schematic of the Beer Game

The aim of the game is to minimise cumulative costs over the length of the game due to excess inventory and stock outs. To set up a performance metric it is commonly assumed that for each unit inventory costs are £0.50 and stock outs costs are £1. It is considered that even if the supplier cannot satisfy the demand during one or several weeks, the products ordered are still required by the customer, thus a backlog is created. The inventory cost is an important measure as it ultimately determines the extent to which we satisfy the customer as well as determining the risk of stock obsolescence. The severity of backlog cost is justified because, no matter how well we control the degree of volatility in the supply chain, if we do not satisfy the end consumer then we will eventually go out of business.

The goal of the game is to demonstrate to the players the existence of the bullwhip phenomenon. Furthermore that it is not induced by external disturbances but is due to the lead-times in the supply chain coupled with the players' feedback based decision-making. While traditionally the "Beer Game" is utilised as a mechanism for allowing participants to experience the demand amplification phenomenon for themselves it may also be used to test different supply chain re-engineering scenarios (Mason-Jones,1998). For the specific purposes of this chapter we have taken the results from Hong-Minh et al (2000) and Disney et al (2002) to highlight the implications of ICT strategies.

Disney et al (2002) analysed the impact of four ICT enabled scenarios by investigating the bullwhip effect using two different delivery management approaches and comparing them to a traditional supply chain. The first approach is based on an analysis of the results of the management flight simulator, the Beer Game. The second approach is based on a quantitative z-transform analysis using the tools highlighted by Disney and Towill (2002).

The five supply chain strategies considered are:

- **traditional** – in which there are four "serially linked" echelons in the supply chain. Each echelon only receives information on local stock levels and sales. Each echelon then places an order onto its supplier based on local stock, sales and previous "orders placed but not yet received".
- **e-Shopping** – the scenario where the manufacturer receives orders directly from the end consumers (possibly via the Internet like Dell) and ships the product directly to them after the production and distribution lead-time. Thus this simple supply chain strategy has exactly the same fundamental structure as a single echelon traditional supply chain.
- **echelon reduction** – where an echelon in the supply chain had been removed. This is representative of, say, the Amazon.com supply chain, where the retailer echelon is by-passed. This is a supply chain that has used ICT to eliminate an echelon in the supply chain. Wikner, et al., (1991) have identified echelon removal as an effective mechanism for improving supply chain dynamics.

- **Vendor Managed Inventory (VMI)** – that is simulated by developing a protocol positioned between two businesses in the supply chain that gives the necessary inventory and sales information, authority and responsibility to the supplier in order to managed the customer's inventory.
- **Electronic Point of Sales (EPOS)** – where information from the market place is transmitted to all enterprises in the supply chain. This is equivalent to the situation in many grocery supply chains, where the EPOS (Electronic Point Of Sales) data is available electronically via the Internet, either directly from the retailer or via a third party, which can be used by supply chain members to generate their own forecasts. Specifically, in this strategy, the end consumer sales may be used by each echelon for there own planning proposes, but each echelon still has to deliver (if possible) what was ordered by their immediate customer. A full-scale investigation of this strategy has been conducted using z-transforms by Dejonckheere, et al., (2001b) inspired by the simulation approach of Mason-Jones (1998).

ANALYSIS OF BEER GAME RESULTS

The five supply chain scenarios researched are summarised in Figure 6. Hong-Minh, et al., (2000) analysed the results from four different teams playing different supply chain management strategies, one of which was the EPOS scenario previously described. Even though the research literature implies great benefits for information sharing (Mason-Jones and Towill, 1997), surprisingly the EPOS strategy yielded the worst result. While the EPOS strategy limited the degree of bullwhip in the supply chain this was at the expense of long periods of backlogs (negative net stock). It was concluded that, although market information was shared with all echelons in the supply chain without any delays, each player of the supply chain had their own insular ordering rule. That is, there was no collaboration between the different players.

To test the hypothesis that although sharing market information is potentially a good thing it will only yield benefits as part of an agreed overall supply chain decision making strategy (Mason-Jones, 1998) the EPOS strategy was re-run by Disney et al (2002) but with the added characteristic that all players were involved in collaborative planning, forecasting and replenishment; in other words, CPFR.

