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DOCTORAL THESIS

The impact of supply chain performance measurement systems on dynamic behaviour in supply chains

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THE IMPACT OF SUPPLY CHAIN PERFORMANCE MEASUREMENT SYSTEMS ON DYNAMIC BEHAVIOUR IN SUPPLY CHAINS.

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THESIS SUMMARY

The amplification of demand variation up a supply chain widely termed 'the Bullwhip Effect' is disruptive, costly and something that supply chain management generally seeks to minimise. Originally attributed to poor system design; deficiencies in policies, organisation structure and delays in material and information flow all lead to sub-optimal reorder point calculation. It has since been attributed to exogenous random factors such as: uncertainties in demand, supply and distribution lead time but these causes are not exclusive as academic and operational studies since have shown that orders and/or inventories can exhibit significant variability even if customer demand and lead time are deterministic. This increase in the range of possible causes of dynamic behaviour indicates that our understanding of the phenomenon is far from complete.

One possible, yet previously unexplored, factor that may influence dynamic behaviour in supply chains is the application and operation of supply chain performance measures. Organisations monitoring and responding to their adopted key performance metrics will make operational changes and this action may influence the level of dynamics within the supply chain, possibly degrading the performance of the very system they were intended to measure.

In order to explore this a plausible abstraction of the operational responses to the Supply Chain Council's SCOR® (Supply Chain Operations Reference) model was incorporated into a classic Beer Game distribution representation, using the dynamic discrete event simulation software Simul8. During the simulation the five SCOR Supply Chain Performance Attributes: Reliability, Responsiveness, Flexibility, Cost and Utilisation were continuously monitored and compared to established targets. Operational adjustments to the; reorder point, transportation modes and production capacity (where appropriate) for three independent supply chain roles were made and the degree of dynamic behaviour in the Supply Chain measured, using the ratio of the standard deviation of upstream demand relative to the standard deviation of the downstream demand.

Factors employed to build the detailed model include: variable retail demand, order transmission, transportation delays, production delays, capacity constraints demand multipliers and demand averaging periods. Five dimensions of supply chain performance were monitored independently in three autonomous supply chain roles and operational settings adjusted accordingly.

Uniqueness of this research stems from the application of the five SCOR performance attributes with modelled operational responses in a dynamic discrete event simulation model. This project makes its primary contribution to knowledge by measuring the impact, on supply chain dynamics, of applying a representative performance measurement system.

Keywords: Bullwhip, Demand Amplification, Supply Chain Performance Measurement, Dynamic Discrete Event Simulation, SCOR.

DEDICATION

Dedicated to my family, especially my beautiful wife Ellie and our fabulous children Oliver and Joseph.

Thank you for all the fun, patience, support and understanding. Without the wonderful distractions I never would have finished.

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Mention should also go to Miles Weaver of De Montford University for his mutual support with my best wishes with the imminent submission of his own PhD, and to Prof Don Taylor, Virginia Tech, for the great fun during the joint work in related areas.

LIST OF RELATED PUBLICATIONS AND REPORTS

ALBORES, P., LOVE, D., WEAVER, M., STONE, J. & BENTON, H. (2006). “An evaluation of SCOR modelling tools and techniques”. Proceedings of the Second European Conference on the Management of Technology. Aston Business School, Birmingham, UK.

STONE, J. and LOVE, D. (2007). “Modelling the relationship between local logistics management decisions and overall supply chain performance: a research agenda”. International Journal of Business Performance Management, Volume 9, Issue 2, Pages 240-252.

TAYLOR G.D., Doug M. LOVE D.M, WEAVER M.W., STONE J (2008) “Determining Inventory Service Support Levels in Multi-National Companies” International Journal of Production Economics – Volume 116, Issue 1, Pages 1-11.

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1. INTRODUCTION

This chapter presents the objectives of supply chain management as a backdrop to the performance measurement systems that exist to support them. The subject of dynamics in the supply chain is discussed and the relationship between dynamics and performance measurement is outlined, finally the research objectives are laid out.

The issue of transmission of dynamics and instability up supply chains has been widely observed in the literature (Towill and Naim 1993); (Houlihan 1985); (Sterman 1989) (Towill and Naim,1993; Houlihan, 1985 and Sterman, 1989). It is largely perceived as a disruptive and negative phenomenon, leading to increasing inventories a degradation of service levels and higher costs. It has been associated to date largely with a body of literature in the general subject area of the *Bullwhip Effect*.

Despite the considerable amount of published material on the subject to date, the recurring theme from both academics and practitioners alike is that the subject requires further study. “The scientific development of supply chain management requires that advancements be made in the development of theoretical models to inform our understanding of supply chain phenomena” (Croom, Romano et al. 2000).

Running in parallel to the development of our understanding in Supply Chain Dynamics, is the development of Supply Chain Performance Measures. Opinion is more widely spread in this body of literature, probably reflecting the range of objectives being satisfied by such measures. The consensus of opinion on the ideal supply chain performance measurement system would include a range of well-defined metrics that can be readily communicated between roles in the supply chain and facilitate continuous improvement.

The fundamental objective of this research is to investigate whether the use of such performance measurement systems actually influences the level of dynamic behaviour in the supply chain, thus degrading the performance of the very systems they seek to improve.

1.1 Supply Chain Management

By definition supply chains do not exist in isolation, they are structures that describe the interrelation of material and information between systems. In the last century however, the aggressive globalisation of markets and supply sources, intensifying competition and an increasing emphasis on customer focus are cited as being the catalyst to a rise in interest in supply chain management (Gunasekaran, Patel et al. 2001; Webster and Lane 2002).

According to Kasi (2005) ‘a supply chain is a set of activities (e.g. manufacturing, distribution) with inputs (e.g. raw materials) and outputs (e.g. finished goods) to achieve a common business objective (low cost, customer satisfaction, etc.)’. Many other definitions of supply chain management exist but the common theme in most is the focus on the external environment of an organisation (Croom, Romano et al. 2000). Supply chains can be simple structures of time and frequency distributions but in general they tend to be complex, owing to the presence of multiple autonomous organisations, functions and people set within a dynamic environment (Van der Zee and Van der Vorst 2005).

The objective of *supply chain management* is “to satisfy the end customer requirements” (Childerhouse and Towill 2000) and the focus is on how organisations utilise the processes, technology, and capability of suppliers to enhance their own competitive advantage. Supply chain management research generally focuses on improving the efficiency and competitive advantage of manufacturers by taking advantage of the immediate supplier's capability (Tan 2001) .

1.1.1 Supply chain perspective

In theory, without an appreciation of the requirement for supply chain management, each echelon in a supply chain would operate independently. Operators at each stage would make decisions based on their own requirements and objectives with little consideration for the constraints imposed on successive echelons, each role attempting to optimise its own operations in isolation. A sequence of locally optimised systems however, does not necessarily constitute a global optimum (Riddalls, Bennett et al. 2000). For example, the logistics of low cost component production usually favour large batch sizes, yet manufacturers like to operate very small inventories to minimize costs and retain the flexibility to change product lines. These competing requirements can only be reconciled through consideration of the supply chain as a single entity (Riddalls, Bennett et al. 2000).

Service providers frequently offer final assembly, packaging and call centre services. In doing so they adopt some of the functions of the manufacturer contributing to the dependence of the manufacturer on third party performance (Van Hoek 2001). Supply chain practices thus apply equally to service industries, as the practice of placing greater emphasis on suppliers is not restricted to manufacturers. Retailers take every opportunity to pass activities such as; quality control, procurement, storage and distribution ‘upstream’. Whether the supermarkets are altruistically attempting to remove waste from the supply chain or simply moving it to some other incumbent is still open to debate. Many suppliers are sceptical over the retailers' approach to partnerships, pointing at the central role of frequently rotated buyers, making it difficult to build long-term relationship. Information sharing remains limited, even with dedicated suppliers - Tesco actually charging their suppliers for Electronic Point of Sale (EPOS) data (Fearne and Hughes 1999).

Such examples highlight the fact that development in the field needs to continue as failures in supply chain management that are still common (Childerhouse and Towill 2000) with apparent gaps between the needs of companies and the wealth of available best practices (Van Landeghem and Persoons 2001). For example, Deloitte Consulting reported that only 2 per cent of North American manufacturers ranked their supply chains as world class, despite 91 per cent viewing supply chain management as important, or critical, to organizational success (Shepherd and Gunter 2006).

This leads us to a point where we need to define not Supply Chain Management but rather "Supply Chain Orientation" - the recognition by an organisation of the strategic implications of the tactical activities involved in managing the various flows in a supply chain (Mentzer, DeWitt et al. 2001). A company has 'supply chain orientation' if its management can see the implications of managing the upstream and downstream flows of products, services, finances and information across their suppliers and their customers. Such a perspective is definitely not short-term, "effective supply chain management is treated as key to building sustainable competitive edge through improved inter and intra-firm relationships" (Shepherd and Gunter 2006).

Supply chain management as a strategy to integrate business processes over multiple firms (as opposed to merely taking advantage of suppliers) features in some of the more progressive definitions (Venkateswaran, Son et al. 2002). At company level there is a progressive shift towards an external perspective with the design and implementation of new management strategies. Unfortunately there are still evident hurdles to overcome, mainly due to the major complexity of the problems to be tackled in a logistics network and to the conflicts resulting from local objectives versus network strategies (Terzi and Cavalieri 2004).

Many of the techniques employed in supply chain management have one common goal 'to create a transparent, visible demand pattern that paces the entire supply chain' (Childerhouse and Towill 2000) i.e. minimise disruptive, dynamic, supply chain behaviour.

1.2 Supply Chain Dynamics

The dynamics within the supply chain can be attributed to two distinct sources, those caused by the dynamic external environment and those due to the design and internal mechanisms within the system.

1.2.1 External environment and dynamic behaviour

Manufacturers no longer control the pace at which products are developed, manufactured and distributed (Stewart 1997). Consumers now impose increasing demands on manufacturers for variety, quick order fulfilment and fast delivery. International competition and consumers demanding a greater diversity of products make demand far more capricious, with shorter product life spans and with greater demand variation (Riddalls, Bennett et al. 2000). The internationalisation and globalisation of markets further exacerbate the problems, offering companies greater possibility to diversify their supply, production and distribution networks. Facing a plethoric supply, customers become more demanding and volatile (Labarthe, Espinasse et al. 2007).

Furthermore, since the balance of power in many supply chains has shifted towards retailers, changing demand patterns are communicated extremely quickly (using Electronic Point of Sale Data) and extremely fast and cost effective logistics systems maintain availability of product.

With the competitive differentiator of quality becoming a market qualifier rather than a market winner, meeting these varied customer demands has emerged as the critical opportunity for competitive advantage.

The changing and ever more volatile external environment has influenced; the design, operation and objectives of supply chain systems (Beamon and Ware 1998). Organizational change and improvement (Kasi 2005) and supply chain design and operating policy (Wilding 1998) remain prominent themes within the practitioner and academic research community.

To maintain competitive advantage organisations are constantly made to redirect resources and refocus on the enhancement of product features such as; quality, cost, options and services (Stewart 1997), flexibility (Ding, Benyoucef et al. 2004) and responsiveness (Christopher 1999). As if this were not enough, the changes are not uniform across sector, industry or geographical region. Companies operate in different industries, in different markets, on different segments with different customer requirements in each (Kamann and Bakker 2004). The net effect of an ever more volatile environment is that all levels of dynamic behaviour in the supply chain is likely to increase

1.2.2 Supply Chain design and dynamic behaviour.

The term supply chain generally encompasses the network of organisations within a distribution channel. Each role in the network see Fig 1 being connected by the flow of material in one direction and the flow of information (orders) and payments in the other direction,.

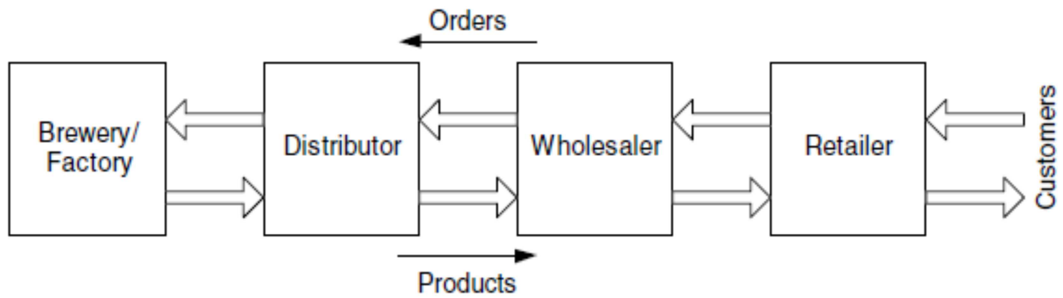

Figure 1. Classic Beer Game Model; source various.

Changes in any one of these components usually creates ‘waves of influence’ that propagate throughout the supply chain. These waves are reflected in prices, flows of material and inventory levels. How these influences propagate through the system determines the “dynamics” of the supply chain (Group 2007).

Throughout the supply chain, there exist various types of uncertainties, e.g., demand uncertainty, production uncertainty, and delivery uncertainty. Making decisions as to how much and when to replenish, often involves a feedback process triggering interaction between system entities (Hwarng and Xie 2008). The time delay observed between decision and effect further complicates the interaction between these system entities.

Bhaskaran (1998) used a simulation model to investigate the transmission of dynamics in an auto assembly supply chain and concluded that controlling or dampening this effect is essential for good supply chain management as stable supplier forecasts lead to reduced inventory levels.

His work largely focused in a manufacturing environment and gives a useful insight into how the scale of dynamics might be assessed. *"Dynamics refers to changes in production rates over time; a schedule has low dynamics if it has a constant operating rate or if rates change gradually over time to accommodate trends"*. Limiting the transmission of variability and/or the dampening of the scale of the variability along a supply chain is a fundamental objective of supply chain management.

1.3 The Bullwhip Effect

The Bullwhip effect is one of the earliest generic supply chain phenomena to be recognized and documented and remains a key area of research in the field. A Google Scholar™ search on the "Bullwhip effect" today will return more than 11,000 references and it is a standard term employed throughout industry.

Demand distortion is a name given to the phenomenon whereby purchase orders to suppliers have a larger variance than sales orders received from customers within a single node or decision point in the supply chain. Variance amplification occurs when this demand distortion "propagates upstream in an amplified form" (Lee, Padmanabhan et al. 1997). Collectively known as the "Bullwhip Effect" (since the oscillating demand magnification upstream is reminiscent of a cracking whip) it was first discussed in these terms in 1961 (Forrester and Wright 1961) and is also known as Forrester or whiplash effect. The expressions demand amplification, bullwhip effect, and dynamics are effectively used interchangeably in practice.

A classic interpretation of demand amplification, by observing that the feedback loops inherent in supply chains create a flywheel effect, was coined by Houlihan (1985) and termed the 'Forrester Flywheel'.

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Figure 2.Forrester Flywheel. source; Houlihan, 1985

Upswings in demand create a perceived shortage somewhere along the chain. This may simply be inventory falling below a target level. Lacking an overview of the entire supply chain, the company concerned then over-orders to protect itself against further fluctuations. This increase in orders triggers further localized protection since it is misinterpreted as real extra orders.

The Forrester Flywheel helped demonstrate that one cause of demand amplification is the internal feedback mechanism, rather than something external to the system (Towill, Zhou et al. 2007). More recent studies have shown (Hwarng and Xie 2008) that orders or inventories may exhibit significant variability even if customer demand and lead time are deterministic, consequently this variability must be caused by some internal mechanism or behaviour. Customer demand may be extremely volatile, information may be delayed and transport and production restrictions might apply, but there is a self-induced worsening of any given situation.

One notable piece of industrial research (Taylor 2000) was the LEAP project - Lean Processing Programme, a three-year research project which commenced in 1997. The project introduced lean supply systems into the upstream automotive component supply chain in the UK, from British Steel Strip Products. This work offers an almost unique insight from a commercial study of dynamic supply chain behaviour, where changes within an organisation were mapped over time, rather than snapshot or simulation. The successful results mentioned; more regular demand patterns, lower inventory, better customer service etc. all come with the caveats that further work is required. What is apparent however is that Demand Amplification was not eradicated and the situation in practice appeared more complex than current theory had predicted.

In many cases supply chain dynamics demonstrate cyclical fluctuations and instability. These fluctuations are typically a result of; information delays (e.g. orders based on inventory information that is several weeks old) and inertia (once orders are there is a delay before the production rate can be changed). The wave of dynamic behaviour is not restricted to travelling back up the supply chain however as many authors describe waves flowing in both directions; Sterman (1989), Hines, Holweg et al. (2000) and Holweg and Bicheno (2002). Bullwhip can induce a second wave of uncertainty - the effect of the ‘supply-wave' or reverse amplification, whereby roles in the middle of the chain get hit by waves from both sides. From the customers' side amplified and distorted demand information is received (the demand wave), hence additional material is being ordered from the supplier to cope with the increase in demand. However, once the initial backlog towards the customer has been cleared, the customer reduces his orders to a normal level or even stops ordering at all. However, since supply orders have been placed, the player will be hit by the second ‘supply' wave, once the ordered material is supplied. The longer the order-to-delivery lead-time from the supplier, the worse this second wave will be.

To counter demand amplification, companies typically increase their buffer/safety inventories in an attempt to smooth production rates. Unfortunately, if this is not done in a coordinated manner, every company in the chain can end up holding ‘safety stock’ against the same contingency. These extra levels of stock also serve to cloud further the perception of any genuine demand fluctuation (Riddalls, Bennett et al. 2000).
The importance of Supply Chain dynamics is clearly evident. Elimination of demand amplification could remove a major cause of the uncertainty and variability which creates fundamental problems for Supply Chain Management (Taylor 2000).

Apparent in over 40 years of academic literature however, is the recurring acknowledgement that the debate on the subject is far from complete. Either communication of the necessary solutions is incomplete “bullwhip tends to be misunderstood” (Lee, Padmanabhan et al. 1997) or the necessary motivation to address the problem is not present (McCullen and Towill 2002) but research around the Bullwhip Effect has certainly not diminished - indeed the topic has increased in importance (Torres and Morán 2006).

1.4 Supply Chain Performance Measurement and dynamic behaviour.

The success of the individual organisation is dependent upon the management of its supply chain (Christopher 1999); in fact it is largely dependent on the performance of its suppliers. Yet typically organisations within the supply chain operate independently with their own objectives which can differ from, even to the point of being antagonistic to, the objectives of their supply chain partners. Due largely to the limited time in which companies can develop trust (Campbell, Goold et al. 1995) it is widely accepted that supply chains require common systems to integrating, *measuring* and controlling key business processes (Childerhouse and Towill 2000).

A performance measurement system provides the information necessary for effective planning and control, decision making and actions. Kleijnen (1993) describes the feedback principle in the context of supply chain performance measurement “A manager compares a target value for a specific performance metric with its realization, and in case of undesirable deviation this manager takes corrective action”.
This feedback principle links an operational response in the supply chain to a given current Key Performance Indicator (KPI). A ‘gap’ between the current KPI value and the established target, triggers changes in local policy and parameters in order to close the gap, thus maintaining the KPI(s) at the required value.
In this respect there is direct pressure placed on responsible parties to bring an errant KPI back within acceptable parameters. Since so much of supply chain management

involves ‘suppliers’ it is not surprising that supplier performance measurement practices, and even supplier selection practices, make full use of such systems - ensuring that any variation in service that causes a degradation of performance is rectified by the supplier. The measurement of performance is a critical concern when third parties penetrate functional areas (Van Hoek, 2001).

At this stage two significant aspects of performance measurement can be introduced.

- The first is the mechanism used to select the ‘objective metrics’ from the range of possible KPI’s. It is recognized (Webster and Lane 2002) that there are an almost unlimited number of factors that contribute to system performance in both general and specific cases. Some of the target values for individual KPI’s may vary with time (seasonality, etc) but also the relative importance of individual KPI’s within the set will change over time reflecting business priorities (e.g. gain market share or maximise profit). With customer requirements potentially differing by sector, geography and product type and those requirements developing over the life cycle of the product and reflecting evolving customer requirements, the challenge of hitting a moving performance target’ become significant. Many methodologies are unable to account for the relative importance of performance measures, which varies among firms (Easton, Murphy et al. 2002).

- The second is the challenge of predicting the measured effect of individual activities on specific KPI’s and the interrelationship between KPI’s. Very few activities are independent in the supply chain and students of the discipline will learn the basic concept of a trade-off analysis at an early stage in their education. Some KPI’s actually demonstrate antagonistic characteristics with others; increased service often incurs decreased profit. Demand pattern, ordering policy, lead time, and information sharing all have direct impact on the performance of supply chains, Chen, Drezner et al. (2000) & Lee, Padmanabhan et al. (1997. There is no account in the literature of the mechanism that allows organisations to predict the change across a range of KPI’s as a result of specific activities. This problem is compounded as each supplier-customer relationship has a different mechanism and each mechanism changes over time.

As with the Bullwhip effect, the academic literature acknowledges that much remains to be done in the area of supply chain performance measurement and whilst the area is possibly more strategically important, it still is not yet sufficiently understood (Holmberg 2000). Although Supply Chain Management has become common practice across all industries, the topic of performance measurement in the supply chain does not receive adequate attention (Chan, Qi et al. 2003).

1.5 Background to this Research

Because experiments involving the Bullwhip Effect are difficult to assess in an operational context a variety of simulation models have often been used ranging from; spread sheets, system dynamics, business gaming and Discrete Event Dynamic Simulation. An account of the criteria for selecting an appropriate method is given later but recent examples of associated research include the following;

- Lee and Billington (1993) simulate a typical decentralized supply chain and utilise the feature whereby each individual player in the supply chain makes decisions based on locally available information.
- Venkateswaran, Son et al. (2002) compare a range of supply chain strategies and examine a range of outputs including the dynamics of the supply chain in order to determine the best strategy.
- Hwarng and Xie (2008) characterise a classical beer distribution model with some modifications and observe the supply chain dynamics under the influence of various factors: demand pattern, ordering policy, demand-information sharing and lead time.

This work seeks to explore if the application of a Supply Chain Performance Measurement System (SCPMS) has an impact upon the levels of dynamic behaviour in the Supply Chain. Since no comprehensive, supply chain wide, performance framework exists for driving local decisions (Stone and Love 2007), a representative system must be identified. In this case a representative Supply Chain, incorporating related and widely referenced features of dynamic behaviour (such as the Bullwhip effect) must be examined with and without a Supply Chain performance measurement system. Via a series of experiments, the dynamic effect of the application of the performance system could then be tested and examined.

If the simulated effect of the application of such a performance measurement system leads to changes in the dynamic behaviour in the model, this would imply that our understanding and representation of the application of performance measurement systems was previously deficient and that practitioners could be applying such systems without appreciating the consequences of their actions.

1.5.1 Research Aims and Objectives

This research aims to:

1. To identify a representative performance measurement framework and abstract the symptomatic operational responses that an organisation would make, in response to variations in the Key Performance Indicators (KPI's).

2. Construct a tested simulation model of a supply chain which incorporates a valid representation of a typical SCPMS with operational responses to the range of KPI's, including the on-going reprioritising of operations in response to various and changing aspects of performance.

3. Conduct effective verification, validation and sensitivity analysis on the model and its variable parameters thus exemplifying the importance of a detailed and realistic supply chain model on the quality of results obtained.

4. Analyse the dynamics of the model across a range of variables and test if a SCPMS has a measured impact on the level of dynamics within the supply chain.

1.6 Conclusion

The success of the individual organisation is dependent upon the management of its supply chain; in fact it is dependent on the performance of suppliers (Christopher 1999). Supply Chain Management principles often involve taking direct advantage of the capabilities of suppliers whilst seeking to minimise dynamic behaviour in the supply chain.

SCPMS's are seldom passive instruments and are often applied to support Supply Chain Management via feedback mechanisms that instigate corrective actions. The direction and particularly the amplitude of the likely management action/response however has not been defined. 'There exists a recognised need for some universally accepted strategic model to coordinate the organisations within the supply chain, integrating, measuring and controlling key business processes effectively' (Childerhouse and Towill 2000), but to date any measured impact of the performance measurement element within such a systems, on the dynamic behaviour within the supply chain, has yet to be examined.

2. DYNAMIC BEHAVIOUR IN SUPPLY CHAINS

In this chapter the development of theories explaining dynamic supply chain behaviour are laid out.

2.1 Development of the Bullwhip Theory

The Bullwhip Effect is not a new supply chain phenomenon. (Schmenner 2001) provides a historical overview of the topic. There is even an account in the literature of artificially amplified orders passing upstream published as far back as the 1920's.

''Retailers find that there is a shortage of merchandise at their sources of supply. Manufacturers inform them that it is with regret that they are able to fill their orders only to the extent of 80 per cent: there has been an unaccountable shortage of materials that has prevented them from producing to their full capacity. They hope to be able to give full service next season, by which time, no doubt, these unexplainable conditions will have been remedied. However, retailers, having been disappointed in deliveries and lost 20 per cent or more of their possible profits thereby, are not going to be caught that way again.
During the season they have tried with little success to obtain supplies from other sources. But next season, if they want 90 units of an article, they order 100, so as to be sure, each, of getting the 90 in the pro rata share delivered. Probably they are disappointed a second time. Hence they increase the margins of their orders over what they desire, in order that their pro rata shares shall be for each the full 100 per cent that he really wants. Furthermore, to make doubly sure, each merchant spreads his orders over more sources of supply.'' (Mitchell 1924).

Whilst Mitchell was indeed describing the bullwhip effect as generated via "shortage gaming" (see 2.2) for detail. But it was not until the 1960's that this effect was studied academically and suggestions for a root cause were proposed.

2.1.1 From the origins of System Dynamics

One key individuals name is synonymous with the Bullwhip effect - Jay Wright Forrester. An appreciation of his academic background adds richness and insight into the origins of his explanations. Born 14/07/1918 he initially went to Engineering College at the University of Nebraska to study Electrical Engineering. In 1939 he went to the Massachusetts Institute of Technology (MIT) to become a research assistant and actually spent his entire career there. Initially he worked on feedback control systems in servomechanisms, in the war years he worked on their application in the control of radar antennas in naval gun mounts at Pearl Harbour, later he also worked in flight simulation.

In 1956 Forrester moved to the MIT Sloan School of Management, where he became Germeshausen Professor Emeritus and Senior Lecturer. Very quickly applying his engineering view of electrical systems to the field of human systems broke new ground when he used computer simulations to analyze social systems and predict the implications of different models. In 1958 he first identified the demand amplification effect and a few years later he introduced the term 'Industrial Dynamics' (Forrester and Wright 1961) which he defined as "the study of the information-feedback characteristics of industrial activity to show how organisational structure, amplification (in policies) and time delays (in decisions and actions) interact to influence the success of the enterprise". This method came to be called "system dynamics," and Forrester came to be recognized as its creator (Seidmann 1995).