While different measures of performance were collected from the game they have been summarised according to Equation 1 (Chen, Drezner, Ryan and Simchi-Levi, 2000).

$$Bullwhip^{i} = \frac{\sigma^{2}_{ORATE^{i}} / \mu_{ORATE^{i}}}{\sigma^{2}_{CONS} / \mu_{CONS}} = \frac{\sigma^{2}_{ORATE^{i}}}{\sigma^{2}_{CONS}} \qquad \text{.....Equation 1}$$

which gives the bullwhip measure, the co-efficient of variation, at echelon *i*, where σ^2 is the variance and μ is the mean of the end consumer sales (CONS) or the order rate (ORATE) at echelon *i*.

Summary results from the game are shown in Table 1. The inventory costs are shown as a relative ranking achieved and normalised so as to be independent of the number of actual echelons in a particular supply chain strategy. We are therefore penalising those supply chains with fewer echelons. Also, two EPOS results are shown. The first is that played in the research described in this paper and has been defined as EPOS-CPFR. The second (named EPOS – no CPFR) is based on the results recorded by Hong-Minh et al. (2000).

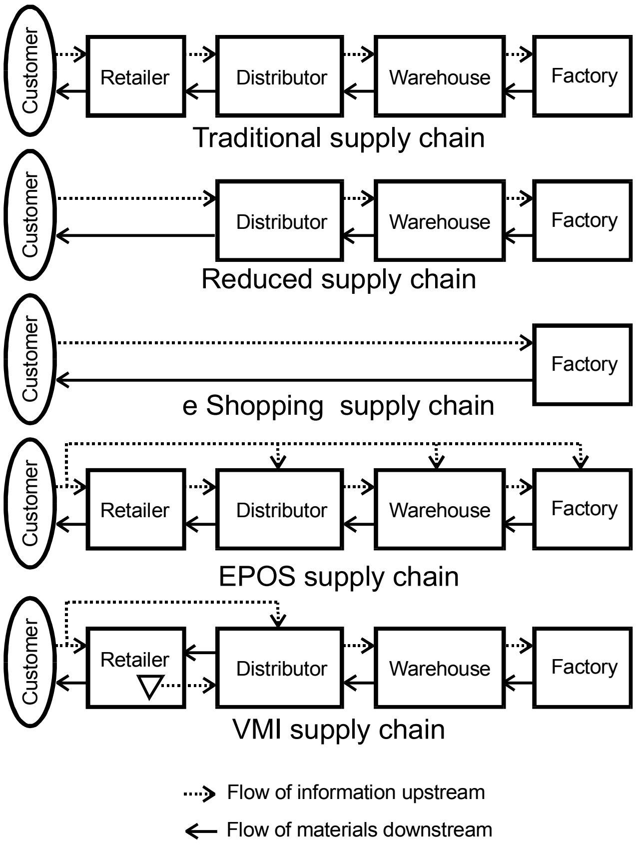


Figure 6 Different supply chain structures (Disney et al, 2002)

Supply chain	Inventory cost ranking	Bullwhip			
		Retailer	Distributor	Warehouse	Factory
eShopping	**1st**				1.50
Reduced	**2nd**	1.00		0.99	0.93
EPOS – CPFR	**3rd**	1.92	1.37	0.99	0.49
VMI	**4th**		3.42	4.68	4.44
EPOS – no CPFR	**Not applicable**	1.85	0.83	0.55	0.69

Table 1. Sample Beer Game results (Disney et al, 2002, rankings based on cumulative inventory costs over length of a game)

EPOS – CPFR again does well at minimising, and in fact is reducing, bullwhip in the supply chain. But, as with EPOS – no CPFR, a price is paid in inventory costs, which is primarily attributable to the supply chain having long periods of stock out. Despite the normalisation of the inventory costs it is evident that a strategy that eliminates an echelon, or a number of echelons, still outperforms alternatives. As has been previously reported (see for example, Wikner, et al., 1991) eliminating an echelon removes both a decision point and reduces total lead-times in one fell swoop. Clearly this double benefit has been achieved.

Even more surprising than the EPOS – CPFR result is that the VMI scenario had both the worst inventory holding costs and the worst bullwhip. It was evident in the game de-briefing that, despite the provision of well-documented protocols, the players had problems in implementing the concept. It is also evident that even in a CPFR scenario if too much focus is given to a single measure (in these scenarios, bullwhip) then this can be to the detriment of other performance indices such as stock holding and product availability.

Disney et al (2002) took two different approaches to understand the impact of ICT on supply chain dynamics. The z-transform analysis indicates that there is an expectation that the innovative use of ICT will outperform alternative strategies. But the Beer Game results have indicated that ICT adds a degree of complexity to human decision-making that is difficult to cope with even if well-defined protocols are provided. There is simply too much information and too many calculations for the human scheduler to manage.

The Beer Game also indicates that poor management of the ICT protocols leads to increased inventory costs. We conclude that although the Beer Game is a simulated and simplified environment, much like the real-world people have to make decisions for which the consequences of which are not immediately known. As Sterman (1989) has indicated people are not good at making decisions in such an environment. In using the passing-on-order algorithm as a benchmark, Sterman (1989) demonstrated that the majority of human decision makers in his large sample performed much worse than this target in terms of stock fluctuations along the chain.

But the good news is that he also established via the same criterion, that a few human decision makers performed much better than this standard. So the search is always for this top performance to be modelled and automated by a DSS. This is particularly important when the business is dealing with many thousands of stock keeping units all of which need to be kept under control. In such a situation the DSS need to operate automatically for the mast majority of items. While ICT offers the opportunity for greater supply chain transparency it also creates an even more complex environment so that when people do have to intervene, the decision-making is even more difficult.

WHAT WE DON'T KNOW: GAPS IN OUR UNDERSTANDING AND PRIORITIES FOR RESEARCH

We still do not understand the dynamic implications of ordering structures and rules afforded by different ICT current and future scenarios. Historically a number of authors have developed dynamic model representations of innovative system structures and have described their behaviour. Although a number of these models were physically infeasible or too costly to implement at the time, with current ICT innovations there is a need to revisit them.

An example of a hierarchy within a known system structure for a decision rule within a single business unit of analysis (managing many process streams) is given in Figure 7 (Evans et al., 1998). The figure shows the progressive development of the system structure. Each additional information source added in the system structure, whilst having the potential for improved dynamic behaviour, increases complexity. Therefore the benefits of increased information flow must outweigh the potential for the system to go unstable either if it is not;

a) designed properly

b) robust to parameter drift

A comprehensive hierarchical suite of system structures needs to be derived and tested that determine the ordering and inventory policy requirements for various units of analysis with due consideration of varying market and operational environments. This coincides with Hill's (2000) order-winner and market-qualifier criteria and the trade off considerations required in process choice. The latter has recently been consolidated within a supply chain context and related to the lean and agile characteristics (Naylor et al., 1999).

Different units of analysis need to be considered. At the lowest level we may analyse individual activities that constitute a work process which in themselves aggregate to a business process (Watson, 1994). Further aggregation yields an entire business unit, dyadic relationship, supply chain and ultimately a whole supply network as indicated in Figure 8 (based on Harland, 1996).

FUTURE KEY DEVELOPMENTS

The chapter highlights the need for systematic approaches to the introduction of ICT in the supply chain. An important phase in many change programmes is the need to simplify existing complex operations. As a Director of Reckitt and Colman stated (Parmenter, 1989).

"Good managers can manage complexity but better managers simplify"

The simplicity paradigm is a powerful model but only within an overall systematic regime. Without understanding what needs to be simplified and how it can be done, can again be detrimental to effective operations (de Bono, 1998).

We propose the approach recently highlighted by Tomke (2001) in the area of product design innovation but to be applied here in the area for supply system design innovation. The ability to develop synthetic environments via behavioural, analytical and simulation tools allows "crashes" to be performed early on in the innovation process prior to their piloting or implementation in the "real-world". An innovation process should develop synthetic environments to allow experimentation with different supply system architectures to aid in detecting counter intuitive behaviour (Tomke, 2001, Sterman, 1989) and spurring even greater innovation. Tomke (in line with the system dynamics movement, e.g. Wolstenholme, 1990) also highlights the impact of synthetic environments in developing the spirit of enquiry in multidisciplinary teams.

Appropriate, sustainable and adaptable innovation processes will thus be developed incorporating strategic design tools. It may be feasible to develop the models outside of the innovation process and implement them within the planning and operation order fulfilment process. Thus, "real-time" models, interfacing with the latest ICT developments that capture information of the different supply system states, such as production rates, inventory levels and work-in-progress levels, will ensure the efficient, efficacious and effective flow of materials throughout the supply chain. Novel and innovative system structures and evaluation tools need to be developed that consider the dichotomy of increased information flows versus increased complexity in the supply system. These will challenge or validate the suppositions of complexity theory and ascertain the role of control theory in deriving "optimal" solutions.