Systems of information feedback control are fundamental to all life and human endeavour; a feedback control system exists whenever the environment causes a decision which in turn affects the original environment' (Forrester and Wright 1961). He also added that complexity leads to the existence of many feedback loops, some of which are unrecognized and undetected and such loops are prone to causing system chaos and breakdown. His acknowledgement that many of these loops are difficult to detect adds weight to the argument in this work – that the negative effect of Supply Chain Performance measurement feedback loops can induce instability in that system, but that their detection to date has not been recognised.

Systems Theory originated in physics and biology but was adopted by business academics in their explanation of organisational systems, organisations and economies (New and Westbrook 2004). A systems theory approach would view a system as a collection of resources and processes existing to meet one overarching objective. The field of operations management has been heavily influenced by this approach and the technique is often applied to enterprises, supply chains and even an entire economy (Slack, Chambers et al. 2007). One aspect of systems theory particularly useful in understanding supply chains is termed Entropy. Unless there is a continuous effort to feedback to a system, with the appropriate inputs, the system has the tendency to debilitate. This gradual and continuous debilitation that leads the system to extinction is called entropy (New and Westbrook 2004). The phenomenon of the 'bullwhip effect' is an illustration of the debilitating effects of poor feedback across the supply chain in that the supply chain cannot continue (competitively) to operate unless some mechanism kicks-in to rectify the problem.

In business operations; orders and stock levels input to manufacturing decisions which satisfy orders and correct inventory levels. Feedback theory explains how; inaccurate forecasts, poor decisions and delays can produce a dramatically unstable operation. Often manufacturing, ordering and transport decisions can actually generate the types of disturbances that would normally be blamed on conditions outside the company. This has since been proved empirically 'Variability in orders or inventories in supply chain systems is not caused by exogenous random factors such as uncertainties in customer demand or lead time' (Hwarng and Xie 2008).

It was partly to investigate the causal relationship between system structure (including feedback loops) and system behaviour that Forrester developed the DYNAMO simulation language and demonstrated that the variability of the order to the manufacturer was usually far greater than the variability of the actual consumer demand. A change in demand being amplified as it passes between organisations in the supply chain. He attributed the cause of this order variability and amplification of demand to irrational behaviour of participants involved in a supply chain, who lacked the holistic view. He also demonstrated that meaningless sales fluctuations can be converted by the system into false seasonality which consequently undermined decision makers. In this respect the behaviour of decision makers in complex systems is counter-intuitive.

Burbridge (1981) published his ‘5 golden rules to avoid bankruptcy' and introduced the concept of ‘multi-phasing' of the information flow. He demonstrated that traditional stock control procedures would tend to amplify variations as demand passed along the chain. Each ordering point considering a demand forecast plus some safety stock consideration before placing (now higher) orders upstream to subsequent order points etc.
It was Burbidge in fact that coined the so called ‘law of industrial dynamics’ which states that; “If demand for products is transmitted along a series of inventories using stock control ordering, then the demand variation will increase with each transfer”.

The term ‘Forridge’ was first coined by Gordon Brace of the Warwick Manufacturing Group, as an expression to describe Towil’s (1997) integration of the Forrester and Burbidge approaches to material flow control. This set of Material Flow Principles describes ‘best practices of communication and material flow in supply chain management’.

Figure 3: ‘Forridge’ triggers to avoid in supply chain design. Source Towill, 1994.

Towill used a systems dynamics approach to develop computer-based simulations of supply chain activity and thereby test various strategies to reduce demand amplification. In particular he explored the impact of current supply chain strategies such as JIT, vendor integration and time-based management on reducing the amplification effect (Towill and Naim 1993; Towill 1996; Towill 1997).

The visible effect of orders to the supplier tending to have larger fluctuations than sales and the resulting distortion propagating upstream in an amplified form can be very concisely portrayed via the use of “propagation curves” (Mason-Jones, Naim et al. 1997).

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Figure 4; Bullwhip Propagation curves. Source Mason-Jones, 1997.

Lee described qualitative evidence of demand amplification in a number of the retailer-distributor-manufacturer chains and then employed mathematical models to demonstrate the impact of decision strategies in creating oscillations in demand. Lee actually attributes the term ``bullwhip effect" to Procter & Gamble experiencing extensive demand amplifications for “Pampers”, the resulting order backlogs and excessive inventories attributed to the phenomenon causing obvious concern (Lee, Padmanabhan et al. 1997). His work is particularly notable as real case study data is actually very rare in the literature.

Two further related threads in the literature are of interest; Geary et al (2006) present a case for the Bullwhip effect on a Macro-Level; the long-wave effect of overexpansion of national production capacity, only to be cut back below normal levels, occurring roughly twice a century. Whether these are the accumulation of organisational level bull-whip or a feature of wider economic activity is not made clear, however the cycle time delays between increased national demand and increased national capacity (capital, plant, labour etc) would replicate Forrester’s classic cycle time delays as a root cause of bull-whip.

Whilst exploring the impact of “chaos” within supply chains, Wilding (1998) demonstrates that computer systems designed to control supply chain activity, because their programmed order mechanisms are simple abstractions of human behaviour, can be inherently unstable and thereby also create demand amplification effects.

2.1.1 Beer Game

Many studies of the bullwhip effect were made by playing the “beer distribution game” (Sterman 1989, Chen and Samroengraja 2000, Jacobs 2000, Chatfield, Kim et al. 2004 and Warburton 2004). Developed as a practical means of communicating their theories by the Systems Dynamics Group at MIT’s Sloan School of Management, the game shows how the inter-relating feedback loops within the supply chain give rise to complex behaviour within what seems to be a very simple business system and has been further developed at other universities (Jeffrey, Jerry et al. 2005).

It has been found that one in four management teams create deterministic chaos in the ordering patterns and inventory levels and that this figure is exacerbated when targets for reduced inventory become extremely ambitious. Participants observe that students have difficulty realising the impact of their ordering decisions particularly because of the time lags between order and delivery. The term “bounded rationality” (Sterman 1989) is used to describe players in the Beer Game attributing the dynamics they experience to external events (i.e. variable end-user demand), when in fact these dynamics were internally generated by their own actions and decisions.

Gaming theory may be an avenue for further study of the impact of performance measurement on supply chain dynamics and certainly for wider communication in teaching, Sterman (1989) continued to suggest that such games are indeed necessary for training operations managers on the bullwhip effect. However as this is the first attempt to explore the impact of supply chain performance measurement on the bullwhip effect, it was considered that more quantitative avenues would be more appropriate.

2.2 Causes of Bullwhip effect

It is probably a matter of opinion just how many individual causes should be present in any list of causes of Bullwhip. Many can be accepted as clear/fundamental causes whereas some, for example *excessive supply-chain echelons* (Sterman 1989), could be argued to merely represent the conditions needed to aggravate the scale of the effect rather than instigate it.

Holweg and Bicheno (2002) present a notable account of the range of contributions in the development of theories explaining the Bullwhip effect, up to the point of their publication, and as such their work is to be regarded as a key reference in the field.

Figure 5: Key literature on Bullwhip. Source Holweg and Bicheno, 2002

The following list represents a summary of causes discussed by all the authors referenced, the first four of which are widely attributed directly to Forrester.

(i) **Control systems**. Bullwhip is primarily a function of decision making in response to variability in incoming demand. As demand varies, decision-makers have a human tendency to over-react to the change. Amounts produced or ordered being exaggerated in order to ensure adequate supply (or avoid overstocking) in future periods. Conversely strong pressure from senior management to minimise inventory for financial reasons could amplify downward swings in demand.

Miragliotta (2006) gives a good critique of various mechanisms and the calculations used in simulations to generate the bullwhip effect, all of which appear to have their own strengths and weaknesses. Incorporating one such referenced and utilised representation of this cause, which can be switched off for experimentation purposes, is considered essential for this work. The mechanism incorporated into ***this*** *simulation model calculates the re-order point as a function of the estimated demand during the period of the anticipated lead time, plus a given quantity of safety stock.*

(ii) **Process time**. The longer the information transmission or material delivery cycle time the greater the effect. In practice this means removing non-value added time from the system. Time lags between the initiation of an action and the consequence of that action cannot be avoided as it always takes time to produce and distribute goods (Disney, Naim et al. 1997).

(iii) **Information transparency**. Providing real-time, accurate data, free of “noise” and “bias” will simultaneously remove information delays and “double-guessing” at multiple decision points. Because electronic data relating to inventories, WIP, flow rates, and orders can now be visible throughout the chain, holistic control via a suitable centralised supply chain planning process should be theoretically possible.

(iv) **Excessive echelons** in the supply chain. Simply by reducing the number of decision locations/possibilities the bullwhip effect can be reduced, whether this is strictly speaking a cause or acknowledgement that the effect can be reduced by actually avoiding it. In a multi-level supply chain various supply chain levels have different visibility or exposure to customer demand, and the amplification of demand or inventory also grows as it moves upstream the supply chain. These factors complicate the chaotic behaviours in a complex supply chain system (Sterman, 1989).

The fifth cause which was implied by Forrester and Wright (1961) but proven by example by Burbidge (1981).

(v) **Event synchronisation**. In Forrester simulations all events are synchronised so that orders and deliveries are visible at discrete points in time. Burbidge showed by reference to multiple customers working on Economic Batch Quantity re-order principles that this produced an emphatic bullwhip effect subsequently eliminated by continuous ordering synchronised throughout the chain.

(vi) **Multiplier effect**. Orders directly multiply in a knock-on effect, usually between product manufacturers and their capital equipment suppliers (Anderson, Fine et al. 2000).

The remaining four causes are widely accredited to Lee, Padmanabhan et al. (1997) but only the first (demand forecast updating) is represented in the Beer Game, the other three could arguably be considered as conditions under which Bullwhip is aggravated as opposed to direct causes;

(vii) **Demand forecast updating**. Attempts to improve forecasts by building in safety factors and trend detection capability may result in bullwhip generation.

(viii) **Order batching**. Full truck load economics or increased month-end activity, time phased aggregation of orders generating ‘‘lumpy’’ demand. Potter and Disney (2006) explored the impact of batch size on the Bullwhip Effect using simulation. Whilst their model considered a supply chain of only two organisations it did include both deterministic and stochastic demand rates and they establish that Bullwhip increases with increasing batch size.

(ix) **Price fluctuations**. Marketing programmes stimulate demand in the short term. As Fisher (1997) demonstrated this effect may cause a backlash by over-ordering so as to take advantage of discounts on offer.

Aston University

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Figure 6; Demand amplification. Source Fisher, 1997

(x) **Shortage Gaming**. As Mitchell (1924) described orders placed to 'hedge' against unpredictable supply.

Forrester and Wright (1961) concluded that the problem of the bullwhip effect stemmed from the system itself with its policies, organisation structure and delays in material and information flow and did not stem from the external forces.

2.3 Consequences of Bullwhip Effect

Stalk (2003) report that the production on-costs, the costs associated with ramping up and down the production level, are proportional to the cube of the deviation about the mean of the production order rate. So demand variation within the factory is amplified to the power of three. Bullwhip induced behaviour is costly not just in terms of stock-out costs and capacity provision but, because there are consequential downturns in demand, stock-holding and obsolescence costs (Metters 1997). *'It is not merely a phenomenon of interest to academics but a source of money haemorrhaging out of supply chains everywhere' (McCullen and Towill 2001).*

Stalk (2003) also provides a case based description of the Bullwhip Effect found in a clothing supply chain with the demand variation typically increasing by an order of 2–1 at each level of the supply chain. Earlier authors point to the challenges in different industries where bullwhip is measured not just at 2:1 amplification but 20:1 and even higher (Holmström 1997).

The positive consequences of effectively tackling the Bullwhip Effect are also discussed in the literature. Geary, Disney et al. (2006) found that for a global mechanical precision product supply chain Bullwhip was typically reduced, via an appropriate Business Process Reengineering Programme, by 50%, and simultaneously stock turn improvements of 2:1 were observed. McCullen and Towill (2001) refer to a similar potential bullwhip reduction of 50%. Metters (1997) advocated that the elimination of the bullwhip effect might increase product profitability by 10–30 percent depending on the specific business environments. In all cases however, despite its importance, 100% elimination of Bullwhip has not been achieved. This is no doubt due to the fact that pan supply chain initiatives are obviously difficult to achieve, but this work postulates that not all causes of Bullwhip have been identified and consequently addressed.

2.4 Solutions to the Bullwhip effect.

Several of the most widely referenced studies (Forrester and Wright 1961; Lee, Padmanabhan et al. 1997; Chen, Drezner et al. 2000) identify the cause of Bullwhip as a lack of supply chain co-ordination. Synchronisation improves the overall supply chain performance, as demand visibility reduces demand amplification (Holweg and Bicheno 2002). However whilst visibility and coordination may assist in managing various backpressures, time lags in manufacture, distribution and ordering make it extremely difficult to manage effectively (Towill, Naim et al. 1992, Van Ackere, Larsen et al. 1993 and Geary, Disney et al. 2006).

Consideration of the practical aspects associated with improved visibility and coordination has also been made;

- Sharing Electronic Point of Sale (EPOS) data, the technological application to the principles of visibility and coordination above (Dejonckheere, Disney et al. 2003, McCullen and Towill 2001 & Chen and Samroengraja 2000). Precisely how to actually benefit from the use of demand visibility is still not well understood (Lapide 1999)

- More effective use of historic demand data provides the same information as information sharing, if both supplier and retailer know the stochastic properties of demand and these do not change over time (Raghunathan 2001).

- The same level of detailed information (if any) cannot be obtained from all of the distribution channels (Stank, Keller et al. 2001). Considering the potential benefits possible via demand visibility, the very limited success achieved to date is rather sobering (Holweg, Disney et al. 2005).

Other suggested solutions to Bullwhip are as follows:

- Lead-time reduction (Forrester and Wright 1961; Lee, Padmanabhan et al. 1997; Anderson, Fine et al. 2000). In some settings the reduction in lead time can have a greater impact on supply chain performance than information sharing (Cachon and Fisher, 2000 and Cachon and Lariviere, 2001).

-

- Reducing Uncertainty, increased levels of uncertainty lead to increased levels of dynamic behaviour (Petrovic 2001 & Swaminathan, Smith et al. 1998).

- Echelon elimination via the implementing Vendor Managed Inventory (VMI) (Disney and Towill 2003)

- Training decision makers for more rational decisions yields improvement (Sterman 1989). However Lee et al. (2004) showed that Bullwhip occurs even in a supply chain where all decisions are made in a completely rational way.

- Designing robust systems that minimize human interactions (Disney and Towill 2003). But recognising that such algorithms (representations of Managerial decision-making rules) need to be appropriately designed (Wilding 1998).

- Appropriate forecasting (Forrester and Wright 1961) and mean and variance of demand estimation (Chen, Drezner et al. 2000).

2.4.1 Measurement of the bullwhip effect

Forrester and Wright (1961) originally displayed Bullwhip as ‘amplification’ of the maximum order made (+10% increase in final demand). They demonstrated the benefit of Bullwhip reduction via a reduction in the reported production peak at manufacturing from +45% to +26% by transmitting the information directly from the customer to the manufacturer.

Supply Chain dynamics has subsequently been measured by increases in standard deviation of demand patterns as they progress up the supply chain (Labarthe, Espinasse et al. 2007). Since Bullwhip could be seen as a step increase in dynamics, the measurement of Bullwhip has also been described in terms of ratios at the interfaces where demand is generated, occasionally in terms of peak value amplification, but more usually in terms of variance; typical amplification ratios observed between two echelons are 2:1 (Towill, Naim et al. 1992) and between four echelons 20:1 (Houlihan 1985).

Holmström (1997) uses aggregate data; averaging the standard deviation of weekly demand relative to average weekly demand or more accurately the ‘coefficient of variation’ (ratio of the standard deviation to the mean σ/μ) being compared pre and post order point.

Other authors point to the increasing degree of forecasting error as a suitable means of measuring Bullwhip (Chen and Samroengraja 2000) the natural inference being that reducing lead times mitigates the bullwhip effect. To this end Zhang (2004) derived the optimum forecasting procedure to minimise the mean-squared forecasting error. One aberration with the use of this measure has been identified (Bhaskaran 1998); because kanban systems are replenishment based and not forecast driven, they do not generate meaningful forecasts for suppliers and thus cause a degradation of stability. In practice the implementation of kanban/Pull mechanisms in supply systems are roundly heralded as extremely foresighted; increasing visibility of consumption/actual demand and reducing the reliance on forecasts altogether.

More recently (Sun and Ren 2005) the 'ratio of standard deviation' has been used simply calculating the variance of 'orders placed' relative to the variance of 'orders received' in order to describe the magnitude of the bullwhip effect. A value for this measure greater than one indicates amplified order variability.

If "$\sigma_{upstream} / \sigma_{downstream} > 1$".... then Demand has been amplified

(Fransoo and Wouters 2000)

The practical measurement of the bullwhip effect entails problems that have to do with the aggregation of data i.e. the isolation of demand data for defined supply chains that are part of a greater supply web. Since there is no standard means to either calculate the period averaged, nor a means to sequence the aggregating of the data, the same basic data can lead to different measurements of bullwhip, so attention must be made to ensure consistent treatment of data in any given study and care taken when comparing different studies.

In considering cumulative or 'Supply-Chain wide' Bullwhip, the effect of using ratios at each interface is spectacular because the measure is multiplicative and not additive. In a three-echelon chain with an amplification of 3:1 across each boundary, the total amplification was actually recorded as 27:1 (Disney, Naim et al. 1997). The counter argument for using the cumulative approach is that it fails to adequately indicate which of the different causes is (chiefly) responsible or which solutions are therefore most relevant.

In this model, since the cause of the Bullwhip effect is extremely important, the standard deviation of demand before each Role, in addition to a comprehensive record of all necessary simulation data, will be used to capture and calculate the cause and scale of any Bullwhip effect.

2.5 Conclusion

The literature does offer the reader an opportunity to appreciate the Bullwhip phenomenon and its components. Many authors over the past forty years have contributed to the discussion of the negative effects and causes of the Bullwhip effect. The seminal work (Forrester and Wright 1961) concluded that the problem of the bullwhip effect stemmed from the system itself with its policies, organization structure and delays in material and information flow and did not stem from the external forces. Whilst many cited causes appear to either compound or aggravate Bullwhip to varying degrees, Forrester’s work is consistently upheld as the significant cause and as such represents such a significant part of the literature concerning dynamic behaviour in supply chains. Inclusion of a representation of Forrester’s ordering mechanism is therefore considered crucial in demonstrating the completeness of an exploration of the application of supply chain performance measures as an additional cause.

A possible measure for the degree of Bullwhip is suggested in the literature, however because it is an aggregate measure, any examination of a newly identified cause of Bullwhip would require that cause to be examined in isolation. As commercial systems do not operate in isolation alternative methods to explore the effect are clearly required.

Studying a cause of Bullwhip via simulation is one candidate for consideration, some authors actually call upon academics and practitioners alike to develop simulation models to solve the Bullwhip problem (Holweg and Bicheno 2002), but a comprehensive treatment of alternative methodologies is presented later in Chapter 6.

A significant quantity of the published research into Bullwhip has utilised the classic Beer Game model, for Supply Chain design purposes, and many authors including Forrester himself (Forrester and Wright 1961) examine the theoretical nature of the subject using simulation. The measured effect of the level of Bullwhip in practice is often lower than that in simulation, implying that models to date may be incomplete.

3 PERFORMANCE MEASUREMENT

When you can measure what you are speaking about, and express it in numbers,
You know something about it . . . . (Lord Kelvin, 1824-1907).

This chapter establishes that supply chain performance measurement systems drive the selection and on-going performance of internal and external suppliers. It also highlights the fact that the measures themselves are still in development and the whole subject of performance measurement is very dynamic in nature.

Systems of performance metrics contain a range of Key Performance Measures (KPI's) many of which are pursuing objectives that are antagonistic to KPI's in the same observed set, for example increased service and reduced cost. The selection of the primary objectives is often a function of the strategic objectives of the organisation and these objectives themselves can change over time.

3.1 Performance Measurement in the Supply Chain

As businesses move into the twenty-first century, the predominant management focus driving many organisations is supply chain management (Brewer and Speh 2000).

These Supply Chains are interdependent in such a way that an individual company's performance affects the performance of other members of the supply chain. Since, a supply chain involves many players and different practices and policies, those complexities result in higher degrees of uncertainty and dynamics within a supply chain (Paik and Bagchi 2007).

Some go even argue that the natural development will be for manufacturing supply chains to change from an order-driven approach to one of capacity booking supported by appropriate search engines (Boughton 2001). In such instances supply chain performance measurement is set to become the dominant operational activity for any organisation.

With the increasing significance in the role of suppliers, supplier management is becoming paramount. In industrial companies the purchasing share in the total turnover typically ranges between 50% and 90% making decisions about purchasing strategies and operations primary determinants of profitability (De Boer, Labro et al. 2001).

The fundamental definitions of the subject vary in scope; some definitions describe merely the measuring activity of Performance Measurement (Neely, Gregory et al. 1995).

- Performance measurement can be defined as the process of quantifying the efficiency and effectiveness of action.
- A performance measure can be defined as a metric used to quantify the efficiency and/or effectiveness of an action.
- A performance measurement system can be defined as the set of metrics used to quantify both the efficiency and effectiveness of actions.

Other definitions clearly include the management activities in its definition; Performance measurement and control systems have been described as the formal, information based routines and procedures that managers use to maintain or alter patterns in organisational activities (Schmitz and Platts 2003).

Supply chain performance measures are used for a number of reasons. They are used to determine the efficiency/or effectiveness of an existing system, or to compare competing alternative systems (Beamon 1998). Performance measures are also used to design proposed systems, by determining the values of the decision variables that yield the most desirable level(s) of performance. Performance measurement provides the necessary feedback information to; reveal progress, enhance motivation and communication and diagnose problems (Chan, Qi et al. 2003). Measuring supply chain performance can facilitate a greater understanding of the supply chain, positively influence behaviour, and improve overall performance (Shepherd and Gunter 2006).

However Performance measurement in Supply Chain management does not receive adequate attention (Chan, Qi et al. 2003) and significant gaps remain in the literature (Shepherd and Gunter 2006). Some even propose that there is no commonly accepted language or conceptual framework concerning the functions of performance measurement (Schmitz and Platts 2003), nor is there any theoretic or more generic approach to studying how companies use performance measurement to manage their relationships and interactions with suppliers and how suppliers respond to the measurement (Schmitz and Platts 2003). It is therefore necessary to construct an abstract of the implied operational responses for any given performance measurement system for the purposes of inclusion in any simulation model.

To assist the reader in finding further sources of information - the overview of performance measurement provided by Neely (Neely, Gregory et al. 1995) has been widely referenced (Beamon 1999; Gunasekaran, Patel et al. 2001; Shepherd and Gunter 2006). Also SM Disney working with his UK based colleagues (Disney, Childerhouse et al. 1997; Disney, Naim et al. 1997; Disney and Towill 2003; Disney and Towill 2003) and more recently on a European basis (Dejonckheere, Disney et al. 2003) are profligate in this area.

3.2 Supply Chain Backpressure

Feedback theory explains how decisions, delays and predictions can produce either good control or dramatically unstable operation (Forrester and Wright 1961).

Kleijnen (2003) describes a principle known as feedback in the context of supply chain management as; “A manager compares a target value for a specific performance metric with its realization, and in case of undesirable deviation this manager takes corrective action”. This feedback principle links *established* operational responses to any KPI shortfall and triggers, through management systems, changes in local policy and parameters in order to re-establish the desired KPI value.

Backpressure is a ramification of the feedback principle applied to a managed organisation, often applied across a range of activities, each of which is monitored by its own key performance metric.

Supply Chain Backpressure is thus pressure applied back up the supply chain, by a customer on a supplier. This pressure exists because, in a competitive environment, organisations are reluctant to accept unexpected reductions in service level (however it may be defined) from a supplier. As a result the consequence of an operational change, in terms of customer measured performance, will ultimately become the responsibility of the upstream role making the change, thus backpressure will be applied upstream to return operational parameters back to pre-change values. A great deal of logistics research is conducted around the premise that a relationship exists between a particular course of action and logistics performance (or effectiveness) (Chow, Heaver et al. 1994).

Practical supplier selection and monitoring practices reinforce supply chain backpressure, ensuring that any variation in service that causes a degradation of a customer’s performance, however measured, is not tolerated by customers. Changing organisational objectives, changing customer requirements and the dynamic nature supply chain operations (e.g. Bullwhip) mean operations require continuous fine tuning in order to maintain existing service obligations and meet new ones. Interestingly there is evidence that metrics drive decisions, Maskel (1991) states that people in the organisation will concentrate on what is measured; thus the performance measure itself will steer company direction. It follows that if individual metrics drive performance then an SCPM framework will drive decision makers to make supply chains more competitive (Stone and Love 2007).

3.3 Supplier Selection

Performance measures are an important consideration in the selection of suppliers, although the specific measures considered for supplier selection and supplier monitoring may not necessarily be consistent. (Braglia and Petroni 2000) observe that the increased concern for supplier selection is motivated by the fact that supplier selection may be the single most important decision in the component procurement process. Operational practice however may lag behind academic theory as Purchasing efficiency is generally improved by working with fewer suppliers of a higher calibre (Barla 2003) yet adversarial attitudes have long dominated business relationships (Stank, Keller et al. 2001).

Performance of any entity in a supply chain depends on the performance of others, and their willingness and ability to coordinate activities within the supply chain (Swaminathan, Smith et al. 1998). The supplier selection problem involves trade-offs among multiple conflicting criteria and involves both quantitative and qualitative factors. As many as 23 supplier selection criteria can be taken into consideration during the decision making process (Çebi and Bayraktar 2003)

Purchasing managers need to evaluate supplier performance periodically, in order to retain those suppliers who meet their requirements in terms of several performance criteria. Frequently used as performance criteria are as follows (Mummalaneni, Dubas et al. 1996):

- On-time delivery
- Quality
- Price/cost targets
- Professionalism
- Responsiveness to customer needs

Deng and Wrtzel (1995) carried out an empirical study of the supplier selection criteria used by US importers in three merchandise categories. In all three categories, the most important criteria were price and product quality, followed closely by on-time delivery. Two criteria that were found to be of little importance in the supplier selection decision were the geographical location of the seller and the seller’s brand name.

It would be wrong to assume that the principle parameters for supplier selection and those used for supplier evaluation are identical. On the subject of Supplier selection criteria;

- Wilson (1994) found that Quality and Service considerations tend to dominate Price and Delivery criteria in current practices of supplier selection.
- Verma and Pullman (1998) on the other hand, point out that although managers say that quality is the most important attribute for the supplier, their actual supplier choice is based largely on cost and delivery performance.
- Supplier selection may be less of a strategic issue for firms at the lower tier levels where price is paramount because they are more likely to be purchasing commodity items from the open market. There are therefore differences across tier levels in supplier selection practices (Choi and Hartley 1996) .
- Morash (2002) questioned over 7000 US and Canadian firms and reports that suppliers are selected based primarily on cost, reliability and ease of doing business, while logistics systems are operated for efficiency and zero defects.
- Cagliano, Caniato et al. (2004) concludes that the main categories of supplier selection criteria correspond to the principal manufacturing performance and competitive priorities: cost, quality, delivery and flexibility', but the priority may vary according to other factors.

Two notable references; (Das and Abdel-Malek 2003) give notable summaries of the literature on Supplier selection and a review of numerous published methods of supporting supplier selection. Whilst the range of reported methods to tackle the complexity of purchasing decisions does not necessarily add insight to this work directly, it demonstrates that different authors have grouped purchased products in a range of dimensions including; stage in the product life-cycle, order penetration point (pre or post assembly), financial impact and supply risk. Then purchasers adopt a range of supplier choice models from statistical comparison, linear weighting and mathematical programming.

Such a range of approaches to supplier selection means that in theory a supplier needs to continuously establish; which methodology the customer is adopting and into which category of purchased products its own product was placed 'for every single client' – if it was to succeed in maximising performance in the key service criteria.

3.4 Supplier Evaluation

Evaluation of supplier performance can assist firms in restructuring their supplier network, for example firms can reallocate resources for supplier development programmes to suppliers with greater performance. But evaluation is generally considered to be the ongoing practice of identifying high and low performing suppliers and adjusting the degree of supply chain backpressure accordingly.

Narasimhan, Talluri et al. (2001) assessed supplier evaluation methods currently used in practice and criticized them in three respects;

1. Many rely on simple weighted score methods that rely on subjective judgements of purchasing managers for the relative importance of selected criteria. Final ranking is heavily dependent upon the assignment of weightings and the arbitrary way in which these calculations are performed.

2. The evaluation process is based purely upon performance outcomes such as price, quality and delivery, also ascribed by other authors (Chan, Tang et al. 2002). These limited measures take no account of the efficiency of the supplier in terms of using resources and their incurred cost of service.

3. There is no consistency in the application of a comprehensive method by which to assess suppliers and consequently organisations have little chance of efficiently meeting the expectations of a variety of customers.

Supplier evaluation is therefore as much a function of the selection method employed by the firm and the leanings of the individuals performing the activity, as it is a reflection on the overall abilities of the supplier.

There is also a difference between the perceived importance of the individual performance attributes used when rating suppliers and when awarding contracts. Managers perceive quality to be the most important attribute but they assign more weight to delivery performance and/or cost - when actually choosing a supplier.
These results imply that even though the managers believe that several attributes (for example, quality) are important for supplier selection, in practice the low cost supplier is selected.

Two possible explanations may apply;

- Operating practices are not completely consistent with their strategic priorities.
- Supplier performance evaluation for selecting suppliers is more weighted towards cost/delivery.

A third explanation might be that the evaluation of suppliers is a dynamic process in itself, reflecting the real time priorities of the decision makers (Verma and Pullman 1998). The priorities could switch in terms of the order of importance or they may vary in terms of degrees; the difference between “meets minimum reliability standard level” and “far exceeds minimum reliability standard level” might become more relevant if internal or external (customer) pressure is being applied on the decision maker.

It can be argued that once the supplier delivered material reach the minimum acceptable quality and service standard levels, management's focus often shifts to Cost reduction and this in itself implies there is a dynamic element involved in supplier measurement and evaluation.

3.5 Adoption of Performance Measurement in Industry

The Lean/Agile (Fisher 1997) discussion is interesting in itself and the subject of much work exploring the merits of different production strategies, it can serve in this case as an example of how any number of industrial initiatives can have a far reaching impact on supplier performance criteria. Organisations reengineer production systems to facilitate the combining of best features of Lean and Agile philosophies (Mason-Jones and Towill 1997; Childerhouse and Towill 2000) and organisations in different regions of the world today apply slightly different criteria to suppliers in order to do this (Cagliano, Caniato et al. 2004). One piece of work (Abernathy, Dunlop et al. 2000) demonstrates that the Lean/Agile option is applicable not merely within a single organisation but within the Stock Keeping Unit (SKU) range of a single product, each of which presumably will have differing performance criteria.

Evidence that industrial practice follows the conclusions of academic literature is likely to be difficult to obtain for reasons of commercial confidentiality. However at a Tokyo logistics conference Garland (Garland, Heaver et al. 1994) noted a Mr. D. Eggleton of Rank Xerox described the criteria on which his performance is evaluated as employee satisfaction, customer satisfaction and company 'rate or return', all which;

- Relate to a single role rather than the supply chain
- Might be argued have antagonistic elements
- Involve a very subjective element in calculation

The concepts of performance measurement across the supply chain are simple and compelling yet mainstream implementation within these industries has been much less than expected, which seems surprising considering the benefits that initially had been claimed.

One view the reason is that collaboration practices are not well understood (Holweg, Disney et al. 2005). An alternate view is that whilst the implementation of these practices is sufficiently understood, it is the ever shifting expectations that make progress so difficult. Seemingly confused and shifting priorities mean management activity is constantly out of phase with requirements as firms often have diverging interests (Cachon and Lariviere 2001). Verma and Pullman (1998) argued that it is extremely difficult for any one supplier to excel in all dimensions of performance. It is also possible that the components delivered by a particular supplier excel in a few quality dimensions (reliability, features) while some other supplier might be superior in other quality dimensions (for example, durability or aesthetics). Therefore an actual choice generally involves a process prioritising various attributes and/or a trade-off among the individual performance level expectations for the various attributes applied to the suppliers in question`.

3.6 Conclusions

This research argues that the customer's supplier-facing metrics (their assessment of their supplier's performance) is ultimately what drives supply chain operations. Any negative change in these key metrics will generate the understandable response from the client, insisting the supplier remedy the situation or face the inevitable financial/contractual penalties. In practice however there exists an absence of a standard means to apply Supply Chain performance measures or indeed a consensus on what measures to apply. The profitability and survival of many organizations is heavily dependent on the effectiveness of their supply chain performance and yet there is very little literature available on performance measurement in the supply chain, especially dealing with system design and selection (Stainer 1997).

Should a performance system be identified the target values for individual KPI's may vary with sector, geography, time (seasonality, lifecycle etc) and business priorities (gain market share or maximise profit). For most firms in a consumer good environment for example, sourcing is a dynamic activity that changes from season to season (Lowson 2001). It is logical to assume therefore that it is extremely difficult for any one supplier to excel in all dimensions of performance; a high service supplier might not be the one with lowest cost.

In order to test if Supply Chain performance metrics have an impact on Supply Chain dynamics therefore, a single plausible application of the performance measurement system must be identified. The need to do this is in itself an indication of the challenges facing commercial organisations when applying supply chain performance measurement and an indication of an opportunity for the academic community to contribute.

4 A REPRESENTATIVE PERFORMANCE MEASUREMENT SYSTEM

Many companies measure their logistics performances using several methods and as a consequence, various sets of indicators can be found in practice (Rafele 2004). This highlights a particular problem in that without a standard approach, the same event can be measured in different ways and a relative performance measurement between two different systems is therefore invalid.

In the academic literature several measures have been proposed for measuring overall supply chain performance (Beamon, 1999). This chapter identifies an appropriate candidate system for use in researching the impact of such measures on Supply Chain dynamics.

4.1 Key features of Supply Chain Performance

No single system is universally accepted as the ideal as such, however the literature includes some very widely cited indications of aspects of performance that must/must not be included in any given system;

- Speed of response to customer demand has long been recognized as a key attribute to business success since customer loyalty can be won or lost on product availability (Mason-Jones and Towill 1997).

- Traditionally financial performance was the primary measure of success in most companies but conventional financially based reporting systems generally do not provide all the required information about logistics performance (Brewer and Speh 2000).

- Swaminathan, Smith et al. (1998) favour Quantitative performance measures (cost, profit, fill-rate etc) rather than Qualitative ones (satisfaction, information sharing etc).
- (Beamon 1998; Beamon 1999) provides a widely cited literature survey of performance measures used in supply chain environments. Identifying three distinct types of measure; Resources, Output and Flexibility. The work continues to identify the two dominant measures; Cost and Customer Responsiveness.

- Neely, Gregory et al. (1995) similarly outlines a widely cited account of the breadth of Performance Measurement systems in the literature as well as the requirements and environmental context of such systems.

- Gunasekaran, Patel et al. (2001) details a very wide range of supply chain metrics both local and pan-supply chain. They do not however define any kind of framework for the relationship between the performance metrics and decisions or activity of operators. As a consequence they are considered as contributing more to the range of individual measures that have been recognised, rather than a system for driving performance change.

- Chan, Tang et al. (2002) propose on solution for dealing with the huge range of performance measures in a supply chain. Their solution involves a mathematical model for calculating a performance index of measures that deals with all types of measure. Whilst practically every other author in this literature review section warns against the use of single measures, Chan's method would lend itself to simulation due to the fact that a single numeric measure is delivered for comparison. It also has the advantage of proposing a method (weighted average of fuzzy sets) whereby even the qualitative measures are accounted for numerically. It is not adopted in practice however, because the use of a single metric does not adequately cover the range of activities (indeed many combinations of operational adjustments could deliver an identical change in performance) nor does it link the mathematically calculated metric to the strategic intent of the firm.

- Meixell and Gargeya (2005) map the primary objective function for many proposed Supply Chain measures over some 20 years (Fig 7). They identify key contributors over the past thirty years but also highlight the enormous range of objectives being considered.

Figure 7 Objectives of Performance measurement constructs. Source MEIXELL and GARGEYA (2005)

4.2 Multiple Supply Chain Performance Measures

Much work has been done since the early 1990's when there was no means to measure performance across the supply chain; "no performance measures for the complete supply chain exist at all" (Lee and Billington 1992). More recent work points towards a solution based upon multiple, cross-functional measures (Bechtel and Jayaram 1997) with the acknowledgement however that such solutions impose their own complications. For example the components of 'Service' include factors that differ greatly from one another and are neither comparable nor numerically linked; lead time & flexibility, delivery frequency & equipment productivity (Rafele 2004). Judging a successful outcome might involve an appraisal of a number of unrelated metrics and because strategy often relies on multiple operational strengths so supply chain managers often employ more than one attribute (Huan, Sheoran et al. 2004).

(Neely, Gregory et al. 1995) suggest that there are two basic types of performance measure which should be included in any such system; those that relate to results (competitiveness, financial performance) and those that focus on the determinants of the results (quality, flexibility, resource utilization and innovation). Whichever set of measures or measurement system is ultimately selected comes with the understanding that pan supply-chain metrics have not been developed in ways that allows them to drive local decision-making; "Traditional performance measures may limit the possibilities to optimise supply chains, as management does not see supply chain wide areas for improvement" (van Hoek 1998). A section of this work must therefore involve the process of mapping local actions to performance outcomes see Chapter 5.

4.3 Performance measurement systems

In the past, attention was mainly given to the performance measurement of a single process or organisation but more recently the focus is on measuring the entire supply chain performance as a whole (Beamon 1998). The treatment of the supply chain in this holistic fashion, as a system of interrelated activities rather than a single activity, is a requirement of any performance measurement system (Gunasekaran, Patel et al. 2001). A variety of systems now exist and all are clearly more than a disparate assortment of individual metrics (Rafele 2004).

Availability of supply chain wide information makes it feasible for operators to make decisions locally with full knowledge of the state of the rest of the supply chain and to use that knowledge to optimise the performance of the complete supply chain. Swaminathan, Smith et al. (1998) produce a framework that provides an ability to simultaneously observe global and local performance of the supply chain. However the global perspective and the local perspective are not necessarily harmonious. They argue that sometimes taking the global perspective may actually be harmful to some of the organisations/entities in the supply chain. In their work they conclude that a global performance measure may be an appropriate yardstick for an intra-organisational supply chain (where most entities belong to the same organisation) however local performance becomes an extremely important feature in more typical inter-organisational supply chains.

This work requires the identification of a representative Supply Chain Performance Measurement to include in the simulation. The literature provides assistance in this respect. Many such systems can be discounted when using the following criteria (Stone and Love 2007):

1. The model must cater for the complex strategic dimension in supply chain management.
2. The model must focus sufficiently on operational activity.
3. The model must be sufficiently widespread amongst practitioners to allow for ready communication and data sourcing.

Utilising these criteria the following three systems were explored and evaluated. Three possible systems were identified as candidates for adoption into the simulation.

4.3.1 Nevem Workgroup model

An early model put forward by the NEVEM Workgroup (Workgroup 1992) proposed four criteria for measuring supply chain success; efficiency, effectiveness, productivity and utilisation. With its Operations Management origins, this model offers considerable insight with the use of ratios as a means to distribute management information.

Figure 8 Nevem Performance Measurement Model. Source Nevem Workgroup (1992).

Notable strengths include the fact that a range of operational parameters are captured and the use of ratios accumulation makes an organisational performance measure possible. In much the same way as Overall Equipment Effectiveness (OEE) uses a ratio of Quality multiplied by one for Rate multiplied by one for Availability. The NEVEM model is not however widely adopted in practice and receives fewer references in the academic literature than some of the more recent models.

4.3.2 Balanced Scorecard

One widely cited performance measurement framework is the “balanced scorecard” (Kaplan and Norton 1996). This selected set of four to six performance measures, usually including; productivity, quality and customer satisfaction which can also be used for diagnosis of service failures. Other authors (Stainer 1997) advocate the use of this particular set of performance measures to determine the efficiency or effectiveness of a system and to compare alternative systems. Since the selection of individual performance measures is a function of organisational requirements, it is unclear how Balanced Scorecard can be applied on a pan supply chain basis.

4.3.3 Process Frameworks

One such framework developed at the Cardiff Industrial System Dynamics Group uses a control theory approach to model the supply chain and provides a structural framework of qualitative and quantitative techniques for reducing supply chain dynamics (Towill 1996). As an early example of a means to standardise and compare processes within supply chains it warrants mention here as does the ‘Process Handbook Project’ conducted at Massachusetts Institute of Technology (MIT) (Malone et al., 1999). This later approach involved collecting examples of how different organisations perform similar processes, and organising these examples in an online tool for sharing business process knowledge. Both these frameworks however have not seen international adoption on any noticeable scale.

In 1995 an American academic (Stewart 1995) presented a new framework for describing business processes; PLAN, SOURCE, MAKE, and DELIVER wherein he suggested that the key metrics to assess supply chain excellence were:

1) Delivery performance
2) Flexibility and responsiveness
3) Logistics cost
4) Asset management.

In 1996 the Supply-Chain Council (SCC), consisting of two consulting organisations together with seventy manufacturing and logistics organisations in the USA adopted the Stewart model as standard (Stewart 1997). The SCC then developed and published its first edition of the Supply Chain Operations Reference (SCOR) model which described as:

'A standard way to examine and analyse a supply chain with a common language for describing activities and participants, a common set of readily manipulated variables and a set of accepted metrics for understanding the dynamic behaviour of supply chains' (Council 2005).

Since then numerous revisions have taken place notably Stephens (2001) an evolution of the framework that extended the scope to include all elements of demand satisfaction starting with the initial demand signal (order or forecast) and finishing with the signal of satisfying the demand (final invoice and payment).

Within the model framework there are multiple levels of detail containing;

- Standard descriptions of management processes
- A framework of relationships among the standard processes
- Standard metrics to measure process performance
- Management practices that produce best in class performance

Four distinct process elements; Plan, Source, Make and Deliver are defined in increasing levels of detail beginning with a description of the overall process.

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Figure 9. SCOR Level 1 Process elements describing 'Deliver'. Source SCOR Manual 6.1

- Level 1.

  The Configuration level provides a broad definition of the plan, source, make, deliver process types, and is the point at which a company establishes its supply-chain competitive objectives (e.g. Fig 9).

- Level 2.

  Defines 26 core process categories that represent the components of a supply chain. A company can configure both its actual and ideal supply chain by selecting from these core processes.

- Level 3.

  The Process element level provides a company with the information it needs to plan and set goals successfully for its supply-chain improvements through detailed process element information for each level 2 category. Planning elements include process element definitions, diagnostic metrics, benchmarks, best practices, and system software capabilities to enable best practices. Each process element has a distinct set of inputs and outputs and the model presents 'best practices' as far down as level 3, this level of detail is useful and necessary for implementation purposes (Kasi 2005; Bolstorff and Rosenbaum 2007).

- Level 4.

  Focuses on implementation, when companies put specific supply-chain improvements into play. Since changes a level 4 are unique to each company, the specific elements of the level are not defined within the industry-standard model and are left to the implementation team (Stewart 1997).

SCOR identifies five aspects of performance for the supply chain; Reliability, Responsiveness, Flexibility, Cost, and Asset management. Fig 10 demonstrates the range of performance measures defined for the five aspects of performance at Level 1. Some advocates (Huan, Sheoran et al. 2004) prefer to operate with four aspects of supply chain performance, combining flexibility and responsiveness, whilst others (Kasi 2005) prefer all five. SCOR defines metrics and measures to evaluate each process in all five aspects of performance at each level of the process hierarchy.

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Figure 10: SCOR Level 1 Performance Metrics and attributes. Source SCOR Manual 6.1

The metrics cater for the various objectives different companies might pursue, whether; Engineer to Order, Make to Oder or Make to Stock. Thus choice of measures and metrics depend on the company's strategy and focus and it is left to the implementation team to choose the metrics they desire. The model therefore, instead of dictating strategy, accommodates the stated objectives of individual roles and calculates performance measures based on a standard, defined calculation.

4.4 Academic opinion of SCOR

The academic literature suggests a widening interest in the model with numerous articles stating; SCOR is poised to become an industrial standard (Van Landeghem and Persoons 2001; Camerinelli and Cantuon 2006) and has been positively received by practitioners (Huan, Sheoran et al. 2004) and consultants (Kasi 2005) alike, largely for its common terminology and standardized metrics.
Many academic studies have made use of SCOR or at least some of its features in exploring different aspects of supply chain management (Stephens 2001; Van Landeghem and Persoons 2001; Huang and Gangopadhyay 2004; Terzi and Cavalieri 2004). Some notable ones include;

- Shepherd and Gunter (2006) categorize measures of supply chain performance by compiling a taxonomy of metrics from 362 articles, published between 1990 and 2005. They subsequently determine '*according to the individual metrics applicability to the five supply chain processes defined in SCOR*' if respective performance measures can be classified as operational, design or strategic. The key assumption is that the SCOR model is considered sufficiently robust that all measures can be examined using it.

- Exploring supply chain strategic decision making, based on a survey, the most promising model is the supply chain operations reference (SCOR) model (Huan, Sheoran et al. 2004).

- Meixell and Gargeya (2005) review model-based literature on global supply chains that spans from 1982 to 2004. More than 100 articles and books on the subject were identified and after screening, reduced to 18 major research articles compared in a series of tables based on selected dimensions, ultimately their preferred model was SCOR due to its multi-dimensional measures of performance and being practitioner-developed.

- Studying the relationship between individual metrics and SC operational design (Make to Stock, Make to order etc) four thousand supply chain professionals, across a range of industries, were surveyed on their use of SCOR (Glaser-Segura and Cirtita 2007). This suggests that the model is widely understood in practice.

Some stated weaknesses of SCOR include:

- The framework lacks a network-oriented logistics-controlling mechanism, being oriented towards local performance maximisation as opposed to a supply chain wide orientation (Bullinger, Kuhner et al. 2002). However it was stated that no comprehensive supply chain wide performance framework exists elsewhere. One explanation for this may be that it is not clear if such an approach would bring benefits to the individual enterprise. Improving the performance of the complete supply chain does not guarantee that all the individual members benefit

- The current SCOR model does not address: sales and marketing, product development, research and development and some elements of post-delivery customer support (Kasi 2005). However the SCC maintains on their website that new editions of the model may yet include additional functions.

- This SCOR target setting does not consider multiple perspectives of the problem owners (Finance and Operations departments desiring different outcomes) nor does it readily accommodate the time phasing of objectives (accommodating changes in a product’s life-cycle).

The Supply Chain Council's SCOR model has not yet been adopted universally, it is popular in the US, Far East and is gradually becoming more so in Europe. It does however represent a real attempt to introduce a common language and common practices in supply chain operations that allow the performance of elements of an operation to be compared and benchmarked.

4.5 Conclusion

The SCOR model as a reference model has a number of application advantages.

- It uses standard nomenclature and terminology to describe standard processes.
- It lays down a framework for the relationships among processes with these defined performance metrics that is readily communicated between the industrial and academic community.
- The time based performance of these processes is measured using common established KPI's
- SCOR metrics are benchmarked to facilitate both internal and external (via membership of the SCC) performance comparison.
- Because distinction is made with policy issues such as order entry point (make to order as opposed to make to stock) extremely specific comparison is possible
- Indications from the literature are that it is now the most developed Supply Chain Performance measurement framework in widespread operation today.

The SCOR model is constantly being developed by the Supply Chain Council (SCC 2006) and the SCOR model version 7 is considered in this work.

As SCOR, or any other measurement system mentioned, does not contain the calibrated relationship between operational adjustments and the resulting changes in any set of given performance metrics, the next section establishes an abstraction of the relationship between changes in performance metrics and resulting operational adjustments which can then be tested in subsequent chapters.

5 PERFORMANCE MEASURES AND THEIR OPERATIONAL RESPONSE

Having identified a candidate Performance Measurement System this chapter seeks to establish how the system metrics register changes in performance and what operational responses an organisation might make in order return those metric values to an acceptable value. Camerinelli and Cantuon (2006) established those dimensions of supply chain performance that respond to the financial indicators that external stakeholders consider when evaluating a firm. They directed accounting professionals to the SCOR metrics, again on the basis that this is the most definitive set to date, and gathered opinion on those most likely to influence specific financial indicators. Whilst their method (survey) might not deliver the quantifiable link sought in this work, it is a validated example of research seeking to establish the relationship between applied pressures (financial) and the operational reaction of the firm as recorded by the SCOR metrics.

Because SCOR defines metrics for each of its *five* aspects of performance, we do not need to establish the link between the metric and the area of interest, in this case operational performance. This Chapter establishes a representative set of operational adjustments and responses to the metrics for each of the five aspects of performance. Furthermore, as SCOR covers such a comprehensive set of business activity (Source, Make, Deliver etc.), these operational adjustments can be established for a range supply chain roles (Manufacturer, Distributor, Retailer) as witnessed in the classic model used to investigate Bullwhip – The Beer Game (see section 2.1.1).

Process Element: Schedule Production Activities	Process Element Number: M3.2
Process Element Definition	
Given plans for the production of specific parts, products, or formulations in specified quantities and planned availability of required sourced products, the scheduling of the operations to be performed in accordance with these plans. Scheduling includes sequencing, and, depending on the factory layout, any standards for setup and run. In general, intermediate production activities are coordinated prior to the scheduling of the operations to be performed in producing a finished product.	
Performance Attributes	**Metric**
Reliability	% Orders scheduled to customer request date Schedule achievement
Responsiveness	None Identified
Flexibility	Schedule interval Upside Production Flexibility Downside Production Flexibility
Cost	Inventory days of supply Plant-level order management costs
Assets	Capacity utilization
Best Practices	**Features**
Build subassemblies to forecast at highest generic level in Bill of Material; maintain flexibility while minimizing cycle time and inventory position	None Identified
Demand-pull mechanisms	Repetitive scheduling or sequencing of unique orders
Schedule reflects current plant status (equipment, jobs, and other resources on-line)	On-line reporting from operations
Schedule optimizes use of shared resources, such as tooling	Resource needs included in routing or Bill of Material
Cellular manufacturing	None Identified
Schedule minimizes changeover costs between products	Algorithms that manage set up times/costs, cleaning times, and ideal job sequences (e.g., color sequencing light to dark)
Schedule includes preventive maintenance program	Interface to maintenance management system
Maximize data integrity and system accuracy by ensuring 99%+ accuracy of BOM configuration, inventory levels, and schedule requirements	None Identified
Design/upgrade production equipment to maximize flexibility and avoid line stoppages	None Identified
Cross-training	None Identified
Additional capacity for overflow demand	Outsource manufacturing and work force augmentation providers connected to production schedules via the internet.

Figure 11. Example of the metrics defined for each attribute of performance in the SCOR model.

Figure 9 is an example of the extensive detail available on each of the Process Elements. This Process element is clearly defined; in this case a process in the Make section of the model (M3.2) and various metrics for each of the five aspects of performance are suggested. It is apparent in this diagram that the number of metrics for each of the five aspects of performance varies, in this case from three to zero. There is also an understandable degree of duplication within SCOR in that specific metrics capture the same aspect of performance for different processes. For example Planning Production schedules and Planning Delivery schedules share common metrics to capture process performance, even though the calculation would be populated with different data and may therefore deliver a different value. For the sake of completeness the defined metrics for *all* the process elements; Plan, Source, Make & Deliver were summarised by each aspect of performance and these are displayed in **Appendices 1,2,3 and 4**. All SCOR Level 2 Performance metrics, across each of the five aspects of performance, are then brought together and the results summarized as a series of Ishekawa/ Fishbone diagrams. Created by Kaoru Ishikawa in 1990 the Ishikawa diagram is typically used in quality defect prevention where it helps identify and communicate potential contributory factors that cause an overall effect. Causes are usually grouped into major categories (people, methods, materials etc.) but in this work such diagrams greatly assist demonstrate the grouping of SCOR performance metrics in each of the four processes (plan, source, make & deliver) for each of the five aspects of performance.

The overarching SCOR Level 1 Metric delivers a single value (in a set of five) that organisations can monitor for each defined aspect of performance. In this Chapter however the Level 2 metrics are considered to allow a richer and fuller consideration of ALL the operational adjustments an organisation might make. For example Production Managers and Transport Planners have very different ‘local levers to pull’ when responding to the same objective. In each Ishekawa diagrams The SCOR Level 2 performance metrics are shown with a solid arrow, indicating the process against which they are applied. Any overlap of metrics and processes are made apparent, for example increasing Stock/ROP would positively influence two distinct metrics; ‘increase perfect order fulfilment’ and ‘reduce post production planning changes’. Finally the operational adjustment (positively influencing the metric) is clearly shown on the diagrams *within solid text blocks*. These reasoned operational adjustments, as well as a discussion of the metrics themselves, are laid out in the following sections.

5.1 THE FIVE SCOR ASPECTS OF PERFORMANCE

Accommodating a range of differing aspects of performance is not an idea unique to SCOR. Hines (2004) puts Performance Measures into five key performance areas; cost, speed, quality, reliability and flexibility. Chan et al (2002) concludes that within a supply chain context, delivery speed and delivery reliability have become key levers for competitive differentiation and increased profitability.

Whilst each of these five aspects of performance is discussed in the literature, there is a range in the level of commonality of definitions used amongst the aspects and even a degree of ‘cross over’ in the terms/expressions used. The following section displays the derived operational adjustments for each of the five aspects of performance, based upon the range of metrics contained within SCOR. It also includes a discussion on the range of opinion for those aspects of performance where in the literature appears divided.

5.1.1 Reliability

At level 1, SCOR defines Reliability as “The percentage of orders that are delivered on the customer’s requested date. Survey indicates (Verma and Pullman 1998) that order quantities and supply lead-times are the two most common changes which occur in supply chains, and are most often the cause of buyer–supplier grievance.