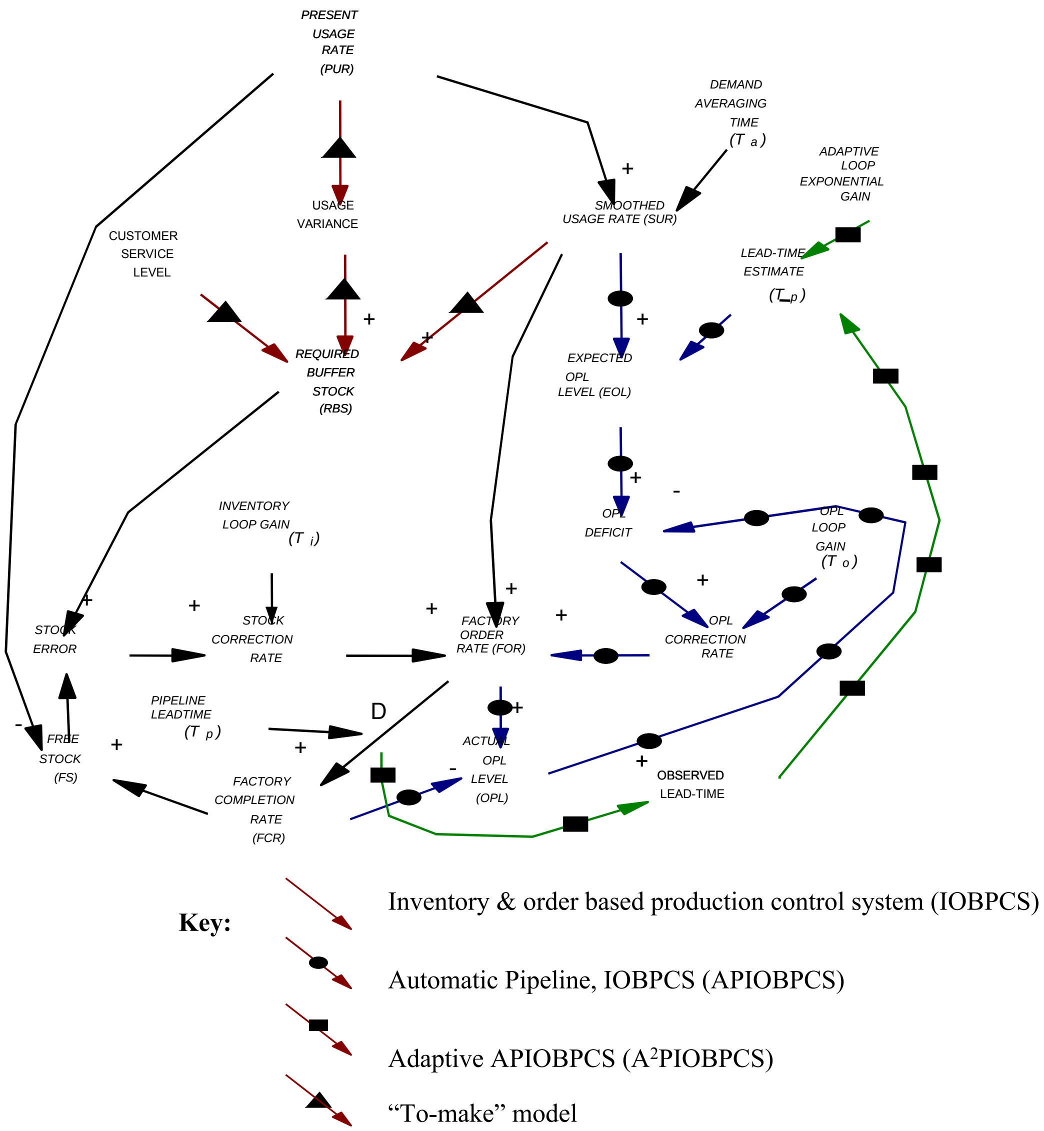


Figure 7 Hierarchy within an adaptive ordering and inventory control model (Evans et al., 1998)

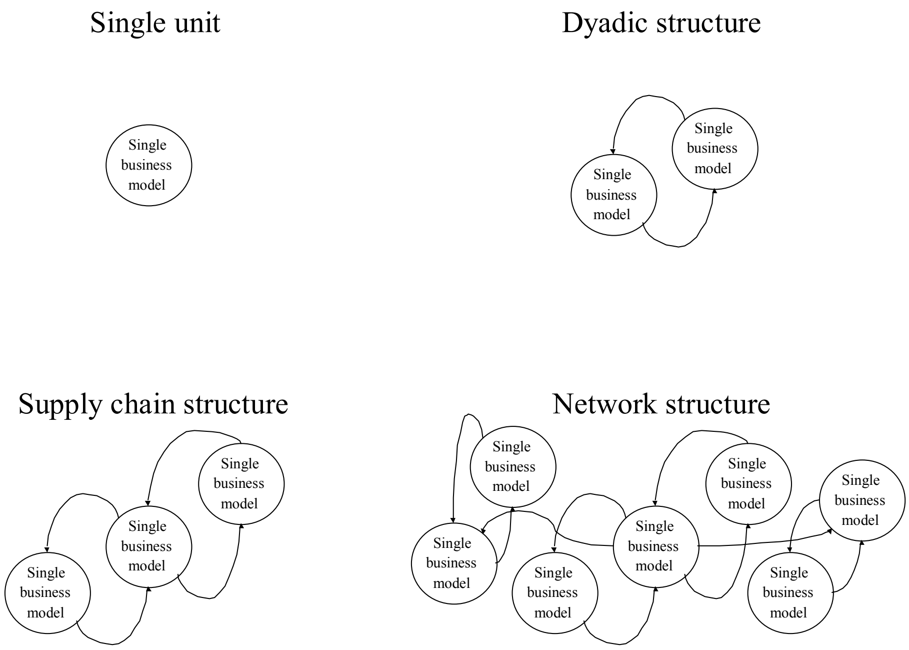


Figure 8 Supply system units of analysis (based on Harland, 1996)

By "optimal" we mean systems that meet a number of criteria including satisfying customer value requirements (summarised as, cost, lead-time, service and quality), making the best use of operational capabilities (such as capacity limitations and human resource capabilities) and ensuring robustness to exogenous and endogenous perturbations.

Through the development of archetypes a "system of systems" will be developed. Each level of aggregation will have defined dynamic behaviour characteristics related to organisational behaviour models, ICT frameworks, management principles and various financial forms. A case based schema that manages to incorporate the intricacies of the archetypes needs to be developed. Artificial intelligence tools, with the associated theoretical infrastructure, such decision theories, probability theory and set theory, will have to be developed to manage the possible complexity of the archetype knowledge base.

The substantive theory underpinning this chapter, and indeed the whole book, is General Systems Theory. This may be summarised as "Gestalt" – the whole is greater than the sum of the individual parts. GST should pervade all branches of science and all human endeavours. It should encompass not only our working environment but also all our social relationships. This will enhance the process approach and develop the social capital needed to sustain integrated supply systems. Within the specific area of supply chain dynamics modelling and simulation there are specific technical core competencies that either have to be embedded within an organisation or "bought in" through appropriate routes. This means the development of system engineers with the ability to relate GST, analytical studies and practical operations.

THE SCOPE MODEL AS A RESEARCH PLATFORM

A robust research framework, based on an holistic approach, is required to support the above future research needs. The unit of analysis previously described is just one dimension of the scope of the research platform we propose. Supply chain dynamics research is in reality a three dimensional problem. Figure 9 shows the ***Scope Model*** developed for this purpose (Evans et al 1999) that describes;

Breadth – the primary axis that determines the unit of analysis as already discussed

Width – that determines the flows to be considered in any given unit of analysis

Depth – the change management factors that enable the implementation of innovative solutions. The depth dimension highlights the need for multi-disciplinary teams in undertaking the research.