Ideally, a firm should attempt to fulfil customers' orders and simultaneously meet all their expectations-delivering 100% of the exact items and quantities ordered on time, damage free, and with errorless invoicing (Stank, Keller et al. 2001). Whilst perfection is an admirable objective Stank goes on to acknowledge that pursuit of a single aspect of performance is not realistic stating that; perfection is not always achievable at reasonable cost. The focus should be on creating as much value for the end-customer as is profitable, and doing this requires coordinated effort among all firms in the entire supply chain.

The multifaceted nature of Reliability (order quantity, delivery time, damage free etc) is further developed by Rafele (2004) who suggests some indicators of customer service are homogenous between a number of performance measurement systems. He sums them up in a value he terms "Level of service towards the customer" (LoS) but notes it is also termed reliability. He defines LoS as a ratio; Deliveries/Orders, where Deliveries are those deliveries that completely satisfy the customer request (correct quantity of ordered goods, on time, in a suitable condition, with no paperwork mistakes etc).

Figure 10 is the Ishekawa/fishbone diagram displaying the SCOR prescribed metrics and deduced operational adjustments (highlighted in the 'boxed' text) for the Reliability performance attribute. The corresponding/representative response from any Supply Chain operator trying to positively influence these Reliability metrics is similarly laid out and any commonality between responses in different process elements can be identified and communicated.

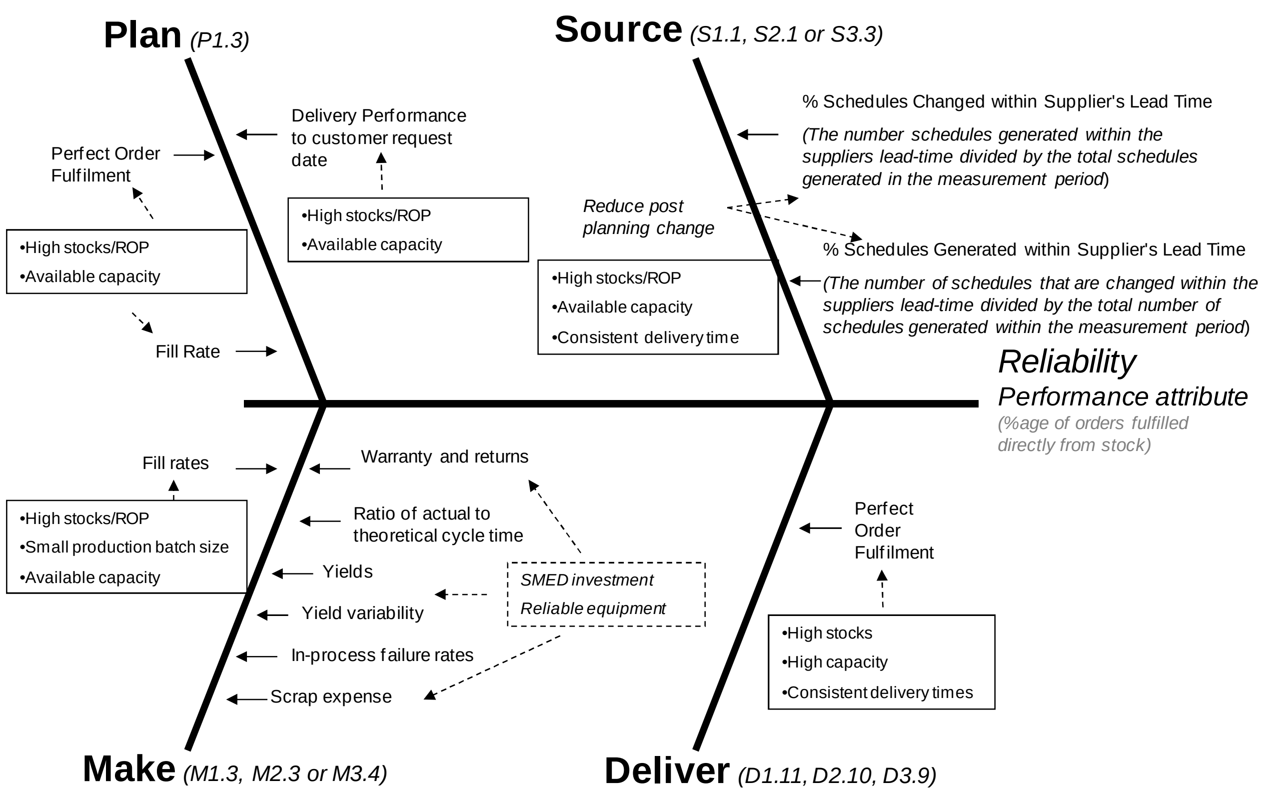

Figure 12. Operational adjustments to Reliability performance.

In this case for example the Plan process element has two SCOR Level 2 metrics; ‘Perfect order fulfilment’ and ‘Delivery performance against customer expected delivery date’. High availability of product and available capacity would logically be typical response to such metrics in a Planning function and these two responses are recurring themes in other process elements. Note that there is an implied reference to the management customer expectation “delivery to customer’s request date”. This aspect therefore does not require instant delivery, but ‘consistent’ delivery within an agreed tolerance of the target delivery cycle time. There is no explicit requirement for short cycle times or fast/expensive modes of freight transport. In practice reliable transport companies will be awarded contacts but since there is no evidence in the literature that one mode e.g. air freight is more reliable than sea freight then it is assumed that operators will work on the basis that earlier transmission of orders in return for cheaper but equally reliable delivery would be a typical solution.

5.1.2 Responsiveness

The increased emphasis today on availability of products and services as well as on-time delivery creates unique needs for a volume flexible response (Vickery, Calantone et al. 1999). Activities that improve Responsiveness do deliver benefits to organisations and in the long-term have a positive impact on a firm’s performance (Jack and Raturi 2002). Order Cycle Time is defined as the time span, an individual flow unit takes to traverse a process from entering to leaving (Jammernegg and Reiner 2007). It follows then that the metric to monitor the actual cycle time ‘from customer order origination to customer order receipt’ is a measured quantity of time, as opposed to a percentage of deliveries made on time.

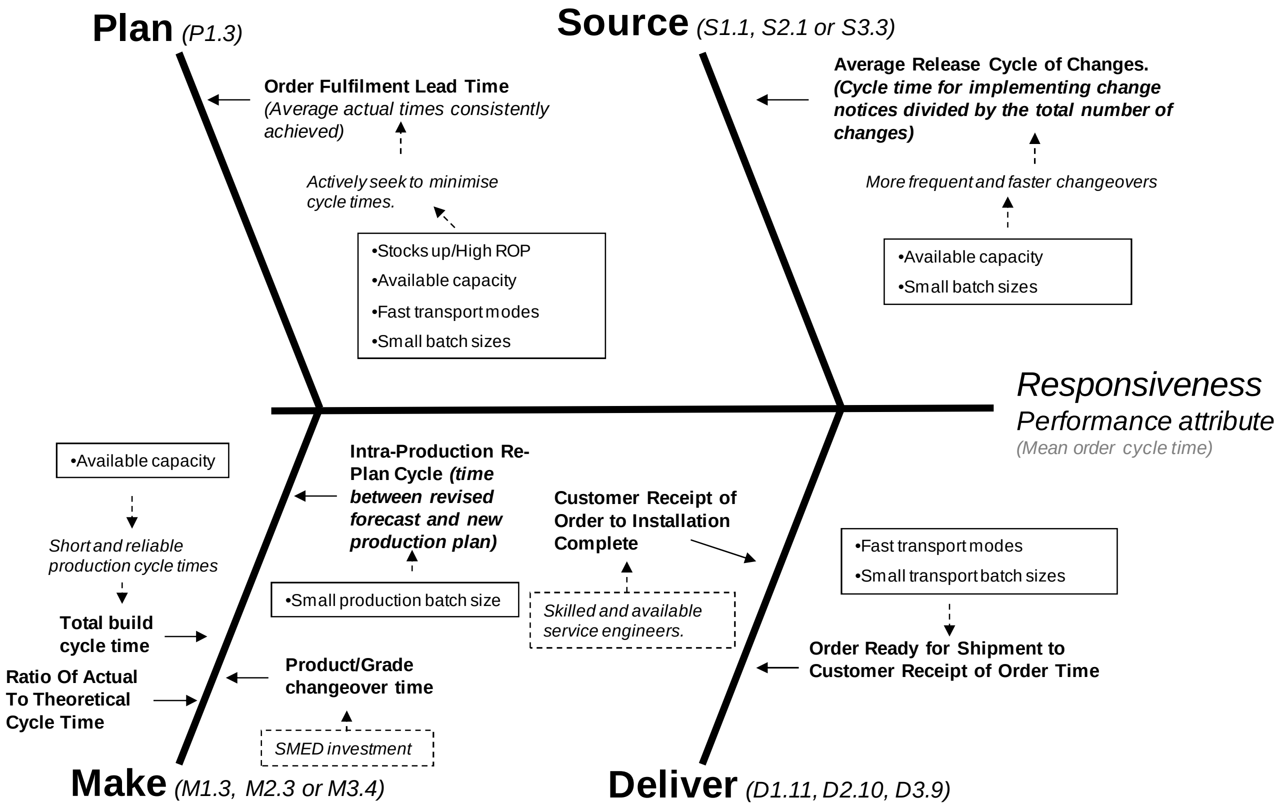

Figure 13. Operational adjustments to Responsiveness performance.

Volume flexibility, which SCOR refers to as Responsiveness, is defined at Level 1 as the velocity at which a supply chain provides products to the customer, in practical terms therefore it is the *moving average order cycle time*.

Figure 13 is the Ishekawa/fishbone diagram displaying the prescribed metrics and deduced operational adjustments (highlighted in the 'boxed' text) for the Responsiveness performance attribute. High availability of product with available capacity for additional stock as required, are again two recurring themes however also apparent is the need for fast modes of transport with short delivery times.

5.1.3 Flexibility

The terms 'Volume flexibility' and 'Range/Variety flexibility' are used to differentiate between the ability to accommodate a change in the volume of demand and a change in the mix/type of demand.

- Volume flexibility represents the ability to change the level of output (D'Souza and Williams 2000). Slack, Chambers et al. (2007) identify 'range' and 'response' as sub dimensions of volume flexibility, where range refers to how far the manufacturing system can change and response focuses on the question of how rapidly and cheaply it can deliver the change in volume.

- Variety flexibility represents the ability to produce a number of different products and to introduce new products (D'Souza and Williams 2000). Jack and Raturi (2002) define *responsiveness* as 'the ability of a system to respond to a change in the type or mix of product(s) being demanded' though it clearly fits in here under the heading of variety/range flexibility.

The literature is largely consistent on the importance of flexibility, Das and Abdel-Malek (2003) observe that over 90% of the respondents emphasized that manufacturing flexibility was key to maintaining competitiveness, but more divided on its dimensions.

- Upton (1994) defined flexibility as the ability to change or react with *'few'* penalties in time, effort, cost, or performance and in so defining it he avoids the dimension issue altogether.

- Two possible calculations for Flexibility (*though termed Responsiveness*) are suggested by Carter (1986); the time required to double the output of a system and its associated cost.

- D'Souza and Williams (2000) proposed that generalized measures would be more appropriate; Time required to increase or decrease output, Cost of increasing or decreasing volume of output.

- Sethi and Sethi (1990) place a different quantitative limitation on the range of volume “The time required to add one unit of production capacity”. In the same paper they also propose “the time required to change volume of output by 20%.

Sethi and Sethi (1990) were obviously key in the development of part of the SCOR model as SCOR definitions exhibit echo’s of their metrics. Some deeper level SCOR metrics, for example *Upside Shipment Flexibility* being defined as “The number of days required to achieve an unplanned sustainable 20% increase in shipments”. Yet there remain clear limitations in these definitions; regardless of the difficulties in testing it - there is no standard definition of *sustainable* nor is there any suggested basis for the apparently arbitrary value of 20%.

When it comes to a *working application* of a measure of flexibility; the ability of a complex system to respond to potential change remains frustratingly defficient, probably because such a measure would test and therefore jeopardising service levels. Verma and Pullman (1998) define supply chain flexibility as the ‘robustness of the buyer-supplier relationship under changing supply conditions’, yet a metric that captures maximum elasticity implies testing the relationship with the client and few organisations are willing/able to do this in a competitive environment. The fundamental issue is that flexibility, because it is defined as the ability to accommodate a variable, represents a capability that *may not ever be utilised*. Gerwin (1993) elaborates on this by suggesting that flexibility is more than just an adaptive response to uncertainty and that flexibility measures should capture the difference between required, potential and actual flexibilities.

- Required flexibility represents management’s strategic determination of how much is needed of a particular type of flexibility.

- Potential flexibility is determined by existing plant capabilities if external conditions are appropriate.
- Actual flexibility stems from the utilization of plant capabilities and is determined by experience.

Olhager (1993) includes a short or long term time dimension in his definition; In the short run, flexibility means the ability to adapt to changing conditions using the existing set and amount of resources. In the long run, it measures the ability to introduce new products, new resources and production methods, and to integrate these into existing operations. Ideally one would want a supplier that provides the needed flexibility to appropriately adjust their supply process as demand conditions change. Ironically JIT production systems demonstrate limited flexibility being able to only accommodate ‘‘noise’’ level uncertainties, Braglia and Petroni (2000) consider some insightful commercial examples of companies that were unable to stop the supply process as demand fell below threshold levels.

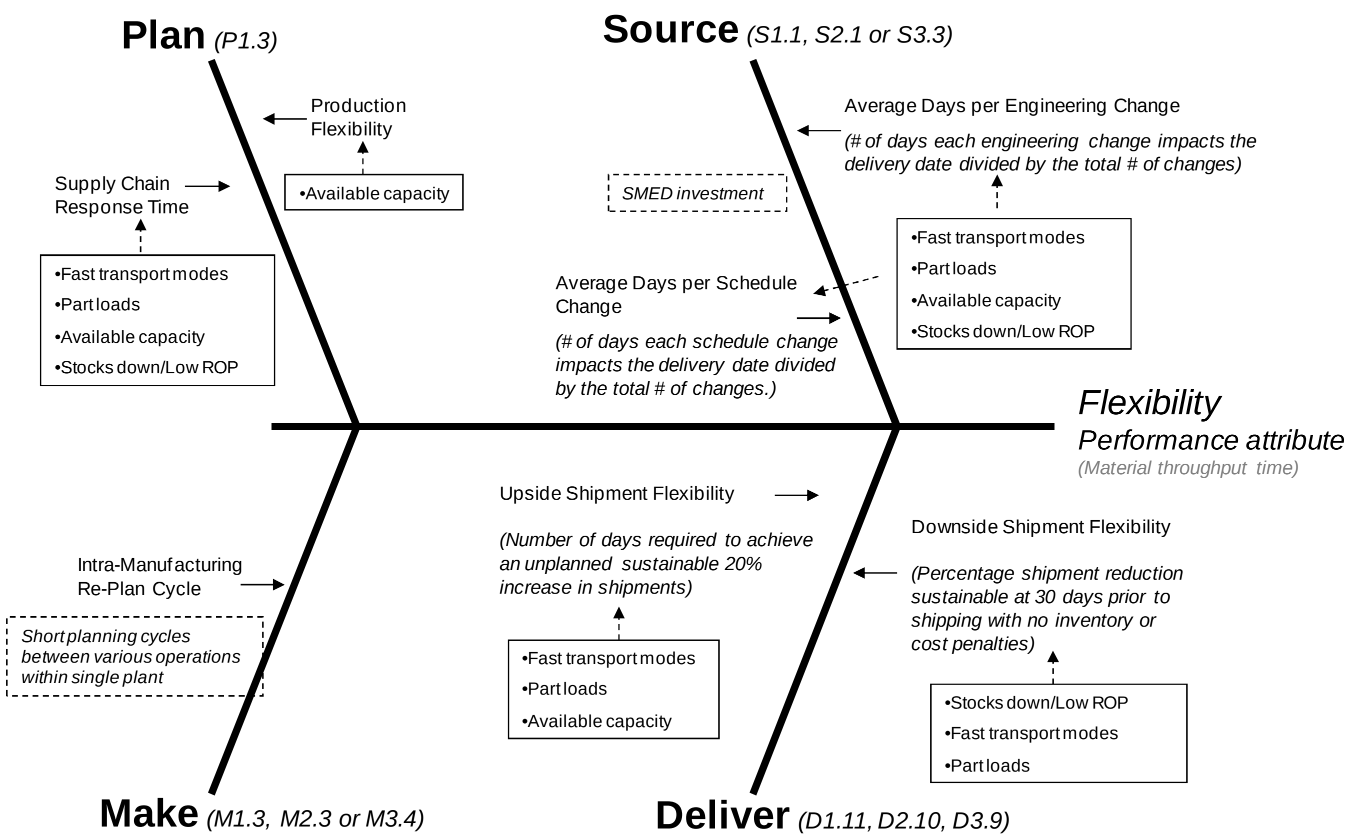

Figure 14. Operational adjustments to Flexibility performance.

Volume flexibility, which SCOR refers to as Responsiveness, is defined at Level 1 as 'Supply Chain Response Time'. Unlike Responsiveness where the performance aspect is concerned with the speed with which the supply chain delivers product, Flexibility is seeking to capture the speed with which the supply chain can deliver a *different* product.

Figure 12 is the Ishekawa/fishbone diagram displaying the prescribed metrics and deduced operational adjustments (highlighted in the 'boxed' text) for the Responsiveness performance attribute. Low inventories of product together with available manufacturing capacity and fast modes for the distribution of the new/different product are required. Considering these very practical elements of flexibility the metric might simply capture and compare the time it takes raw material to transit the system and be delivered as finished goods to the consumer – 'the velocity of material transit'.

5.1.4 Cost

Cost is clearly a fundamental consideration for commercial competitiveness if not survival in the commercial environment. Academics also prioritise cost when evaluating systems; Zeng (2003) used 'logistics costs' and 'cost to value ratio' as performance indicators when evaluating global sourcing alternatives in the aviation industry. The SCC offers its members access to metric data for benchmarking purposes and also aggregates this data for use in wider publications; *'excellent supply chain performance can lower cost by up to 7% and enhance cash flow by more than 30%'* (Stank, Keller et al. 2001).

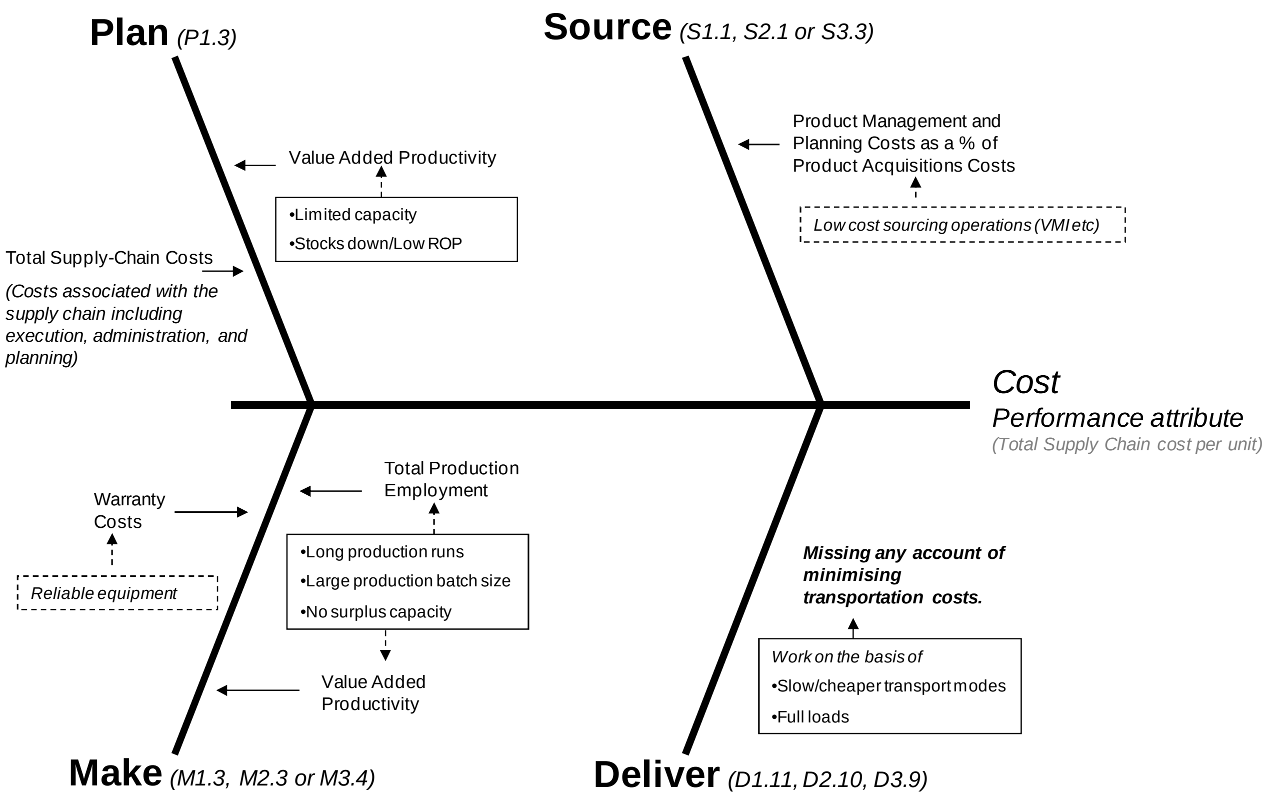

Figure 15. Operational adjustments to Cost performance

Cost is defined at Level 1 in the SCOR model as the ‘Cost of Goods Sold’ and Figure 13 is the Ishekawa/fishbone diagram displaying the prescribed metrics and deduced operational adjustments (highlighted in the ‘boxed’ text) for the Cost performance attribute. Low inventories, low cost transportation options and limited but well utilised manufacturing facilities describe the operational responses and adjustments to this performance priority.

5.1.5 Utilisation

Many authors (Beamon and Ware 1998) refer to utilisation as capacity used/available capacity and similarly the SCOR model, at the lower level, defines metrics that seek to drive up capacity of plant and equipment throughout the supply chain. It seeks to maximise the value adding activities in the supply chain whilst reducing the time material and orders (including payment for orders) is spent waiting for various processes.

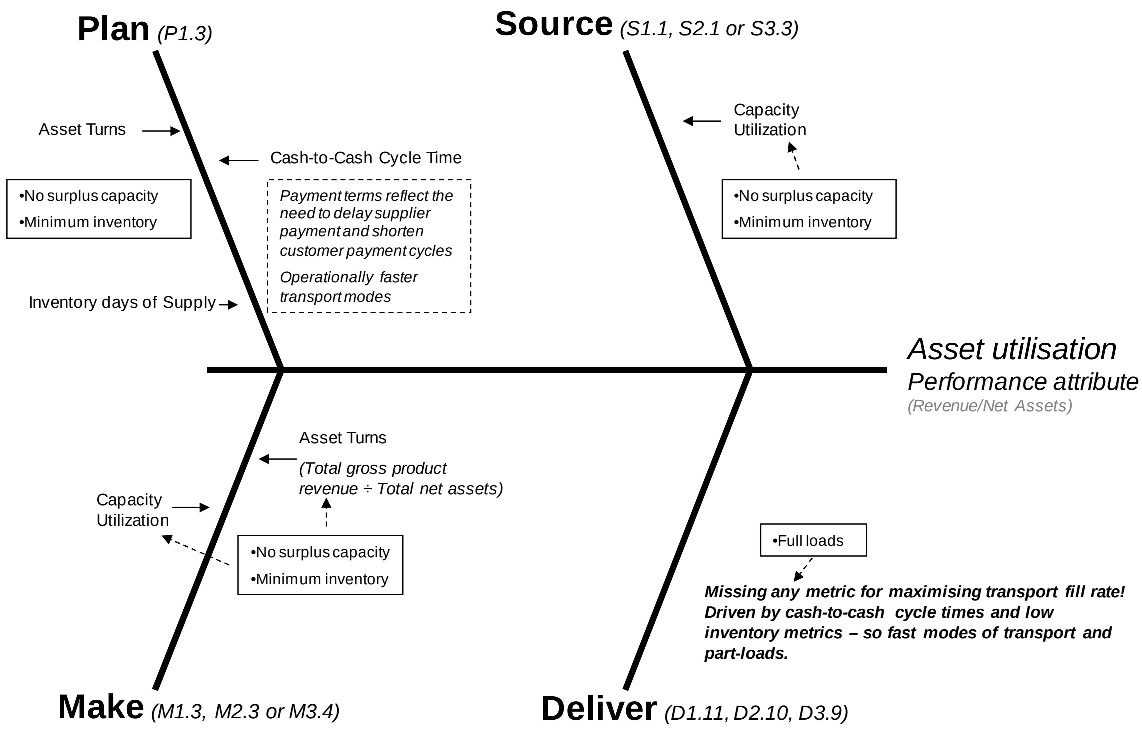

Figure 16. Operational adjustments to Utilisation performance

Moving away possibly from its Operational roots (capacity used), Utilisation is defined at Level 1 as the Total gross product revenue / Total net assets.

Figure 14 is the Ishekawa/fishbone diagram displaying the prescribed metrics and deduced operational adjustments (highlighted in the 'boxed' text) for the Utilisation performance attribute. Low inventories, fast transportation options and limited but well utilised manufacturing facilities describe the operational responses and adjustments to this performance priority.

5.2 Operational settings for each aspect of performance

By applying any developed and complex performance measurement system (such as the SCOR model) an organisation is in effect establishing the feedback mechanism by which it will adjust appropriate operational parameters in order to achieve some target performance value(s). Fig 17 is a useful summary of the deduced operational settings/adjustments for each aspect of performance described in section 5.1 along with a single, defined metric for each of those five aspects.

The initial work in this field (Forrester and Wright 1961) used a model with four links; Retailer, Wholesaler, Distributor, and Factory. By analysing how these links react to deviations between actual and target inventories it was established that ‘common sense’ strategies may actually amplify fluctuations in the demand up the Supply Chain. Later it was established (Lee, Padmanabhan et al. 1997) that this amplification was one of the causes of the Bullwhip effects. The format of the supply chain used in the initial studies, four roles, has since been repeated frequently and is the basis of much work in this field.

Whilst the Beer Game model is clearly appreciated by academics and trainers alike, both of whom make wide use of it, the model does contain a number of simplifications. Two such simplifications are; the single route network (with only one supplier, customer etc.) and a single product/SKU. Whilst the bullwhip effect can clearly be generated and studied in the Beer Game model, the SCOR model was designed for more complex systems (multiple suppliers, products, plants etc.). As a consequence of this some of the operational adjustments and their associated metrics, for example SMED (Single Minute Exchange of Dies) would be inappropriate in this supply chain and, following SCC implementation guidelines, would not be implemented locally.

				Using these three variables alone we can identify unique operational settings for all five aspects of performance		
Aspects of SC-Performance	***Metric***	***SCOR explanation of the metric***	***Source reference for metric***	***Capacity***	***Safety Stock***	***Transport***
Reliability	**Percentage of orders delivered within customers lead time.**	Delivery Performance, Fill Rates & Perfect Order Fulfilment. The percentage of orders that are delivered on the customer's requested date.	*SCOR Version 6.1 2004 Page 7*	**Up**	**Up**	**Sea/Regular**
Responsiveness	**Average Cycle time of all orders**	Supply Chain Responsiveness - The velocity with which products are supplied to the customer. SCOR L1 metric "Order Fulfilment Lead Times"	*SCOR Version 6.1 2004 Page 7, Page 281*	**Up**	**Up**	**Air/Courier**
Flexibility	**Material throughput time**	Supply Chain Flexibility - The agility of a supply chain in responding to marketplace changes to gain or maintain competitive advantage. SCOR L1 metric "Supply Chain Response Time"	*SCOR Version 6.1 2004 Page 7*	**Up**	**Down**	**Air/Courier**
Cost	**Total cost per unit delivered**	Supply Chain Costs - The costs associated with operating the supply chain. SCOR L1 metric "Cost of Goods Sold"	*SCOR Version 6.1 2004 Page 7*	**Down**	**Down**	**Sea/Regular**
Utilisation	**Asset turns**	Asset Turns - Total gross product revenue ÷ Total net assets. This includes the management of all assets: fixed and working capital	*SCOR Version 6.1 2004 Page 7, Page 280*	**Down**	**Down**	**Air/Courier**

Figure 17: Operational Settings for the 5 SCOR aspects of performance.

Three key areas of operation are represented;

- Capacity (warehouse and/or manufacturing).
- Safety stock levels (in order to meet uncertain customer requirements).
- Transport which has been given an operational connotation to aid explanation (sea freight as opposed to airfreight and/or regular delivery as opposed to courier service).

Restricting the breadth of the operational adjustments to these three key areas, still delivers a unique arrangement of abstracted settings for each of the five aspects of performance (Fig 17) but also maintains the key benefits from choosing the Beer Game supply chain; simplification to minimise complexity and a standard form to ease comparison with other studies and communication in general.

5.3 Prioritising aspects of performance

There is no apparent mechanism, within the SCOR model, for dynamically prioritising the five performance aspects; indeed the SCOR model literature indicates it may actually be deficient in this respect. “The first necessary compromise focused on how to distribute the channel performance requirements” (Bolstorff and Rosenbaum 2007).

During the initial stages of applying the model the current organisational strategy is established and this in turn dictates the performance priority, **Appendix 5** is a copy of an email from the SCC confirming this approach for establishing ‘Advantage’, ‘Superior’ and ‘Parity’ performance targets for different aspects of performance. This approach does appear to be somewhat intermittent however, with no facility to make changes in strategic direction or accommodate a dynamic commercial environment without a major Project undertaking. The commercial reality of long-term trends such as global sourcing and short-term realities such as the credit crunch might realistically require on-going adjustments of priorities on a more immediate basis.

Once the SCOR model is applied however the priority of each of the five aspects of performance is examined as the value of individual metric changes in relation to the fixed (or otherwise) performance target. Where more than one value is below the target then some stated preference/priority exists to ultimately dictate which combination of operational adjustments/settings is applied.

5.4 Setting SCOR performance targets

The approach advocated by the SCC (Bolstorff and Rosenbaum 2007) for applying the SCOR model involves not only the measurement and benchmarking of performance for any number of processes, but also a review of; market plans, financial performance and a SWOT analysis of the company. Thus the “AS-IS” model of the supply chain and the “TO-BE” positions are agreed. Figure 18 represents the “AS-IS” and “TO-BE” process objectives and phrases such as ‘Superiority’ and ‘Advantage’ refer to actual metric values relative to ‘Parity’ being the benchmarked SCC standard value against which the organisation compares itself. This is potentially useful in practice as a set of target metric values can be established, admittedly qualitatively as these values are the output of the ‘consultancy’ phase of SCOR implementation.

Aston University

Illustration removed for copyright restrictions

Figure 18. Strategic objectives leading SCOR metrics. Source Kasi, 2005

Being a normative modelling approach (forcing the user to select from pre-specified sets of activities) in theory SCOR could identify bad performance in areas previously unidentified. SCOR certainly helps identify areas where the company is performing well and areas where the company is performing at levels lower than the wider SCOR community (SCC members).

Such reference models, where companies can benchmark individual processes without divulging financial performance, can improve cost competitiveness whilst protecting commercially sensitive data and may explain the continued popularity of reference models amongst practitioners (Van der Zee and Van der Vorst 2005). They are also used in academic research; in one simulation experiment (Chan, Tang et al. 2002) establishes the optimum order release mechanism to achieve a delivery reliability of 69%, as opposed to a benchmarked *'norm'* of 57%. Whilst 69% may not be a target reliability performance measure that many firms would wish to advertise, it might be argued that investment in improvement of any one aspect of service should be reduced once an organisation achieves a position of 'best in class' as further investment offers reduced levels of return.

5.5 Conclusion

The top tier of the SCOR metric system evaluates the overall strategic organizational activities in a supply chain context. These metrics adhere to the standard recommended (Schneiderman 1996) in that; a metric system should contain no more than five top tier metrics given that a large number diffuses the focus of the strategic activities and they should consist of internal and external results performance.

In selecting the SCOR model Level 1 performance metrics, a single objective metric can be used to monitor each of the five different aspects of supply chain performance; delivery reliability, flexibility and responsiveness, supply chain cost, and asset utilisation. There is a precedent for this approach (Wang, Huang et al. 2004) where the SCOR model level 1 performance metrics were used as the decision criteria in an investigation of the lean/agile and functional/innovative nature of supply chain design.

A set of plausible operational changes/adjustments, for each of the supply chain roles (Manufacturer, Distributor, Retailer), in order to bring any of the five metric values back to an acceptable value has been established. These adjustments consider the entire range of Level 2 SCOR metrics for each of the five aspects of performance and involve the three significant adjustments; Production Capacity, Safety Stock levels and Mode of Transport. Whilst individual adjustments may be common across more than one priority, the combination of three areas of adjustment also delivers a unique arrangement of settings for each of the five aspects of performance.

6. METHOD

This chapter presents the key literature used in identifying and selecting an appropriate method for investigating whether the application of the identified Supply Chain Performance Measurement system has an impact on the variability of demand up the Supply Chain/*the Bullwhip effect*. The notion of utilising selected previously published approaches to explore an idea that has previously been unobserved is not necessarily a weakness.

"You might be surprised to find that many of today's hot problems were pretty much of concern from the start and that many of the proposed solutions are really elaborate versions of ideas that originated early on. This realization might be slightly humbling. But on the other hand, the sense of continuity with the past and the future might prove extremely satisfying."
The most useful applications of business process modelling and simulation will likely be those that further elaborate on ideas that have already been explored but, for any number of reasons, have never been fully elaborated (Barnett 2003).

To this end, the method and approach taken in much of the published work on *causes* and *measurement* of the Bullwhip effect has been utilised in the following sections.

6.1 Supply Chain Methodologies

It would be possible to base the research methodology on a survey of real supply chains to determine if a correlation between applied performance measures and demand variability could be established. Such an approach however requires that;

- Supply chain (or chains) exists where such a holistic framework is in use.
- Results could be successfully generalised from a single supply chain or that a suitably large number of supply chains could be found.
- A suitable range of conditions can be observed that allow conclusions to be drawn about the circumstances in which demand variation occurs.

The difficulty with establishing the validity of these assumptions means that a case-based approach is likely to be very limited in scope and general validity of conclusions and as a result a proven approach is required from the literature.

One extremely widely cited review of Supply Chain methods is that of Beamon (1988). Riddalls, Bennett et al. (2000) also produced a notable work appraising the various methodologies that have been applied to supply chain analysis over the last 40 years, evaluating each technique for the extent it reveals the dynamics of the process involved. This criteria is key as only through knowledge of the dynamics can we gain a full appreciation and understanding of the factors that affect Supply Chain performance.

The objective then is to select a methodology that can capture dynamic behaviour in Supply Chains whilst accommodating the level of complexity required in order to capture the operational performance metrics. "Whenever faced with a complex supply chain operational problem, most people develop a solution by building a model of the situation". various hypotheses can be readily and quickly tested in an abstract or idealized manner" (Group 2007). In this context the model is an abstract representation of the supply chain that reduces complexity and represents only the details necessary. The rationale for this approach is that models of modest complexity can provide an insight into the factors that are common to much larger 'live' systems. Such symbolic models were early recognised (Mihram 1972) as one of the primary methods by which operational research is progressed.

Computer simulations are dynamic representations, *in this case of a supply chain*, executed step-wise within a computer program. Such models are highly accurate and given an accurate representation of the processes and an initial set of conditions, can be used to replicate system behaviour within the system. Exchanges, events and time can be readily included in the model and an assessment of performance changes over time can be observed. Such a process however requires considerable effort as the user has to understand the characteristics of the internal operations of the whole supply chain (Persson and Olhager 2002).

Researchers have in the past adopted different methodologies to construct various models to explore Bullwhip. Statistical methods (Chen and Samroengraja 2000), System-Thinking approaches (Anderson, Fine et al. 2000) and Control-Engineering (Dejonckheere, Disney et al. 2003 and Disney and Towill 2003) all investigate ‘demand forecasting methods’ as a cause of Bullwhip. All four papers reach similar conclusions; that the number of observations used should be high in order to minimise the bullwhip effect, but this demonstrates the options available to the researcher in this case.

The literature (Labarthe, Espinasse et al. 2007; Mason 2009) identifies three main approaches to Supply Chain Modelling; Analytical, Organisational and Simulation. These together with a fourth, more recent approach; ‘agent-based’ modelling - all warrant consideration.

6.1.1 Analytical approach to modelling

Analytical approaches, including *optimization* based models, are solution approaches that utilize the mathematical modelling of the problem to find the optimal solution. Modelling supply chains using mathematics holds great appeal for the control theorist, because many of the influential characteristics of the problem can be succinctly expressed as differential equations. However since differential equations produce ‘smooth’ outputs, they are not suited to modelling the progression of individual entities through the system (Riddalls, Bennett et al. 2000) and often lack an estimation of the variability or robustness of a solution (Geary, Disney et al. 2006).

Such models generally require simplifying approximations which impose restrictions and have limitations when considering the time based behaviour of the supply chain. Supply Chains are considered at an aggregate level; stocks and flow rates, in which individual entities in the system (products) cannot be considered. Consequently, these methods are not suited to processes in which each individual entity has an impact on the fundamental state of the system.

Some authors (Barnett 2003) positively advocate alternative methods better able to trace the cause to effect and thus generating explanations for any optimums identified. However if system dynamics are not a key issue then the use of static and/or optimization-based models is indeed appropriate as, given the appropriate expertise, these models can be produced and tested relatively quickly.

6.1.2 Organisational approach to modelling

Organisational based approaches deliver some amount of optimization capability but generally consider more simplistic, static models. The organisational approach relies on process modelling based largely on systems theory and again the models produced do not produce a means to evaluate dynamic behaviour over time when dealing with stochastic environmental inputs. Such models have a limited applicability (Van der Zee and Van der Vorst 2005) as the complexity of supply chains obstruct such evaluation. More recent work on Supply Chain performance measurement actually recommends more elaborate tools such as simulation (Labarthe, Espinasse et al. 2007).

6.1.3 Simulation approach to modelling

Computer simulation is well established as a problem-solving tool which can easily handle; uncertainty, complexity (Banks and Malave 1984) and capture the dynamic nature of supply chains involved (Kasi 2005). A model typically has the following characteristics (Barnett 2003):

1. It is a quantitative, mathematical, computer model.
2. It is a dynamic model; i.e., it has at least one equation with at least one variable that refers to at least two different points in time.

3. The model is not solved by mathematical analysis; instead the time paths of the elements are computed, given the initial state of the simulated system, and given the values of the exogenous (input) variables.

Simulation therefore does not give a ‘closed form’ solution, instead different input values and model structures are investigated in terms of output, so-called sensitivity analysis and the level of effect can thus be established. Because simulation can be applied to operational problems too difficult to model and solve analytically (for example the impact of variability) it is an especially effective tool to help analyze supply chain logistical issues (Schunk and Plott 2000). In fact even when an analytical model is applied to a problem, simulation is frequently used to study the practical implications of the assumptions underlying the analytical model (Al-Zubaidi and Tyler 2004).

Towill and his co-authors have studied the bullwhip effect using a computer simulation model numerous times (Towill, Naim et al. 1992; Towill and Naim 1993; Towill 1996; Mason-Jones, Naim et al. 1997; Mason-Jones and Towill 1997; McCullen and Towill 2002; Towill, Zhou et al. 2007). The results of this anthology of studies indicate that information and/or material delays are major contributing factors to the bullwhip effect as demonstrated when demand amplification was significantly reduced once these delays were eliminated in the model. Furthermore simulation has been used to show that the bullwhip effect is evident across a range of forecasting methods (Dejonckheere, Disney et al. 2003; Towill, Zhou et al. 2007).

However an approach based on simulation imposes the prior definitions of all the factors (and their related model parameters) that are of interest, consequently detailed models take a long time to simulate becoming impractical if the model is too big (Terzi and Cavalieri 2004). This means effort must be made to simplify the model wherever possible; One common mistake in modelling and simulation is to build an overly complex model, resulting in an over-abundance of data and great confusion in analysis of the results (Barnett 2003). Such simplifications must still be justified however as simulations can be challenged on the grounds that they are an attempt to reproduce the real world and thus if that representation is inappropriate or incomplete then the results produced from the model will be unreliable. Fortunately validity and verification procedures (Herman, 1967) have been developed to deal with this issue.

6.1.4 Agent based models

In recent years, many researchers (Barbuceanu and Fox, 1995; Van Parunak and Vanderbok, 1998) have used multi-agent technology in Supply Chain modelling. In agent-based modelling, organisation units and processes are designed as agents that have their own; objectives, behaviours and interfaces. Intelligent decision and learning rules are defined within agents and as the model runs agents exchange messages. Supply chain performance is said to be improved through agent co-ordination, however the main limitation is that current agent technologies are rich in decision logic but less developed in terms of tracking the dynamic individual elements required for supply chain reengineering (Al-Zubaidi and Tyler 2004).

6.2 Use of Simulation to study the Bullwhip effect

Simulation as a technique for understanding and predicting the behaviour of supply chains offers several advantages (Terzi and Cavalieri 2004);

- Simulation offers the most realistic observation of behaviour.
- Facilitates analysis of the **dynamics** of the supply chain.
- Can observe changes over time.
- Simultaneously represent organisational decision making processes.
- Analyse the interdependencies of roles within the supply chain.
- Analyse the consistency between the coordination modes and the decision policies.

- Can evaluate the effectiveness of new policies before implementation (Venkateswaran, Son et al. 2002).
- Unaffected by politically and emotionally charged circumstances under which such decisions are often made (Swaminathan, Smith et al. 1998).
- No identified mechanism for measuring the bullwhip adequately indicates which of the different causes is (chiefly) responsible or which solutions are therefore most relevant. This question can be addressed via simulation but it is not feasible in practice.

Unsurprisingly numerous researchers have used simulation models of a supply chain to study different aspects of the supply chain such as the instability of the chain, performance effects and demand amplification (Venkateswaran, Son et al. 2002). Widely referenced in the literature Towill, Naim et al. (1992) use simulation techniques to evaluate the effects of various supply chain strategies on demand amplification. Strategies investigated include;

1. Eliminating the distribution echelon by including it in the manufacturing echelon (make and send directly from factory)
2. Integrating the flow of information throughout the chain.
3. Introducing a JIT policy to reduce lead time delays.
4. Improving the movement of WIP by modifying order quantity procedures.
5. Modifying the parameters of the existing order quantity procedures.

The simulation model successfully showed that the echelon removal strategy (1) and the JIT strategy (3) were observed to be the most effective in smoothing demand variations. To select simulation as a suitable method for the analysis of dynamic Supply Chain behaviour is therefore a defensible decision. Simulation models can handle stochastic behaviour throughout the SC and by doing that, queuing situations and other phenomena dependent upon uncertainty in operation and transportation times can be evaluated (Persson and Olhager 2002).

6.3 Types of Simulation

Within the area of simulation modelling are a number of identifiable options.

6.3.1 Spread sheet models

Most spread sheet models are static in nature and are simple aggregations or consolidations of data that are sometimes described as simulation. Steady-state models are valuable, but they hide or gloss over the actual behaviour that occurs in a real, dynamic process (Holweg and Bicheno 2002).

6.3.2 System Dynamics

System Dynamics is a computer-aided approach for analysing and solving complex problems with a focus on policy analysis and design (Angerhofer and Angelides 2000). System dynamics views companies as systems with six types of flows; materials, goods, personnel, money, orders, and information. In so doing it assumes that managerial control is realized through the changing of rate variables which in turn change flows and hence stocks. A crucial role is played by the feedback principle; i.e. a manager compares a target value for a specific performance metric with its realization, and in case of undesirable deviation this manager takes corrective action.

6.3.3 Gaming

Acknowledging the fact that it is relatively easy to simulate defined operational processes but far more difficult to model human behaviour, mention must be made in this section of the possibility of simulation via business gaming. This solution, whereby managers themselves operate within the simulated world of a Supply Chain and its environment, offers many benefits particularly when demonstrating to practitioners. As described in section 2.1.1 gaming may be an avenue for wider communication in future, however as this is the first attempt to explore the impact of supply chain performance measurement on the bullwhip effect, more quantitative methodologies are considered appropriate.

6.3.4 Discrete Event Dynamic Simulation (DEDS) Models

The objective of DEDS is to understand the dynamics of the system and ultimately to identify strategies to minimise inefficiencies in the systems. Such systems comprise of jobs and resources; jobs are physical entities that travel from resource to resource where their attributes are changed as they progress through the system. For example, in a model of a supply chain, the jobs are products that progress through transport and buffer inventories (both resources) to arrive at the retailer.

The main reasons to use discrete event simulation are;

- Able to capture system dynamics where time dependant relations are analysed.
- Permits the evaluation of operating performance (Chang and Makatsoris 2001)
- Has the capability of capturing uncertainty and complexity (Jain, Workman et al. 2001)
- Computationally efficient, intuitive and easy to understand (Barnett 2003).

DEDS has advantages over Analytical methods as the complexity of Supply Chains obstructs analytical evaluation (Van der Zee and Van der Vorst 2005) and is the preferred method used for simulation of supply chain (Terzi and Cavalieri 2004)

6.4 Conclusion

This chapter has established from the literature that; Analytical and Organisational approaches to Supply Chain behaviour typically consider only average demand under static conditions and cannot deal with the complex interactions within a supply chain (Swaminathan, Smith et al. 1998). Phenomena like demand amplification (*the purpose of this study*) must be investigated by methods based on the dynamics of the system (Riddalls, Bennett et al. 2000) and Simulation is the most widely supported tool for examining how the dynamic behaviour of the Supply Chain reacts to controllable factors.

Which type of Simulation is appropriate however, depends on the problem to be solved;

- System Dynamics can readily demonstrate the bullwhip effect and offers useful qualitative insight.
- Games can educate users whilst studying the effects of qualitative factors (such as type of decision support system.
- DEDS simulation can track the sequence of linked decisions arising as an order proceeds through the physical supply chain, whilst measuring the performance of systems and its individual components.

The ability of DEDS to capture events and express them numerically, with the ability to reproduce a scenario under differing experimental conditions for sensitivity analysis, means it is the method of choice for investigating dynamic behaviour in supply chains and will be adopted in this work.

The decision process itself would also need to be simulated so that changes in performance priorities are reflected in the decisions made. In a Simulation context this is little unusual since in most studies the policy, level of safety stock levels for example, is constant throughout the simulation run. In this case that policy would be reviewed as the model runs so that, in this example, the target safety stock would be recalculated each period. The way the SCOR performance metrics were incorporated in this review process would also have to be defined. This type of review would apply to all the operations processes in the supply chain and thus would encompass reviews of resource levels, order policies, production and transport alternatives. This type of modelling is more common in System Dynamics than in DEDS but there is no reason why a discrete simulation could not incorporate such processes (Stone and Love 2007) and to do so would further enhance the originality of this work.

7 THE MODEL

From previous Chapters it has been established that this model must;

- Generate and capture the quantitative level of Bullwhip within a simulated supply chain. Since dynamic behaviour is itself a function of the structure of the system (Disney, Naim et al. 1997) use will be made of the (remarkably few) system designs that have been used to successfully study Bullwhip present in the literature.

- Simultaneously record SC performance across all five SCOR aspects of performance, at each of the three roles; Retailer, Distributor and Manufacturer, and compare them to individual sets of target values.

- Incorporate an *optional* (as testing IF the application of performance metrics changes the dynamic behaviour of the model is fundamental) mechanism to dynamically prioritise one of the five aspects of performance, at each role and adopt the predefined operational settings see fig 19.

- Record the 'standard deviation of demand at each order point' (as dictated in section 2.3) and to record necessary model parameters in order to; assist in debugging of the model and to indicate the cause of any dynamic behaviour within the supply chain.

Binary Switch.

A 2nd facility (which same unit cost but additional fixed cost) may be available.

Utilised as required (queue length) this offers available capacity but at higher production cost.

Binary switch.

Air Freight has a higher cost and a smaller min batch size than Sea. Air departures are more frequent and transit times are shorter. Reliability is the same.

Similarly for Courier transport as opposed to domestic haulage.

	Manufacturer			Distributor		Retailer	Consumer	*Level 1 associated metric*
The five SCOR aspects of performance	Production Capacity	ReOrder Point	Transport International	ReOrder Point	Transport domestic	ROP	Demand	
Reliability	2 facilities	ROP up	Sea	ROP up	Regular	ROP up	Mean and std dev. to describe size and intervals of orders.	*Fill rates*
Responsiveness	2 facilities	ROP up	Air	ROP up	Courier	ROP up		*Order Fulfillment lead time*
Flexibility	2 facilities	ROP down	Air	ROP down	Courier	ROP down		*Supply Chain Response time*
Cost	1 facility	ROP down	Sea	ROP down	Regular	ROP down		*Total Supply Chain cost*
Utilisation	1 facility	ROP down	Air	ROP down	Courier	ROP down		*Asset turns or 'revenue/assets'*

ROP is the primary policy adjustment in the model.

Figure 19. Process configuration and Performance priority. Source author

7.1 *Outline Model Structure and Requirements*

The typical simulated supply chain (see Fig 1) consists of; Customer, Retailer, Distributor, Manufacturer and a Supplier. The Customer/consumer places orders with and receives goods from stocks kept by the Retailer. The Retailer places orders with and receives goods from stocks at the Distributor. The Distributor, in turn, place orders to and receives goods from stocks at the Manufacturer. The Manufacturer produces the goods, in its facilities, utilising materials it has ordered from the Supplier.

In this case (see Fig 20) the three 'roles'; Retailer, Distributor and Manufacturer all operate independently; generating forecasts and referring to target stock levels so as to place orders and meet local demand as necessary. Such double forecasting, whereby incoming forecasts are generated at every decision point and then submitted to the preceding role where the same process occurs (Lee, Padmanabhan et al. 1997), is the original/principle driver for the bullwhip effect and consequently some, lower level Bullwhip should be witnessed prior to the application of the simulated performance metrics.

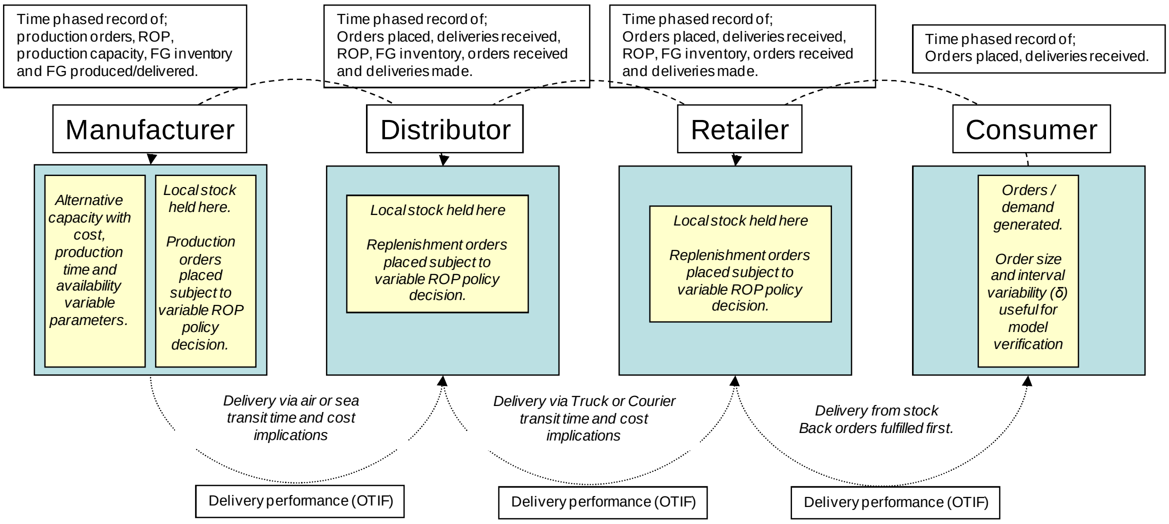

Figure 20. Model roles and required functionality

Each role will also independently monitor all five aspects of SC performance continuously, prioritising aspects of performance as necessary and applying the appropriate pre-defined settings accordingly. This again can be justified by reference to the literature, a typical supply chain involves multiple (semi)autonomous parties, which may have several possibly conflicting objectives (Van der Zee and Van der Vorst 2005).

The Customer represents the consumer demand and its role is limited to delivering the simulated demand and measuring delivery performance. The Supplier has unlimited material which it delivers to the Manufacturer as required, it does not measure performance or undertake any calculation or order processing activity.

The Retailer–Distributor (R-D) interface and the Distributor-Manufacturer (D-M) interface are serviced by independent transportation systems, Air or Sea transport for the D-M interface and Courier or Road haulage for R-D. The differing order intervals, quantities, transport batch sizes and transit times between each relationship pair define the model as an *asynchronous* supply chain (Das and Abdel-Malek 2003).

The specific simulation software used is not considered an issue in terms of the fundamental issues examined. In the past combinations of the simulation tool Arena and the procedural programming language Visual Basic for Applications (VBA) have been used to simulate supply chain systems with integrated decisions (Banks and Malave 1984). Developments in software mean that the model logic and the more complex algorithms programmed in VBA can now be accommodated in a single piece of software. For expedience; in terms of pre-existing licence agreements and local simulating expertise the model has been designed, implemented and run on Simul8 2007 and runs on a PC under the Windows operating system.

7.2 Assumptions

The art of simulation lies in deciding what should not be included in the model since the closer the model structure reflects that of the real system the more complex and inefficient it becomes (Love 1980). In all simulation studies it is relevant to specifically point out the model assumptions made (Balci 1998).