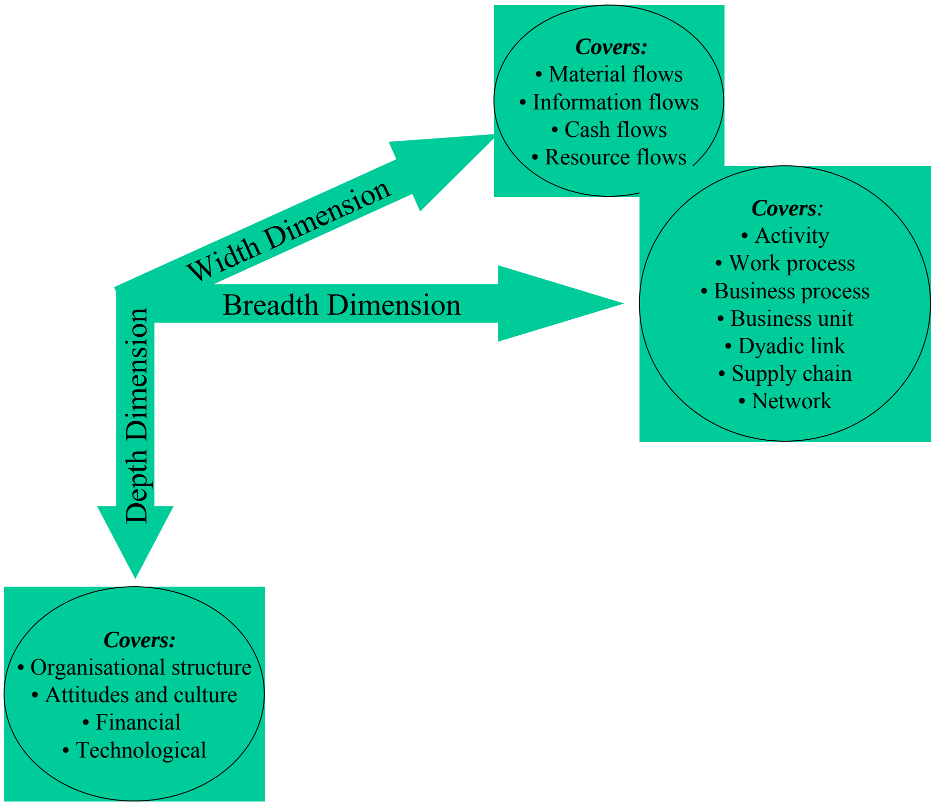


Figure 9: The Scope Model as a Platform for Supply System Dynamics Research (based on Evans et al., 1999)

This Scope Model emphasises that tackling individual elements is a supply chain will have limited benefit to the chain as a whole (Hall et al., 1993). Instead a holistic approach is required which integrates along each dimension, and yet simultaneously welds the activities across dimensions. The Scope Model makes it transparent, for example, that material flows cannot be managed in isolation of each other. But neither can they be managed just within discrete functional silos if the total chain is to benefit. And all this is pointless without the right supporting organisational, financial, technological, and cultured infrastructure.

Computer packages, coupled with increased computing power are now available that are specifically designed to study the dynamic performance of supply chains. This allows a step change in sophistication that can be incorporated into a control systems' analysis. This has come at a time when computers have also enabled sophisticated control systems to be developed (such as VMI), as ICT allows efficient gathering and distributing of large amounts of information.

Such research will for the first time quantify the benefits of ICT technologies, such as eBusiness, on product delivery from raw materials to the end customer. It will take "hard" analytical studies and relate them to the current and future scenarios envisaged for ICT enabled customer-driven enterprises. A research process will have to be defined that incorporates fundamental concepts and theories, action research and development, implementation changes programmes, and monitoring studies.

CONSEQUENCES AND CONCLUSIONS

This chapter has indicated the extent of our current knowledge base in the field of supply chain dynamics. There is an abundant and rich history to the modelling and synthesis of supply control systems going back at least 50 years. Mathematical and simulation techniques originally developed for the design and control of hardware systems have found applications in production, inventory and ordering systems.

It is our view that the "social capital" associated with our field of endeavour is almost lost to us as the technical knowledge base of the UK, and in fact much of the Western world, has differentiated between "engineering" and "management". A number of organisations do have the competencies to undertake the analytical studies required and implement them in their operations. Unfortunately, such organisations are few and far between. As Sir Karl Popper said "It is often better to be vaguely right than precisely wrong". In focusing on computers for data processing we may be in danger of overlooking those principles of system design which guarantee stable and successful operation. In other words we see the detail at the expense of the architecture.

The problem of system complexity is very real and as we have shown has the potential to increase with the addition of ICT enabled data flows. Solutions have to be developed that not only strive to cope with complexity but also must endeavour to simplify where possible. Horizontal research studies will not shed any light on such matters due to averaging effects (Fisher, 1997). Vertical and longitudinal action research is required to address the operational realities of organisations (Coughlan & Coghlan, 2002). Emerging paradigms will be tested using a procedure already evaluated on the Time Compression Principle (Towill, 1999).

The research will requires a breadth of disciplines and approaches involving both observation and problem solving. The research will bring together

- Business and management studies
- Systems and process thinking
- Engineering and technology

i.e. there is a need for Business Systems Engineering of ICT enabled supply systems.

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