- Like the Beer Game the model is largely a single product retail distribution game, it does not therefore not take product conversion into account.

- Production facilities have finite capacities but because only one product is represented, machine setup and capacity allocation processes are not simulated.

- Supply material resources are assumed to be infinite and instantaneously available.

- Process reliability and quality problems are not included.

- Accurate information is assumed to be available.

- Each role replenishes the succeeding inventory, and places orders on the preceding inventory in the SC.

- Order cancellations are not permitted.

- Scheduling, ordering, purchasing and information transmission is instant.

- Aggregation of several activities into a single deterministic delay. For example, the entire manufacturing process and the transportation activities are represented simply as point delays.

- Complete back-ordering is assumed. If an order from a role exceeds the stock of the preceding inventory, the order is only partially filed and unmet quantity is backordered. When a part or the whole backordered quantity becomes available in stock, it is sent to the succeeding Role in the next delivery period. This delivery process continues until the whole ordered quantity is delivered

- All three Roles follow a continuous inventory review policy, calculating inventory levels, comparing them against their calculated re-order point (ROP) and placing an order of a defined batch quantity.

7.3 Inputs

The last decades of the twentieth century have witnessed considerable growth of global supply chain networks across a wide variety of industries. The level of interest in global supply chains and global operations management has actually been studied quantitatively (Meixell and Gargeya 2005) the number of articles published in 28 leading operations management journals has increased from 32 in 1986 to 88 in 1997. It seems appropriate therefore to include an international aspect to the model.

The Demand data used, Production, Purchase, Transport and Carrying Costs were based upon a brand of coffee-pot described in the published literature (Ulrich and Pearson 1998). This data has also been developed and used subsequently in work considering SC dynamics and the Lean/Agile debate (Taylor, Love et al. 2008) where standard deviation of demand values of 0.033, 0.133 and 0.33 were used to represent distinct Lean/agile parameters.

The opening Inventory levels, Reorder Points and Reorder Quantities (all input via the Input Spreadsheet) were established in the verification phase and plausible values that readily accommodated the model achieving steady state were established, for example;

Retailer

Opening Inventory	1000 units
Retailer ROP	1500 units
Retailer ROQ	200 units

Distributor

Opening Inventory	1500 units
Distributor ROP	1500 units
Distributor ROQ	200 units

Manufacturer

Opening Inventory	5000 units
Manufacturer ROP	5000 units
Manufacturer ROQ	200 units

7.3.1 Demand

Spread sheet functionality within Simul8 allowed for numerous parameters to be altered and entered quickly and easily.

Consumer Demand		
Interval	5 days	*Order arrives every 5 simulation days*
Inter-arrival time	1.6 days	*0.33 stdev*
Quantity	200 units	*Demand is 4000 Coffee pot's/day average = 40 orders per day.*
Std Dev	60 units/order	*0.33 stdev*

For ease of simulation (largely to achieve a workable simulation run time on a typical research standard desktop computer) 1 unit represented an order of 100 coffee pots. Key parameters describing individual orders; size and inter-arrival time were subject to their own separate stream of random numbers during the simulation runs.

By default, when the clock is set back to the start of the simulation time, all the random streams are reset to their starting seeds. This means that a second run of the same simulation will produce the same results. Seeds for the random numbers are changed by selecting; TRIALS > RANDOM SAMPLING from the main menu. This randomness ensures the model does not become deterministic.

7.3.2 Purchase and Carrying Costs

Various sets of published simulation work (Lambert and Pohlen 2001) might have provided cost data for the simulation model, each with its own varying level of deficiencies, but since first-hand experience had been established with a particular set of data (Taylor, Love et al. 2008) this formed the basis of the inputs.

TRANSFER PRICE		
Supplier	\$500/unit	\$5/pot
Manufacturer	\$4500/unit	\$45/pot
Distributor	\$5500/unit	\$55/pot
Retailer	\$7000/unit	\$70/pot

CARRYING COST	**per unit/day**	**30% p/a of Role sale price**
Manufacturer	3.699	\$4500/unit x 30% x 1/365
Distributor	4.521	\$5500/unit x 30% x 1/365
Retailer	5.753	\$7000/unit x 30% x 1/365

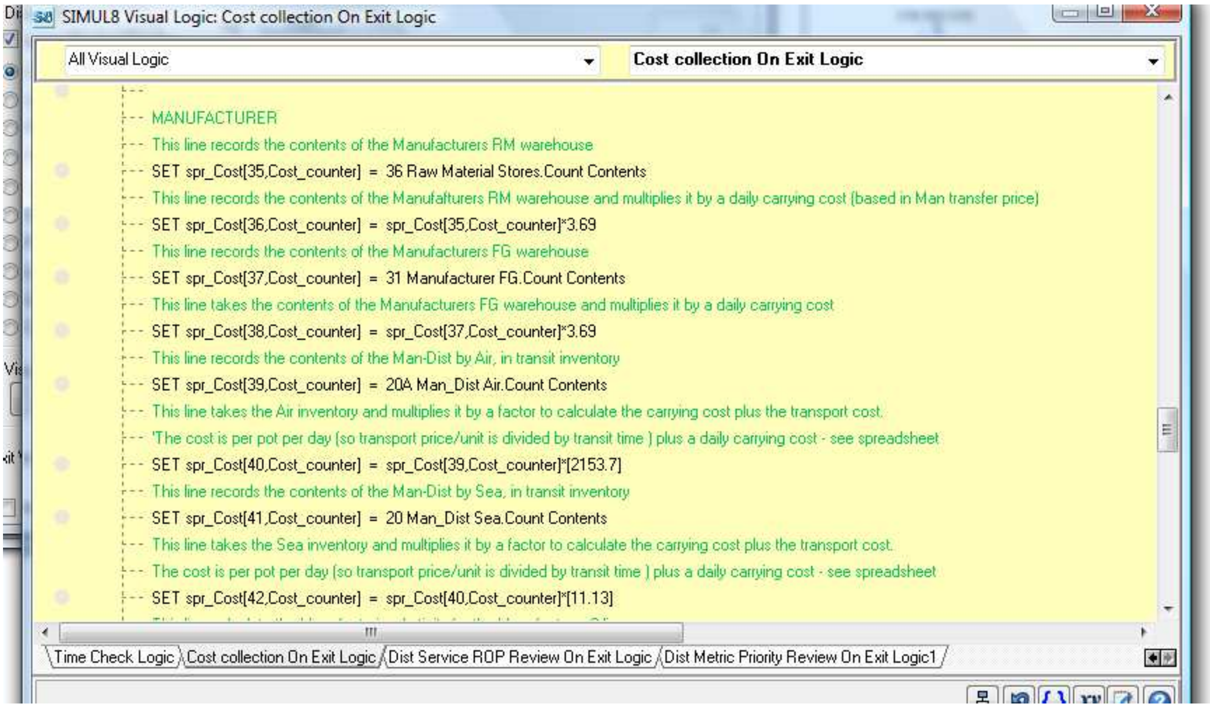

Figure 21. Example of visual logic calculating transport carrying costs. Source author.

Since they reflect realistic/commercial values the Purchase Prices and Carrying Costs for the material/coffee-pots were hard coded into the visual logic (Fig 21). Investigation of the relative weighting applied to the performance metrics associated with Cost and Utilisation could be varied readily as necessary and this would avoid unnecessary complication of the model.

7.3.3 Transportation

Based on the packed dimensions: 30cm x 25cm x 40cm = 0.03cbm, standard Pallet (base dims 1m x 1.2m) carries some 1.2 cbm cargo or 40 pots/pallet. Standard ISO container (approx 30 cbm usable space) carries some 12 pallets double stacked so 48 pallets in total (48 x 40) or 960 pots/container.

There are two interfaces where a choice in transportation mode will occur; Manufacturer-Distributor and Distributor-Retailer. Labels are associated with orders according the Role's performance priority and these flags determine the transport route these orders take (Fig. 19). The Supplier-Manufacturer interface is assumed to be serviced perfectly by the Supplier, in real terms this might represent a Cost Insurance and Freight (CIF) INCO term. The Retailer-Customer interface is similarly assumed to enjoy zero transit time, representing the Customer operating the transport themselves as with most retail store operations.

Since the desired model has to be sufficiently sophisticated in order to capture; transport costs plus the inventory costs of the goods in transit (in order to fully capture the cost implications of transport options), the visual logic is programmed to capture the daily content of the transport element and use this to calculate; the daily transport cost (the unit total transport cost/transit time) + daily carrying cost (transfer price x 30% x 1/365).

Manufacturer – Distributor Transport costs:

- China – US Sea Freight costs: $2,500 per container or (2500/960) with a transit time of 6 weeks (Taylor, Love et al. 2008) is some $0.11 per coffee pot per day.

- China – US Air Freight costs: 2 pallets of air freight @ $4.70/Kg (Zeng 2003) with price adjusted for years (Taylor, Love et al. 2008) is some $21.15 per coffee pot per day.

Manufacturer - Distributor				
Sea transport batch size	14 units	*1400 pots per container*	Sim item 19 prop, route in	
Sea transport transit time	35 days		Sim item 20 prop	
Sea transport cost (incl CC)	$11.13/unit/day	$2.60 per pot by sea (So) $260/batch ... (260/35)*transport/day* +(4500x(0.3x(1/365))*daily carrying cost*		
		per pot = (2.60/35)+(45*(0.3*(1/365))) =	0.111272016	
Air transport batch size	14 units		Sim item 19, routing in	
Air transport transit time	1 day		Sim item 20a, prop	
Air transport cost (incl CC)	$2,153.70/unit/day	$21.05 per pot by air (So) $2105/batch ... (2105/1)*transport/day* +(4500x(0.3x(1/365))*daily carrying cost*		
		per pot = (21.50/1)+(45*(0.3*(1/365))) =	21.5369863	

Distributor - Retailer Transport costs:

- Standard: 3 day groupage service freight rates $30 per pallet or $0.75 per pot (based upon a competitive city centre delivery tariff) or $0.295 per pot per day.

- Courier: 1 day (next day) service freight rates $50 per pallet or $1.25 per pot or $1.295 per pot per day.

Distributor - Retailer				
Road batch size	1 unit	48 pots per pallet	Sim item 7, prop, route in	
Road transit time	3 days		Sim item 10, properties	
Road transit cost	$29.52/unit/day	$30 per pallet of 40 pots OR 0.75/pot (So) (0.75)/3 day transit +(55x0.3)x(1/365)) daily carrying cost		
		per pot = (0.75/3)+(55*(0.3*(1/365)))=	0.295205479	
Courier batch size	1 unit		Sim item 7, prop, route in	
Courier transit time	1 days		Sim item 10A, properties	
Courier transit cost	$129.52/unit/day	$50 per pallet of 40 pots or 1.25/pot (So) (1.25)/1 day transit +(55x(0.3x(1/365)) daily carrying cost		
		per pot = (1.25)+(55*(0.3*(1/365))) =	1.295205479	

7.3.2 Production Costs

Production costs for the standard product are based upon previous published work using the coffee pot data. Typical production costs are $10.85 per coffee pot and this facility is incorporated into the model in the simulation item number 30 labelled "Manufacturer".

There is an additional production facility; 30A, labelled "Manufacturer 2" representing an optional additional production facility but in theory could represent the range of feasible production strategies a manufacturer might employ to cover periods of excess demand; overtime, outsourcing and/or additional/excess capacity. (*Excess in so far that the standard; "Manufacturer" has capacity equal to mean Consumer demand i.e. 40 units each day).* The standard cost for this additional facility was initially set at standard facility plus 50% or $16.28 per coffee pot and the sensitivity of this figure was investigated in the model verification phase.

Production						
Manufacturer (1)						
Production time	0.6 days/unit/workcentre		Input SS (2,5)			
Capacity	27 workcentres	27 workcentres @ 0.6 days/unit; 45 units/day	Sim item 30, prop, Replic.			
Production Cost	$1,085/unit	should be $10.85 per pot so $1085 per unit	Sim item Cost Collection, Visual logic hard code,			
			Cost SS; Daily count of both Man elements X their cost/unit			
Manufacturer (2)						
Production time	0.6 days/unit/workcentre		Input SS (2,5)			
Capacity	27 workcentres	27 workcentres @ 0.6 days/unit; 45 units/day	Sim item 30, prop, Replic.			
Production Cost	$1,194/unit	Production costs $20 per pot so $2000 per unit	Sim item Cost Collection, Visual logic hard code			

When the link to "Manufacturer 2" is available (Fig 19), the link being established according to the Manufacturer's performance priority (see section 7.4), then orders are directed to this, more costly, option when the primary facility "Manufacturer" is engaged.

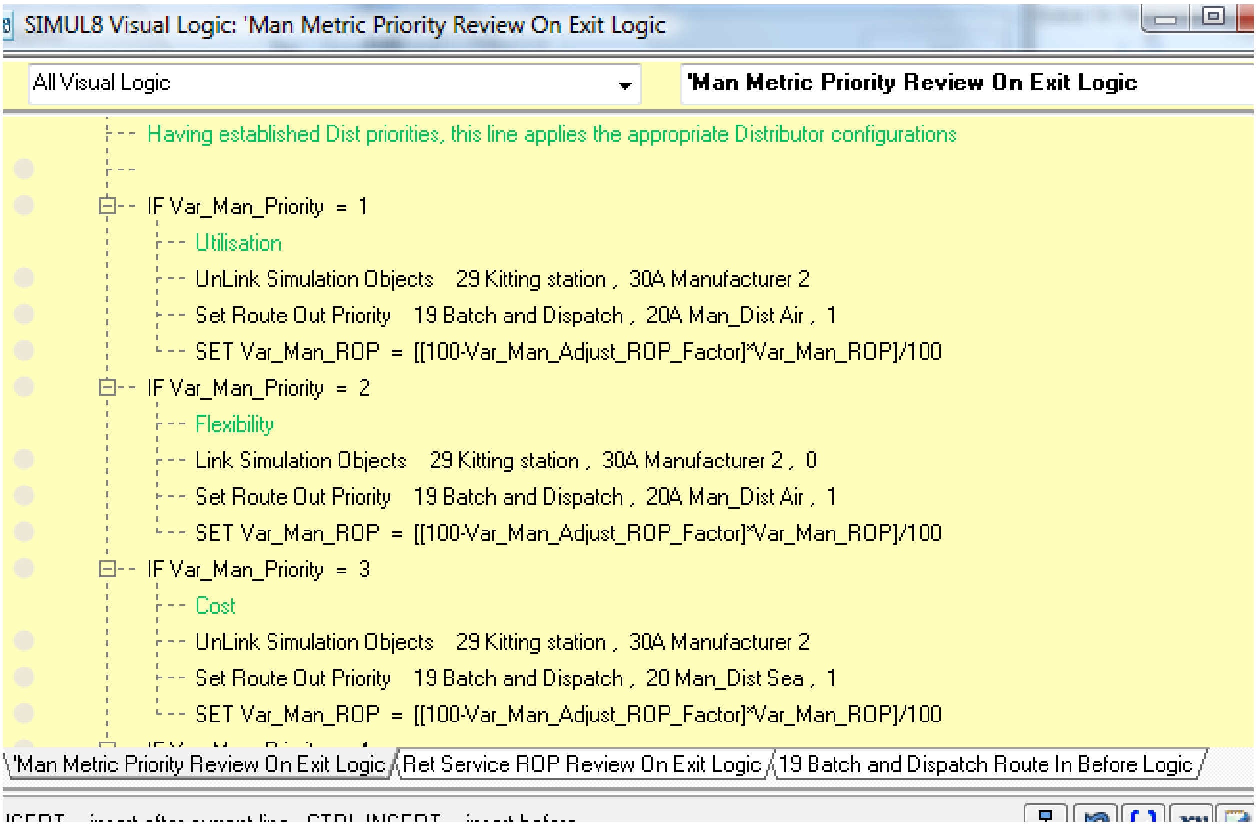

Figure 22. Additional manufacture facility 'linked' according to Manufacturer performsnce priority.

7.4 Re-order Point calculation

Various articles give detailed accounts of the ordering mechanisms used in Bullwhip simulations. (Al-Zubaidi and Tyler 2004) give a valuable account of the merits of the mathematical expressions whilst Holweg, Disney et al. (2005) graphically represents the ordering processes with a water tank model.

Aston University

Illustration removed for copyright restrictions

Figure 23: Water tank model with independent ordering decisions. Holweg 2005

Inventory levels are continuously monitored and as soon as total inventory drops below the reorder point, a replenishment order is triggered.

As in other models, the order point is determined by estimating the expected usage during lead-time plus some expression for calculating a safety stock (Al-Zubaidi and Tyler 2004). This demand forecast will be calculated as the moving average of the demand over a given (variable) number of periods. Disney, Naim et al. (1997) discusses the merits of the various averaging options including moving average and exponential smoothing.

Alternative mechanisms might be tested in due course but on the grounds that the fundamental question requires merely the inclusion of a representative mechanism then a simple moving average method is utilised. The calculated average demand is multiplied by a variable input figure (Bullwhip ROP Review Multiplier) which acts as a classic safety stock multiplier. This mechanism generates the required Bullwhip effect and readily facilitates adjustment of the scale of the effect for simulation purposes.

SET Var_Ret_ROP = Var_Ret_Bull_ROP_Multiplier*Var_Ret_Avg_Demand

RETAILER POLICY	Trigger Level %	Multiplier	Change ROP by (%)	Number of Weeks Averaged	Review Interval (Days)	
Service ROP Review	0.9		5	20	20	tri
Finance ROP Review			-12		999999	
Bullwhip ROP Review		1		10	20	
Capacity (stns) Review - Reduce	10		-1	5	30	
Capacity (stns) Review - Increase	100		1	5	30	

NB Num stns is increased or decreased based on the length of backlog queue at mfg. NB Averag

MANUFACTURER POLICY	Trigger Level %	Multiplier	Change ROP by (%)	Number of Weeks Averaged	Review Interval (Days)	
Service ROP Review	0.9		5	20	20	tri
Finance ROP Review			-12		999999	
Bullwhip ROP Review		3		10	20	
Capacity (stns) Review - Reduce	10		-10	5	30	tri
Capacity (stns) Review - Increase	100		10	5	30	tri

NB Num stns is increased or decreased based on the length of backlog queue at mfg. NB Averag

Figure 24. ROP calculation and Bullwhip. Source author

In Fig 24, for validation purposes only, the Retailer ROP is based upon a 10 week moving average of downstream (Consumer) demand, multiplied by a Bullwhip Multiplier factor of 1. The Bullwhip Multiplier is essentially a 'safety stock' multiplier which is multiplied by the average demand in order to establish a reorder point that includes a level of safety stock. The Manufacturer ROP (in this example) is based upon a 10 week moving average of downstream (Distributor) demand, multiplied by a different Bullwhip Multiplier factor of 3. These two distinct components of ROP calculation were considered important as whilst the Bullwhip Multiplier offers an immediate way to directly influence the size of safety stock held at various Roles, the demand average period is noted in much of the published work as a key experimental variable in simulating the Bullwhip effect, longer periods actually reducing the quantity of Bullwhip.

In the model a replenishment order is placed as soon as the inventory level drops below the reorder point. In the case of the Manufacturer, Economic Batch Quantity (EBQ) rules dictate the order size.

This replenishment triggering is based on the *effective* inventory level (Merkuryev, Petuhova et al. 2002), which is the quantity on hand plus the quantity on order minus the unshipped backorders to customers

This is represented in the Visual Logic as follows;

- SET Var_Man_Total Stock = [[31 Manufacturer FG.Count Contents+30 Manufacturer Count Contents]+[[26 Queue for Send Production Order.Count Contents+27 Send Production Order]*Var_Man_EBQ]]+28 Queue of production orders. Count Contents
- IF Var_Man_Total Stock < Var_Man_ROP
- Add Work To Queue Production Order , 26 Queue for Send Production Order

7.5 Outputs

The merits of DEDS become apparent in the *behaviour analysis* stages when modelling complex systems. Arguably (Disney, Naim et al. 1997) the method makes it possible to model a total system beyond an individual's capacity. Required parameters for each process can be output in many forms, in the case of Simul8 directly to spreadsheets, and the parameters surrounding the transit of individual orders, as they progress through the model, can therefore be mapped and recorded for later analysis.

Primary outputs in this model include; the simulated time unit, customer demand for each simulated time unit, data about each individual inventory, orders made by all roles, replenishment quantities received from the preceding role, calculated ROP's and performance against all five aspects for Manufacturer, Distributor and Retailer. These outputs can either be recorded and written to modifiable spreadsheets or displayed graphically which can be useful in quickly identifying changes and patterns in data trends Fig 26.

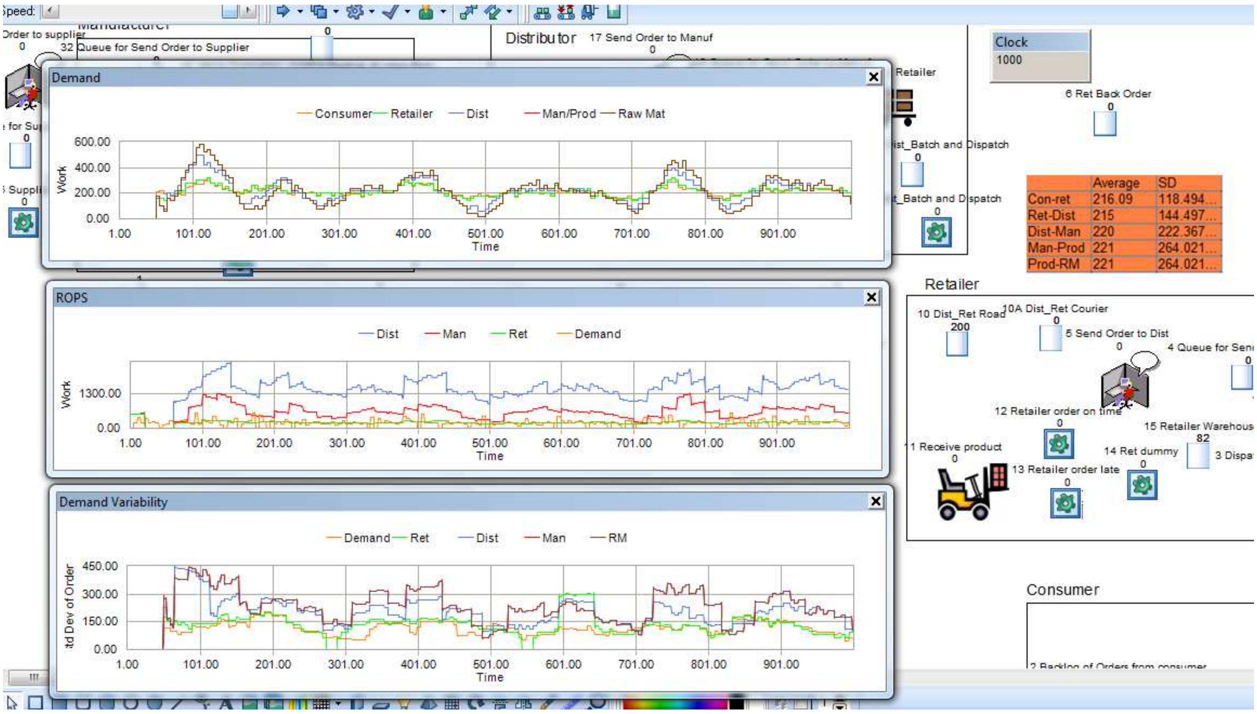

Figure 25. Graphical output of simulation model parameters

Because of the more limited spread sheet functionality in Simul8 the Standard deviation of demand calculation in order to assess the level of Bullwhip was written into the visual logic (Fig 21).

```
Record of orders arriving at Manufacturer
SET Spr_Orders_Out[19,Var_Counter_Week+3] = 17 Send Order to Manuf.Completed*Var_Dist_ROQ
SET Spr_Orders_Out[20,Var_Counter_Week+3] = [17 Send Order to Manuf.Completed*Var_Dist_ROQ]-Spr_Orders_Out[19,Var_Counter_Week+2]
IF Var_Counter_Week >= Var_Man_Bull_Pers_in_AvgDemand
    SET Var_Man_Avg_Demand = 0
    SET Var_SumSD = 0
    LOOP [[Var_Counter_Week-Var_Man_Bull_Pers_in_AvgDemand]+3]+1 >>> Var_Loop_i >>> Var_Counter_Week+3
    SET Var_Man_Avg_Demand = Var_Man_Avg_Demand/Var_Man_Bull_Pers_in_AvgDemand
    SET Spr_Orders_Out[21,Var_Counter_Week+3] = Var_Man_Avg_Demand
    This line loops the peiod across which the Local Standard Deviation (SD) is calculated (same as average)
    LOOP [[Var_Counter_Week-Var_Man_Bull_Pers_in_AvgDemand]+3]+1 >>> Var_Loop_i >>> Var_Counter_Week+3
        This line is the manual calculation for the nominator of the local SD within the period (loop).
        SET Var_SumSD = Var_SumSD+[[Spr_Orders_Out[20,Var_Loop_i]-Var_Man_Avg_Demand]*[Spr_Orders_Out[20,Var_Loop_i]-Var_Man_Avg_Demand]]
    this line calculates the SD (Sqrt of ths sums of the difference dividied by N-1) and then writing it to the speadsheet
    SET Spr_Orders_Out[22,Var_Counter_Week+3] = SQRT[Var_SumSD/[Var_Man_Bull_Pers_in_AvgDemand-1]]
```

Figure 26; Std Dev Calculation in the Visual Logic. Source author.

7.6 Performance Metrics

7.6.1 Reliability

Assuming that a downstream Role negotiates an acceptable mean delivery/transit time (adjusted according to role) and calculates an order-point that accommodates this figure, Reliability is the percentage of orders available/allocated directly from finished goods stock. This is implemented through the use of labels, applied according to the given criteria, that dictate the route through the simulation to storage areas where ‘count contents’ can be tracked, Reliability calculated and results output to a spread sheets (Fig 27).

Orders are investigated at critical points in the model and, in the case for example the Retailer, the Label for ‘Order Time In’ is deducted from the ‘Simulation time’ and a time of less than 1 indicates delivery from shelf as opposed to a longer period. This calculated value, of less than 1 or more than 1, determines the characteristic of a second label which dictates the order route and the cumulative value of such routes are used to calculate Reliability on the associated spreadsheet.

```
IF Simulation Time-Lbl_Cons_Order_Time_In  <=  1
   SET Lbl_fulfilled_on_time  =  1
 ELSE
   SET Lbl_fulfilled_on_time  =  2
```

Sheet: Spr_SL_Results

	A	B	C	D	E	F	G	H	I	J	K	L	M	
1		Consumer/Retailer						Retailer/Distributor						Dis
2	Week	On time cum	Late Cum	WkOT	WKLt	WkSL	Ret_Avg_SL	On time cum	Late Cum	WkOT	WKLt	WkSL	Dist_Avg_SL	On
3														
4	1	223	0	223	0	100%		400	0	400	0	100%		
5	2	627	0	404	0	100%		400	200	0	200	0%		
6	3	813	0	186	0	100%		600	200	200	0	100%		
7	4	1200	0	387	0	100%		1000	200	400	0	100%		
8	5	1418	0	218	0	100%		1200	200	200	0	100%		
9	6	1653	0	235	0	100%		1200	200	0	0			
10	7	1874	0	221	0	100%		1200	200	0	0			
11	8	1874	0	0	0			1200	200	0	0			
12	9	1900	106	26	106	20%		1400	200	200	0	100%		
13	10	1994	157	94	51	65%		1600	200	200	0	100%		
14	11	2143	157	149	0	100%		1600	200	0	0			
15	12	2212	288	69	131	35%		1800	200	200	0	100%		
16	13	2319	381	107	93	54%		1896	304	96	104	48%		
17	14	2586	489	267	108	71%		1988	612	92	308	23%		
18	15	2811	489	225	0	100%		2188	612	200	0	100%		
19	16	3034	581	223	92	71%		2588	612	400	0	100%		
20	17	3191	581	157	0	100%		2988	612	400	0	100%		
21	18	3719	581	528	0	100%		3188	612	200	0	100%		
22	19	3887	617	168	36	82%		3788	612	600	0	100%		
23	20	4211	617	324	0	100%	84%	3788	612	0	0		91%	
24	21	4476	617	265	0	100%		3988	612	200	0	100%		
25	22	4690	617	214	0	100%		4588	612	600	0	100%		
26	23	5153	617	463	0	100%		4788	612	200	0	100%		
27	24	5436	617	283	0	100%	84%	5388	612	600	0	100%	91%	
28	25	5574	617	138	0	100%		5388	612	0	0			
29	26	5574	617	0	0			5388	612	0	0			
30	27	5814	617	240	0	100%		5788	612	400	0	100%		
31	28	6026	617	212	0	100%	84%	5988	612	200	0	100%	92%	
32	29	6414	617	388	0	100%		6188	612	200	0	100%		
33	30	6414	617	0	0			6188	612	0	0			
34	31	6578	617	164	0	100%		6388	612	200	0	100%		
35	32	6824	617	246	0	100%	93%	6588	612	200	0	100%	92%	

Figure 27. Output spreadsheets calculating Reliability performance service levels

A moving average Reliability performance (calculated over a ‘variable input’ number of weeks) is then calculated periodically (Fig 28).

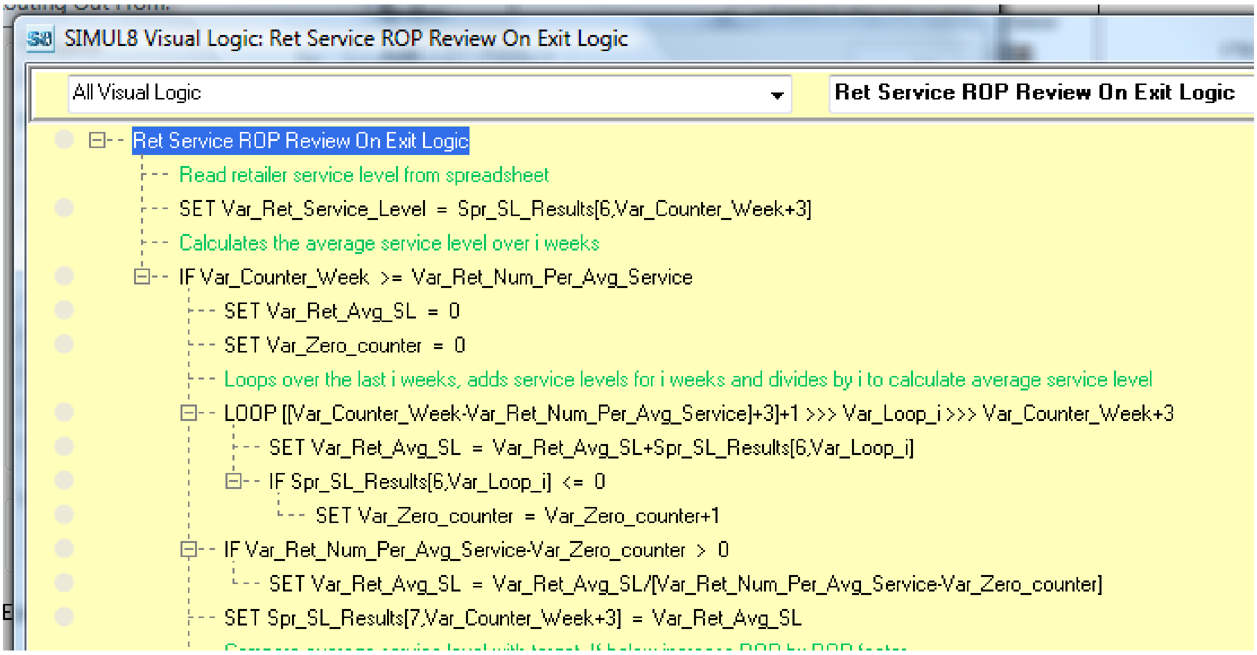

Figure 28: Moving average Reliability calculation. source author

7.6.2 Responsiveness

Defined within SCOR as Order Fulfilment Lead Time or more simply as 'the velocity at which a supply chain provides products to the customer', this metric is associated with Reliability above, but distinct in the sense that it does not seek to capture the ratio of 'goods delivered from stock/total demand', instead it seeks to capture the average cycle time for the satisfaction of ALL demand. Average cycle time of all orders at each of the three interfaces is captured by adding a time flag to each order and deducting the flag value from 'simulation time' value at the delivery event (fig 29), calculated in the visual logic.

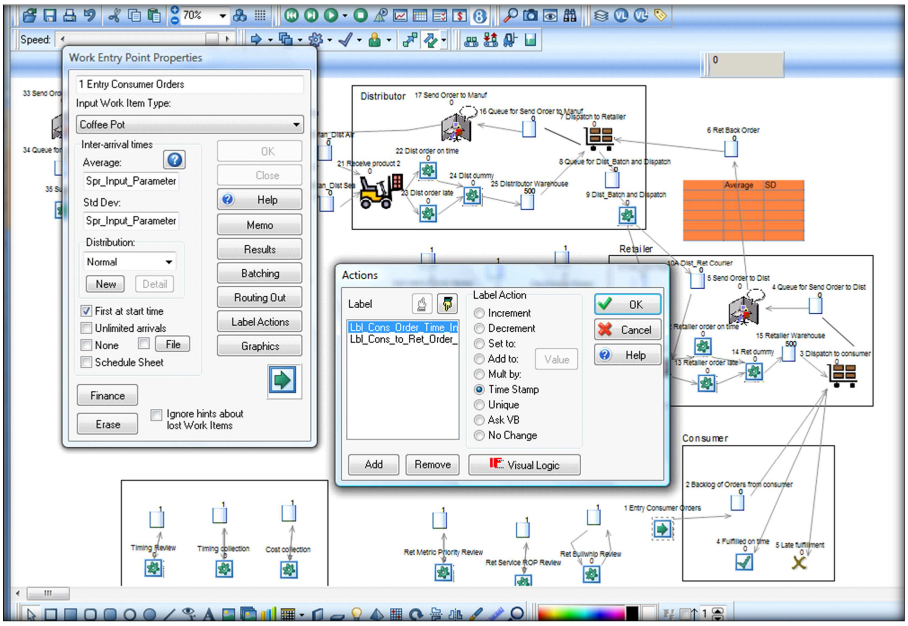

Figure 29. Adding time flags to monitor performance

7.6.3 Flexibility

Supply Chain Flexibility, the agility of a supply chain to respond to marketplace changes to gain or maintain competitive advantage is captured in the SCOR L1 metric as ‘Supply Chain Response Time’. This is interpreted, in this single product model as ‘material throughput time’. Time flags are added to the simulated elements representing raw material as they are delivered to the Manufacturer by the Supplier. As the now finished goods, are delivered to the Customer this ‘entry time flag’ is deducted from the ‘simulation time’ and the required throughput time calculated.

In the case of both Flexibility (and Responsiveness) a more realistic moving average is required as organisations do not make significant operational changes in response to each and every individual order. The SCC suggests that 'average' values are tracked in relation to performance. Therefore a moving average flexibility value across 200 orders (total time for batch/batch size) is monitored and recorded (Fig 30).

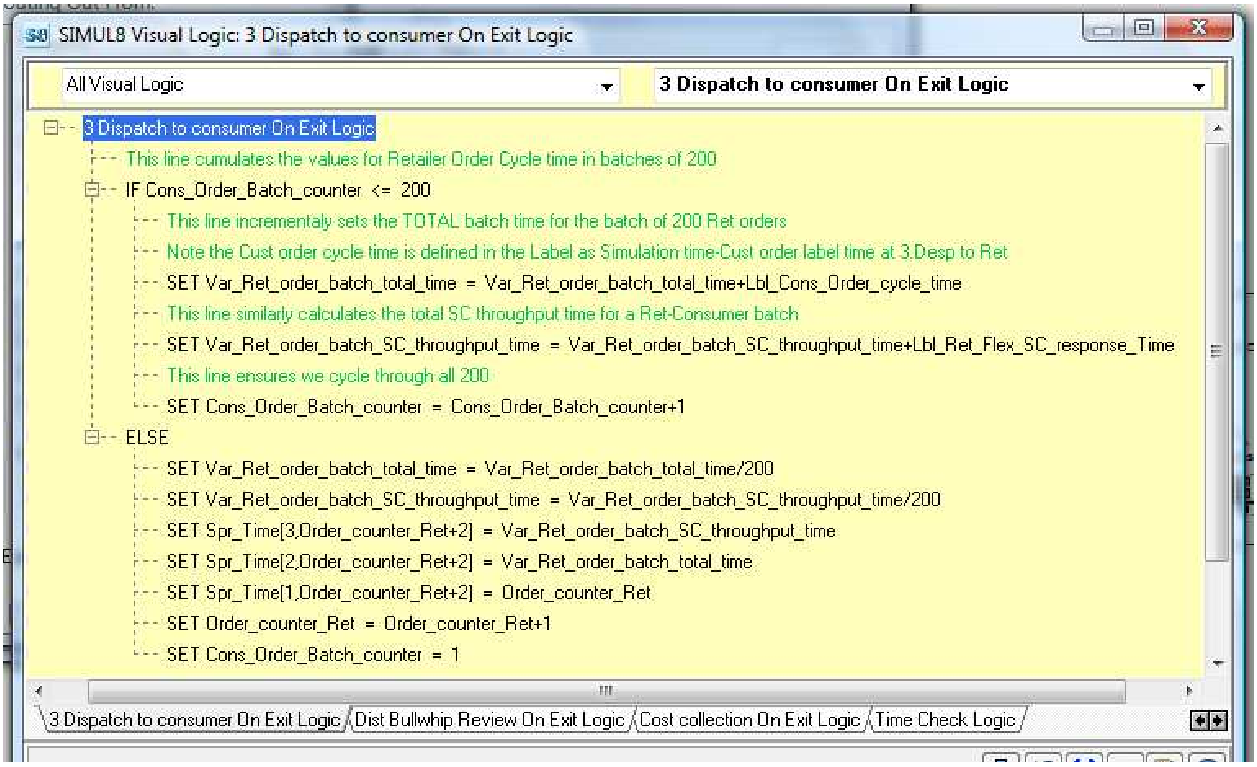

Figure 30. Averaging metrics over a number of values

7.6.4 Cost

According to the SCOR framework the level 1 metric for cost is; 'Cost of Goods Sold'. With a single product and simplifications that take for example a single transport cost to represent all costs associate with transport and 'pipeline' inventory (goods in transit) costs, a single spread sheet can be used to calculate and display all the relevant cost data for the model.

Dist W'hse inventory	Dist W'hse holding cost	Truck transport pipeline inventory	Truck (pipeline and freight) cost	Courier transport pipeline inventory	Courier (pipeline and freight) cost	Dist Total cost	Total Cumm deliveries by Distributor	Daily deliveries by Distributor	Daily Distributor cost per unit delivered	8 week moving average Distributor cost per unit delivered	Dist Rev
500	2260.25	0	0	0	0	2260.25	0	0	0		
100	452.05	400	11808	0	0	12260.05	0	0	0		
688	3110.104	400	11808	0	0	14918.104	0	0	0		
688	3110.104	398	11748.96	0	0	14859.064	0	0	0		
688	3110.104	0	0	0	0	3110.104	400	400	7.77526		
688	3110.104	0	0	0	0	3110.104	400	0	0		
488	2206.004	200	5904	0	0	8110.004	400	0	0		
698	3155.309	200	5904	0	0	9059.309	400	0	0		
698	3155.309	200	5904	0	0	9059.309	400	0	0		
698	3155.309	0	0	0	0	3155.309	600	200	15.776545		
498	2251.209	200	5904	0	0	8155.209	600	0	0		
694	3137.227	200	5904	0	0	9041.227	600	0	0		
694	3137.227	200	5904	0	0	9041.227	600	0	0		
494	2233.127	200	5904	0	0	8137.127	800	200	40.685635		
690	3119.145	200	5904	0	0	9023.145	800	0	0		
690	3119.145	200	5904	0	0	9023.145	800	0	0		
490	2215.045	200	5904	0	0	8119.045	1000	200	40.595225		
700	3164.35	200	5904	0	0	9068.35	1000	0	0		
700	3164.35	200	5904	0	0	9068.35	1000	0	0		
700	3164.35	0	0	0	0	3164.35	1200	200	15.82175		
500	2260.25	200	5904	0	0	8164.25	1200	0	0		
696	3146.268	200	5904	0	0	9050.268	1200	0	0		
696	3146.268	200	5904	0	0	9050.268	1200	0	0		
696	3146.268	0	0	0	0	3146.268	1400	200	15.73134		
696	3146.268	0	0	0	0	3146.268	1400	0	0		

Figure 31. Cost performance calculated on the Cost spreadsheet.

Since on specific days zero deliveries will be required (as downstream roles naturally fluctuate order patterns) the daily calculation of costs will occasionally deliver a zero value. In order to avoid erroneous decisions based upon zero values a moving average calculation for cost is calculated across a number of days (Fig 32).

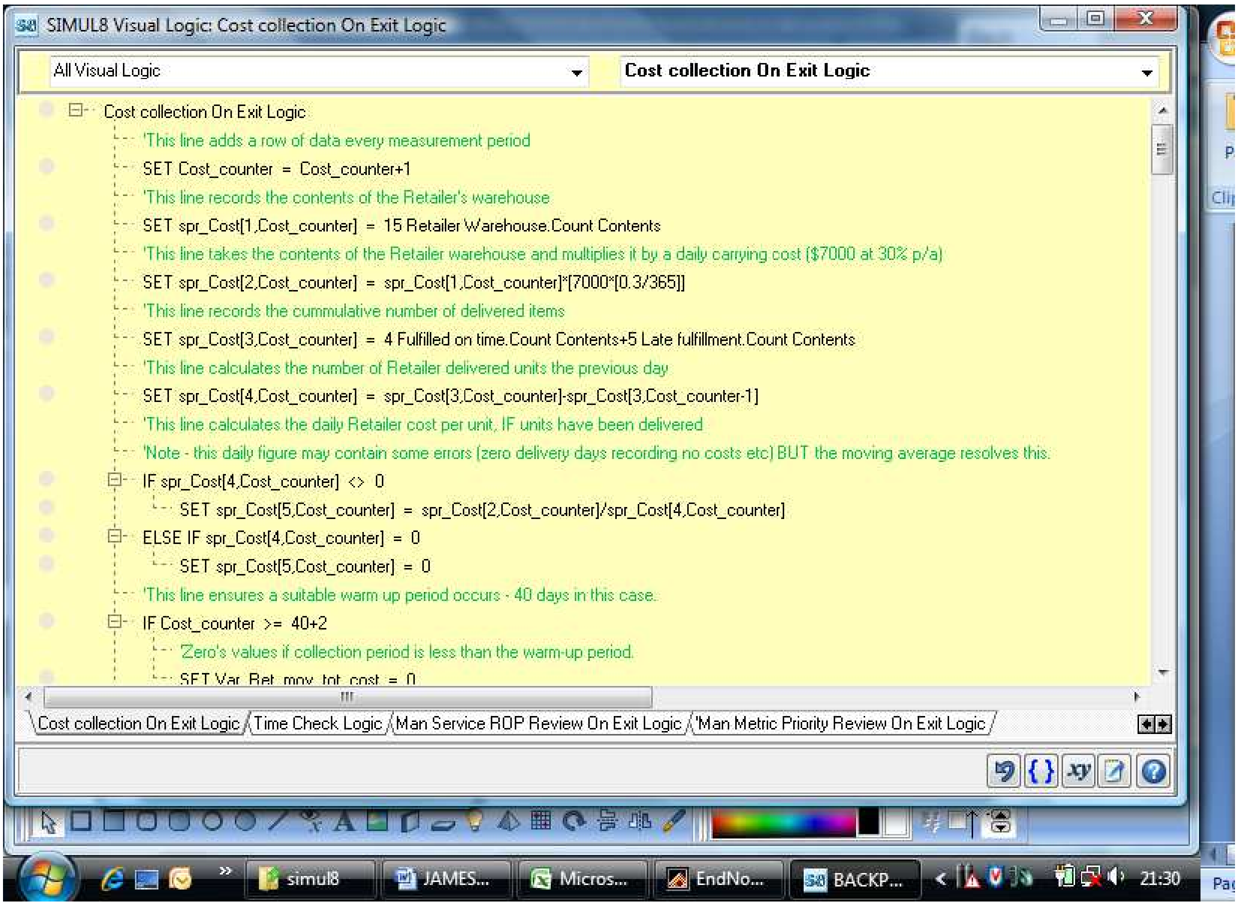

Figure 32. Coding of Cost Data into Visual Logic, Source author

7.6.5 Utilisation

Utilisation is defined at SCOR Level 1 as;

Total gross product revenue ÷ Total net assets.

This expression, also described as Asset Turns, includes the management of all assets including fixed and working capital. In the interests of realism, the moving average across which the nominator and denominator are calculated reflects the fact that costs are calculated across a moving average of 20 days (to represent a 1 month period) and revenue is calculated across a similar number of days (20) but time delayed by one month (day -40 to day -20) to reflect a typical payment term of 30 days on sales invoices (Fig 33)

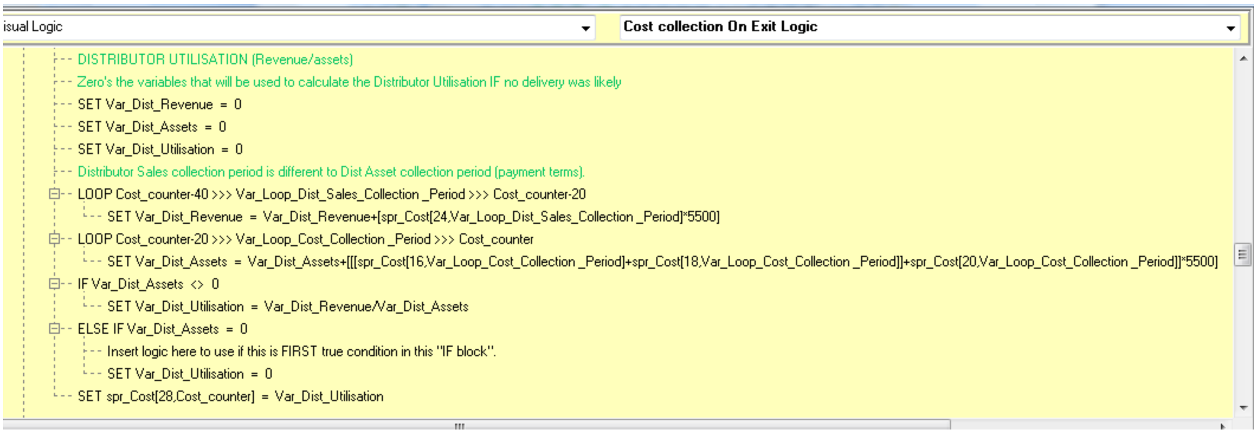

Figure 33: Utilisation calculation incorporating 30 day payment terms. Source author.

7.6.6 Prioritising aspects of performance

There are two ways of handling multiple objectives in classical optimisation, namely weighted sum and pre-emptive optimisation. The weighted sum approach requires determination of relative importance of different performance metrics; whilst the pre-emptive approach requires determination of absolute priority (Huan, Sheoran et al. 2004). The outcome in all cases is that the decision is dependent upon the user's priority(s) and the various performance outputs at the time. The SCC advocate prioritisation based upon the outcome of the strategic evaluation/analysis stage of applying the SCOR methodology (Appendix 2). Prioritisation based on strategic intent would imply that similar environmental conditions may not necessary lead to similar priorities and also implies that priorities will change over time.

In simulation terms, the objectives of this work (investigating whether the application of performance measures influences Bullwhip) require merely that a realistic set of priorities be included in the model. The sequence of priorities was investigated for verification and validation purposes, where the sensitivity of sequencing was investigated. The specific sequence coded in the model the model (Fig 35) was a logical interpretation of typical organisations/SCC members' strategic priorities. A plausible and representative set of priorities that would operate, should the performance review mechanism be applied.

The sequencing was written into the visual logic (fig 34) in reverse order, with the desired primary objective being written into the code last. Should the minimum/target value for the priority/final aspect of performance be achieved then the subsequent aspect of performance, failing to meet its target value will become the Roles performance priority and the prescribed operational settings will be adopted (fig 35).

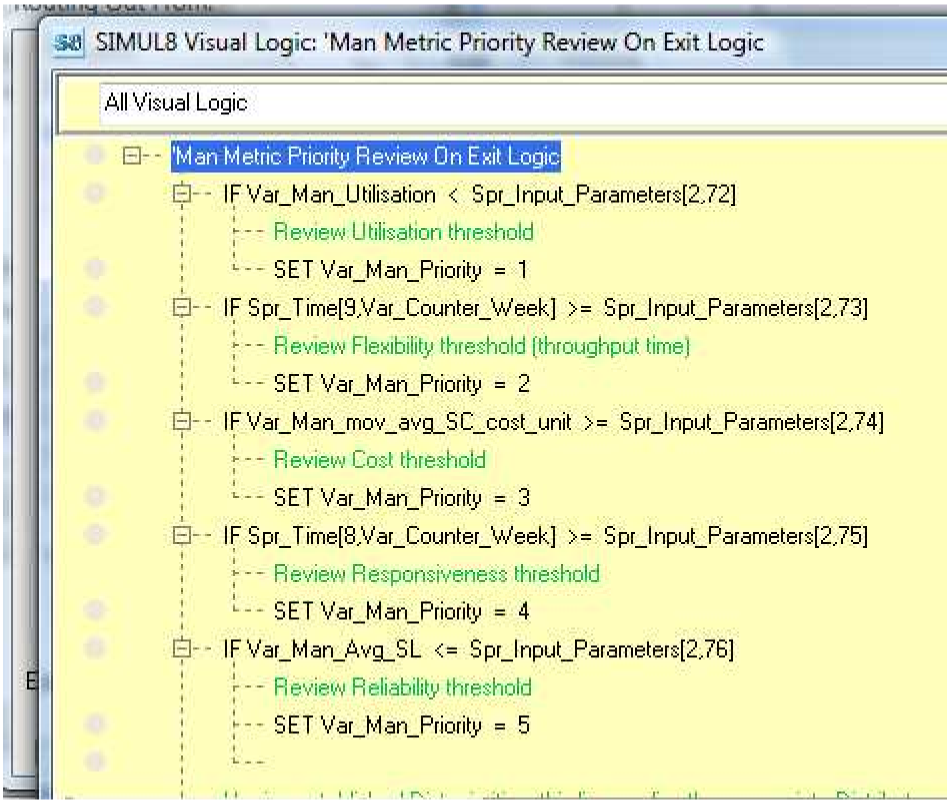

Figure 34: Sequencing of performance priorities. Source author

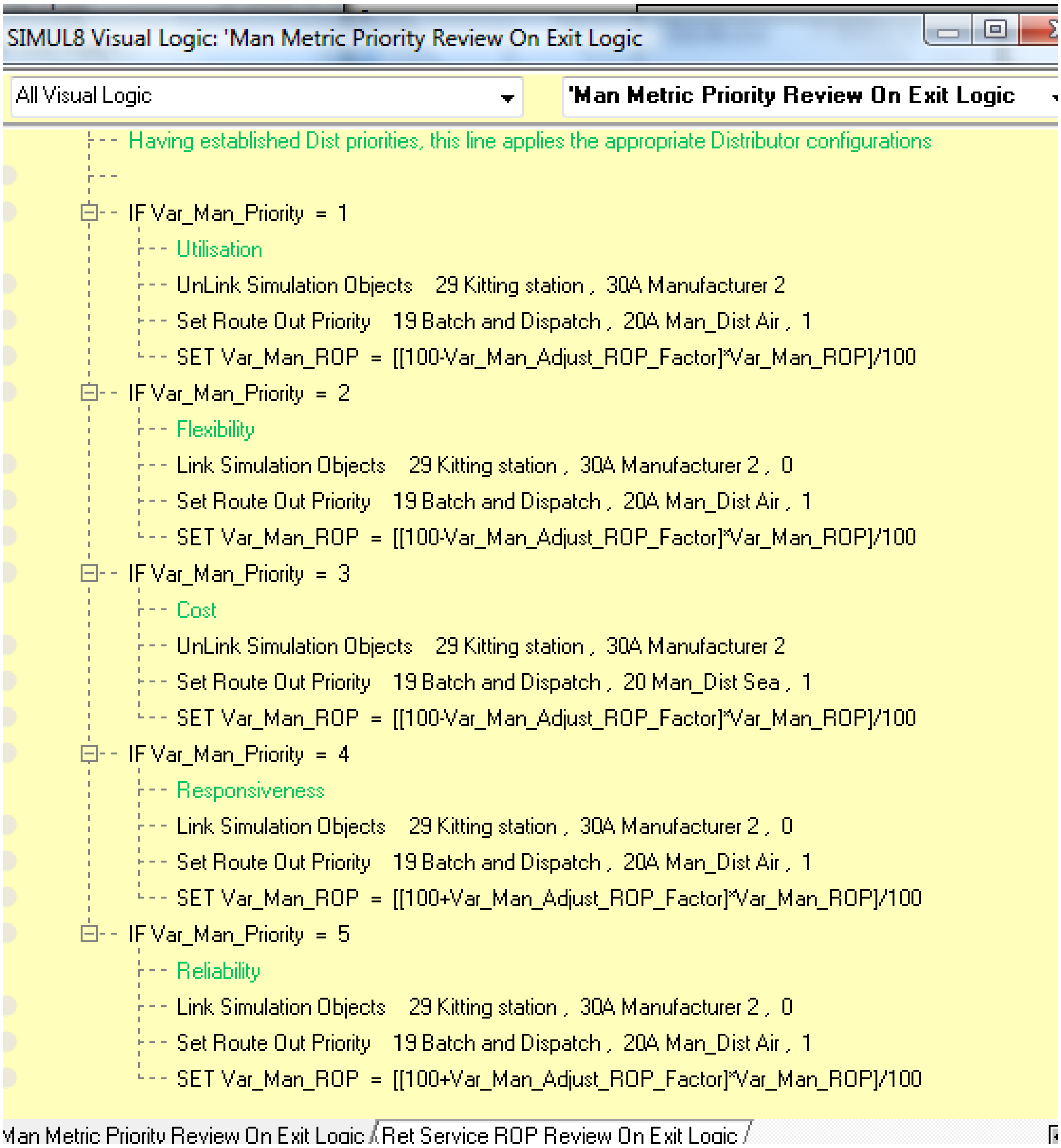

Figure 35. Operational settings applied according to performance priority.

The variation in performance priority for all Roles is recorded on an output spreadsheet (Fig 37) where detailed analysis can be conducted.

V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH
Retailer	Retailer	Retailer	25	26	Distributor	Distributor	Distributor	30	31	Manufactu	Manufactu	Manufacturer
ROP	Priority	Order			ROP	Priority	Order			ROP	Priority	Order
525	5				525	5				525	5	
525	5				551.25	5				551.25	5	
525	5				578.8125	5				578.8125	5	
525	5				578.8125	5				578.8125	5	
0	5				0	5				0	5	
0	5				0	5				0	5	
0	5				0	5				0	5	
0	5				0	5				0	5	
0	5				0	5				0	5	
0	5				0	5				0	5	
0	5				0	5				0	5	
0	5				0	5				0	5	
196.6	5				1029	5				252	5	
196.6	5				1029	5				252	5	
196.6	5				1080.45	5				264.6	5	
196.6	5				1134.4725	5				277.83	5	
196.2	5				1470	5				819	5	
196.2	5				1470	5				819	5	
206.01	5				1543.5	5				859.95	5	
206.01	5				1620.675	5				902.9475	5	
267.7	5				1960	5				1260	5	
267.7	5				2058	4				1197	3	
267.7	5				2160.9	4				1137.15	3	
267.7	5				2268.945	4				1080.2925	3	
297.8	5				2240	4				1320	3	
297.8	5				2352	4				1254	3	
297.8	5				2469.6	4				1191.3	3	
297.8	5				2469.6	4				1191.3	3	
230.7	5				1596	3				969	3	
230.7	5				1516.2	1				920.55	3	
242.235	5				1440.39	3				874.5225	1	
242.235	5				1440.39	3				874.5225	1	
213.4	5				1330	3				513	1	
213.4	5				1263.5	3				487.35	1	
213.4	5				1263.5	3				487.35	1	

Figure 36. Spread sheet recording Performance priority changes for each Role. Source author

7.7 Conclusion

The simulation model developed (Fig 37) incorporates many of the features ascribed as being causes of the Bullwhip effect; multiple forecasts of demand used in subsequent order point calculations, information delays, transportation delays and batching rules. Roles in the model independently monitor downstream demand, calculating a reorder point based upon average demand multiplied by a given factor. These input variables generate the classic Bullwhip effect as demonstrated by Forrester and is important because the model must demonstrate the effect of

Performance Measurement Systems on a simulated Supply Chain and the reality is that a classic supply chain will exhibit Bullwhip.

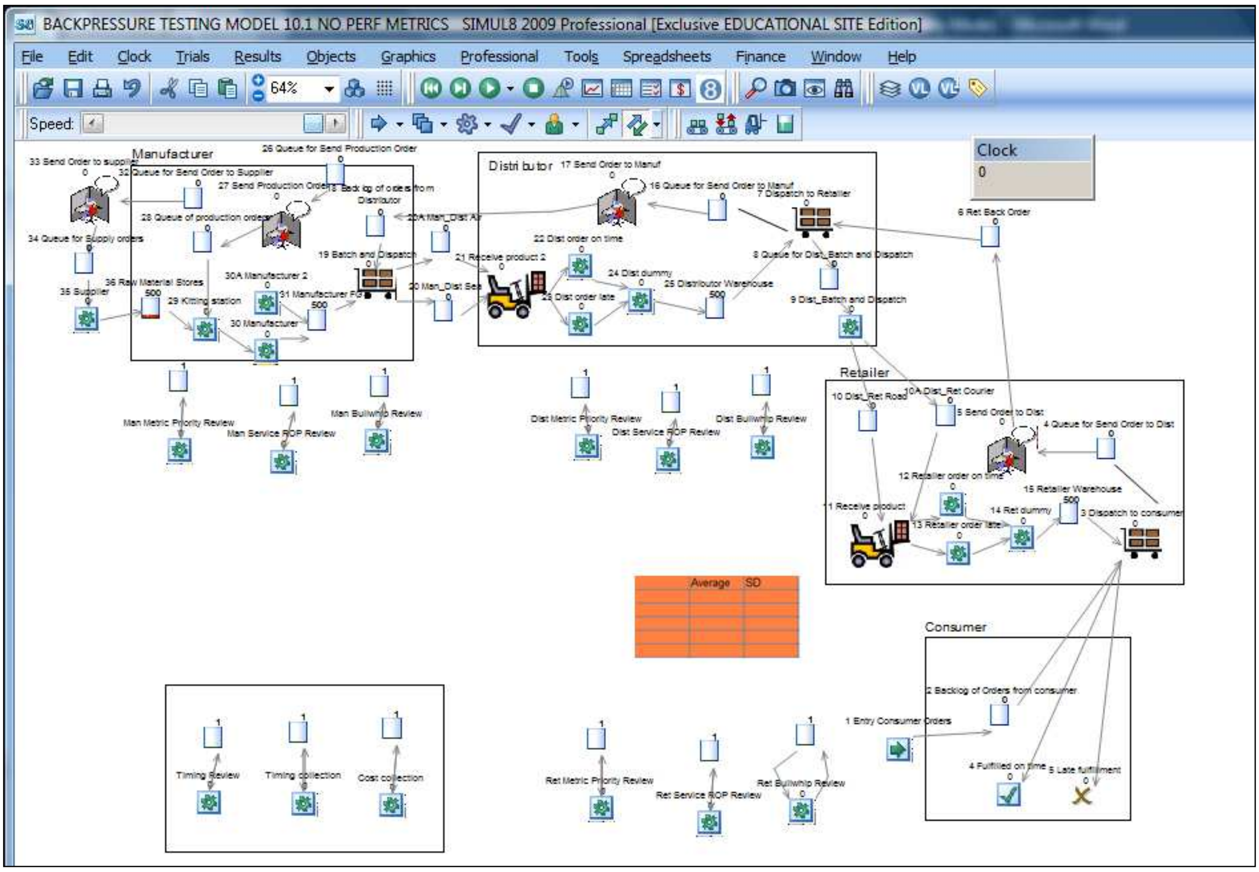

Figure 37 the Simulation model. Top Level

In addition to the ROP calculation, the model also incorporates operational characteristics established from the literature including optional capacity and transportation alternatives between various roles. Each Role monitors all five SCOR aspects of performance and the level of the Bullwhip effect to demand is calculated automatically at the end of each run. Each Role can prioritise aspects of performance and, by comparing values against a target, apply the prescribed operational adjustments in order to bring that aspect of performance to its target value.

8. VALIDATION AND VERIFICATION OF THE MODEL

Numerous methods for ensuring models are appropriate for purpose and rigorously tested are described in the literature. One such method is a nine-step model (Persson and Olhager 2002) whereby successive activities must be performed before the simulation study is complete.

1. Project planning.

The time to carry out the project is estimated and the first set of experiments is defined. The time estimation actually proved to be far too optimistic as a great deal of time was initially spent developing a model in the 'E-Scor' software which was ultimately abandoned in favour of DEDS.

2. Conceptual modelling.

The real system under examination is described in a simple flowchart or in a text document, the objective being to capture the system logic and data necessary. In this case numerous published accounts of Beer game simulation models proved invaluable in providing detail, allowing time to be spent in the design and development stages.

3. Conceptual model validation.

The conceptual model is examined and corrected if necessary. Time was spent ensuring that the SCOR aspects of performance and in particular the method of prioritisation of the different performance aspects, was accurately incorporated into the model. Ultimately confirmation was sought and gratefully received from the SCC confirming that priorities are established in the analysis stage of SCOR implementation and actually reflect the strategic intent of the organisation rather than some prescribed SCC set of objectives. Such a confirmation established the possibility for a range of prioritise across similar organisations under similar circumstances and highlighted the opportunity to simulate and test a realistic range.

4. Modelling.

The conceptual model is transformed to a computer-based simulation model. In this case the simulation software package Simul8 was chosen, based largely upon the opportunity for full access to an acclaimed software under existing University license agreements and the offer of training/attending lectures and wonderful individual help from Dr Pavel Albores with his great experience in developing models in the software.

5. Verification.

Verification aims at testing the computer-based model against the conceptual model. This process is discussed in more detail later in this chapter.

6. Validation.

Validation aims at testing the computer-based model against the system itself. This process is discussed in more detail in later. Earlier but more widely referenced work (Hermann 1967) considers Validation prior to Verification, ensuring the fundamental structure is sound (ensuring the model is credible) and this sequence is adopted in this chapter.

7. Sensitivity analysis.

Assessing the effect of varying inputs levels on the output levels was considered at an early stage and many of the possible input variables were deliberately written to an Input Spread sheet, rather than hard coded into the Visual Logic, to more easily facilitate this process.

The sensitivity analysis served two objectives: it provided insight into the behaviour of the model and gives a shortlist of critical experimental factors. To estimate the statistical significance of the estimated effects, each scenario needs replication using different, non-overlapping pseudo-random numbers (PRN). In the case study, the number of replications selected was seven which corresponded with similar models (Kleijnen 2003) published in the literature.

8. Experimentation and analysing output data.

The defined experiments are run and output data collected and analysed. During this stage new sets of experiments were realised and defined and the experimentation phase repeated.

9. Implementation.

Output data is analysed and used to prove/disprove the hypothesis and to establish or recommend some action in practice.

Of vital importance are the validation and verification activities (Persson and Olhager 2002). If these activities fail to correct all model errors, the result of the simulation study can be questionable, proven methods for these activities were therefore sought.

8.1 Model Validation

Model validation can be defined (Sargent 2004) as “substantiation that a computerized model, within its domain of applicability, possesses a satisfactory range of accuracy consistent with the intended application of the model”.

Making certain a supply chain model is credible broaches common challenges in any simulation project, such as finding appropriate and accurate input data and describing the manufacturing system's logic. A Supply Chain (SC) model however poses some additional unique problems;

1. A SC consists of a number of operations and storage points, all connected with the flow of materials. In a common manufacturing simulation study, all these activities are performed in the same plant or at least in the same firm. This is not necessarily the case for a SC where several organisations may be involved with their own methods of collecting and analysing data (Persson and Olhager 2002).

2. There rarely exist personnel familiar with SC systems in several different plants or firms (Balci 1998) able to describe accurately system behaviour

3. Not because of a lack of appropriate SC performance measurement systems (in this work SCOR is the system simulated) but because of the lack of SC performance measurement *values* for the whole SC to compare with the simulation output (Persson 2007).

In terms of assessing whether the validity of this model is established, a number of criteria have been proposed (Hermann 1967);

1. Internal validity – Numerous replications whilst maintaining stable inputs helped determine whether the internal stochastic variability was excessive. A high amount of variability would call into question the mechanisms within the model and possibly even the system being investigated.

2. Face validity – Subjective opinions regarding the surface or initial impression of the models realism were sought. Many Aston academic colleagues actually referred to the same widely referenced Bullwhip model articles, upon which the model is based. This static technique helped confirm the logic of the conceptual model as correct and that the model's input-output relationships were reasonable.

3. Variable parameter validity – 'sensitivity testing' in order to ascertain whether the effects of the changes in the input variables are comparable with changes in output. Parameters include varying; demand characteristics, demand averaging periods, transit times etc. Recorded responses to parameter changes were consistent with those one would expect from a reliably working model The sensitivity analysis usefully demonstrated that the model remained stable over a range of parameter values which greatly increased confidence in its robustness.

4. Event/Predictive validity – Numerous comparisons of predicted model responses with actual model output were undertaken, however the model could not be used to predict real system behaviour as the sets of data in any existing operational SC are not available. Whilst the absence of real/commercial ‘event-validity’ is recognised as a possible weakness, the general behaviour of the model in relation to the other criteria was felt to justify confidence in its application.

5. Hypothesis validity – Relationships between system elements were explored and the model faithfully reproduced connected responses such as; downstream performance requirement changes influencing ROP’s and configuration settings etc.

Further additional criteria have since been proposed (Sargent 2004);

6. Animation: The model’s operational behaviour was displayed graphically as the model moves through time. The cyclical nature of performance changes over time and their relationship with averaging periods for example were able to be repeatedly mapped.

7. Degenerate Tests: The model’s behaviour was tested following the deliberate selection of deteriorating input values. For example ROP continued to increase with respect to time when the Delivery Lead time was larger than the Reliability requirement.

8. Extreme Condition Tests: The model structure and output was plausible for extreme and unlikely combinations of values. For example zero ROP’s generated zero output when service requirements were switched off.

9. Operational Graphics: Values of various performance measures; for example SC Performance Priorities and ROP shown graphically as the model ran, display plausible dynamic behaviour.

10. Traces: The path and behaviour of product was traced/followed to determine if the model's logic was correct.

11. Comparison to Other Models: Attempts were made to ensure that output from the model was similar to that of other models. General trends in output could be mapped to other work (Taylor, Love et al. 2008) when the performance priority feature was disabled.

Two extreme views are apparent in the literature in relation to validation of models (Sargent 2004); The Rationalist view (Forrester and Wright 1961) asserts that the validity of the model rests merely in the acceptance of those assumptions which underlie the model as being obvious basic truths, proven by mere statement. Acceptance of the rationalist view is clearly dependent upon how 'obvious' the truth of the basic assumptions is, which is itself an extremely qualitative judgement.

The Empiricists view asserts that ALL assumptions must be verified exclusively by experimental means, i.e. by comparison of model and SC data. Empiricism requires every assumption and outcome to be empirically validated in absolute terms.
Care must be used however since even if such a data source exists, subsequent modifications to the model destroys the basis for comparison and any validity implied by the exercise (Love 1980).

All the validation methods completed above are clearly rationalist. However like Forrester's original work and numerous subsequent models, such methods when conducted thoroughly are considered valid enough for the purpose presented here – namely demonstrating in principle that applying SC performance metrics may influence the level of Bullwhip. The entire effort of a simulation's construction is the creation of a credible system representation from which inferences regarding the actual system's performance and behaviour can be made without the need of resorting to costly experimentation with the actual system (Mihram 1972).

8.2 Verification of the research model

Model verification ensures that the computer programming and implementation of the conceptual model are error free (Sargent 2004). Primarily concerned with ensuring; the simulation language has been properly used, that decisions and calculations have been properly replicated and that rigorous and methodical debugging of code has taken place. The complexity of this model called for a significant verification process.

The initial stage of verification consisted of a lengthy process of manually calculating rough values of variables over random time intervals and using this data in the debugging process. Later processes included holding variable inputs to a given value (e.g. maintaining transport delays at zero with no batch restrictions) and observing the output data and fixing order mechanisms (Fig 38). When the ROP level was set at one, Bullwhip/demand forecasting mechanisms were switched off and SC Performance reviews were also switched off the model displayed; consistent demand at each Role, stability across all ROP’s, and equal demand variability at every order point. Instability would indicate faults or errors in the model, since the logical relationship should result in stable output.

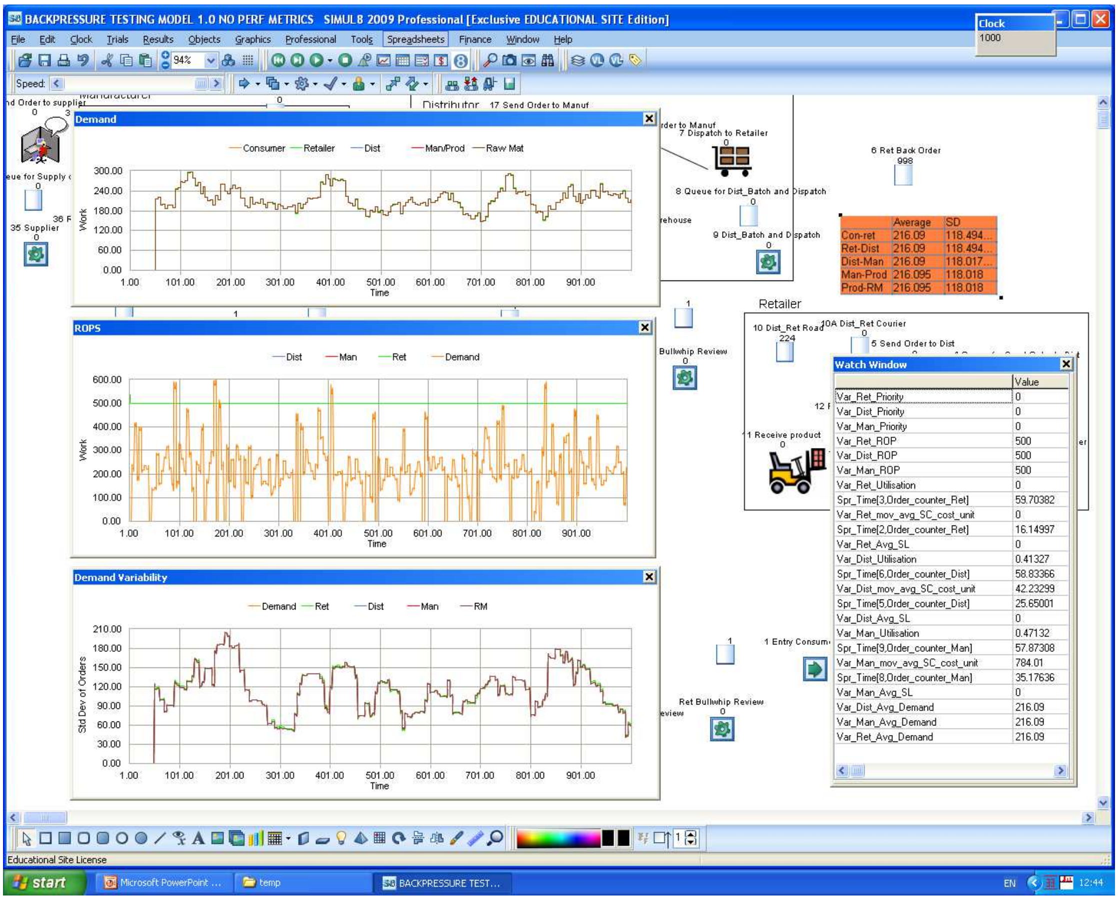

Figure 38. Validation Example. No Bullwhip mechanism, No Performance Review, ROQ=1

The model continued to produce consistent output when the run time was extended to 10,000 days (circa 50 years allowing for shifts, weekends, holidays etc) however since the detailed output data was written to spread sheets, generating these large files adversely affected run times and a run time of 1000 days (24/7) was found to deliver satisfactory output.

After a degree of debugging and some structural modifications (particularly in areas of demand aggregation and averaging) the model satisfied the following statements.

- The load generated on the production alternatives was consistent with that calculated from Distributor orders upon the Manufacturer.

- The movement of orders is consistent with the relative difference between stock levels and orders for all experimental runs.

- The movement in Re-Order Points is consistent with changes in performance priority during the experimental runs.

Throughout development of the model extremely valuable input was received from colleagues and fellow researchers as to the fundamental logic of the proposed model and of their experience in real and simulated systems. Over a period of time agreement was reached that the model did show responses typical to those anticipated from a real system.

8.3 Conclusions

Any conclusions as to the validity of this model should be considered in light of the purpose for which it was created. The simulation model strove to:

1. To represent the identified features of the SCOR performance measurement framework in a Beer Game model and simulate the symptomatic operational responses to variations in the KPI's, particularly the ongoing reprioritising of operations in response to various and changing aspects of performance.

2. Analyse the dynamics of the models across a range of variables including; demand patterns, lead times and performance priorities and measure the impact on the level of dynamics within the supply chain.

Since the system being modelled clearly didn't exist, it was impossible to establish event validity for the model. The experiments performed with the model did allow a limited form of 'variable parameter validity' testing. Whilst the equivalent changes in parameter values could not be made to a real system (even if it had existed, it would not have been economically viable to do so) the response of the model was consistent with the results expected from analysis. In this context the deficiencies which arose in the validation and verification stages were not considered to be of sufficient magnitude to undermine the validity of the conclusions reached in relation to the purpose of the experiments.

9 EXPERIMENTS AND RESULTS

9.1 Introduction

In this section the experimental areas to be explored are laid out for the reader. Since exploring the effect of applying Performance Measures on dynamic behaviour in the Supply Chain is the objective - it follows that all ‘factors’ attributed to dynamic behaviour are first identified. Each *dynamic factor* is investigated in isolation, in order to establish how precisely it influences dynamic behaviour and sets of experiments are run twice; once with the Performance Metrics turned off and then turned on.

The purpose of the experimental design phase was actually twofold: (1) To examine the key variables that impact on the level of dynamic behaviour and (2) To examine the impact of the performance measurement system on the recorded level of dynamic behaviour. By understanding the variables and the relationships within the model that contribute to variability then any observed change as a result of applying Performance Metrics could be better understood. Such an approach will both establish fundamentally whether the Performance Metrics influence Bullwhip and also identify which factors and mechanisms are being influenced.

9.2 Planned Experiments

Some key factors attributed to dynamic behaviour are highlighted in the literature;

- Forrester and Wright (1961) concluded that the problem of the bullwhip effect did not stem from the external forces rather the system itself; its policies, organisation structure and delays in material and information flow. It is a function of decision making, however Lee et al. (2004) showed that Bullwhip occurs even where all decisions are made in a completely rational way.

- The primarily decision in question is generating a replenishment order in light of variability in incoming demand (Petrovic 2001).

- Appropriate forecasting (Forrester and Wright 1961), mean and variance of demand estimation (Chen, Drezner et al. 2000) are part of that decision, as is the building in of safety factors (Lee and Padmanabhan 1997).

- The longer the information transmission or material delivery cycle time the greater the effect (Disney, Naim et al. 1997).

- Order batching, the time phased aggregation of orders, generates variability in demand (Potter and Disney 2006).

All the above factors indicate that; demand averaging, safety stock, lead time, the variability of incoming demand and order batching must all be considered as dynamic factors to investigate.

Additional factors that were not included are as follows;

- Reducing the number of decision locations (Sterman, 1989) which could be achieved figuratively (by centralising decision making or normalising data and decision protocols) or physically (simplifying the model). In both cases it was considered that such measures would similarly reduce the instances of applying Performance related decisions and would therefore contribute little to the experiments.

- Price fluctuations (Fisher 1997) and ‘Shortage Gaming’ (Mitchell 1924) create variability in demand but since variations in demand could be simulated directly it was considered that these additions were unnecessary.

The number of variables in the model exceeded a hundred; some of which were hard coded within model elements (e.g. transfer price for product between roles) and some of which were read from an 'Input Spread sheet' at the start of each run. In order to manage these variables and better explore specific relationships, the sets of variables were split into four functional groups (see Fig 40);

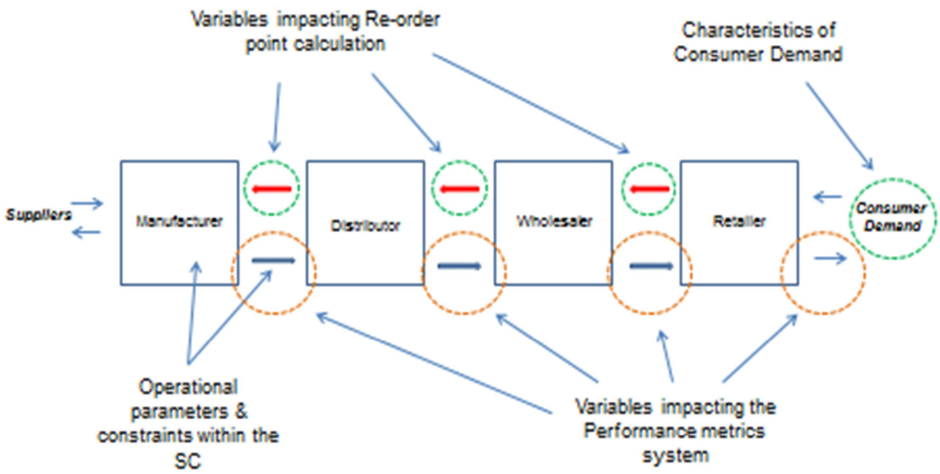

Figure 39. Groups of experimental variables

The planned experiments and reasons for them are laid out as follows;

9.2.1 Re-Order Point Calculation.

The key variables in the ROP calculation are the Safety Stock multiplier (which ensures stock is present in order to meet varying Demand) and the two variables affecting the calculation of the Average Demand namely; the period across which demand is averaged and the frequency (or the interval) that calculation takes place. To understand which of these three ROP variable factors has the greater influence on Bullwhip an initial ROP sensitivity experiment was conducted. A high, medium and low value for each of the three ROP variables is set;

	High	Medium	Low
BW/ROP Multiplier	10	5	1
Review Interval (weeks)	60	20	5
Average Period (weeks)	52	12	4

The Bullwhip Multiplier ranges from a low value of 1 (where the order point equals average demand during the set lead time or *zero* safety stock) to a high value of ten (where the order point is ten times the average demand).

The Review Interval ranges from a low value of 5 weeks (where the average demand is recalculated every 5^{th} week) to a high value of 60 (where the average demand is recalculated every 60 weeks).

The Average Period ranges from a low value of 4 weeks (where the average demand is calculated over the last month) to a high value of 52 (where the average is calculated over the last year).

Experiment 1 is a set of simulation runs, conducted across all 27 possible combinations of initial values for ROP variables with the results being sorted in ascending order according to the quantity of measured Bullwhip (Fig 42).

Each of these three factors is then examined *in detail,* in order to identify critical points/values in the level of Bullwhip. In every case the experiments are conducted in pairs in order to establish if the application of PM influences the level of Bullwhip in any given set of conditions.

Demand Average Period

Experiment 2 is a set of simulation runs carried out both with and without the application of PM's, to investigate levels of BW across incremental changes in demand average periods from 2 to 70 weeks. The review period is fixed at 20 days (reflecting monthly updated sales forecasts - a representative frequency for reviewing this data in practice) and the BW multiplier is set at 1 (no safety stock), 5 and then 10, the results being displayed in Fig 43.

Bullwhip/Safety Stock Multiplier

Experiment 3 is a set of simulation runs carried out both with and without the application of PM's, to investigate levels of BW across incremental changes in the safety stock multiplier from 1 to 20 times the calculated average demand. The review period is again fixed at 20 days (reflecting monthly updated sales forecasts) and the demand average period BW multiplier is set at 1 (no safety stock), 5 and then 10, the results being displayed in Fig 44.

Demand Average Interval

Experiment 4 is a set of simulation runs carried out both with and without the application of PM's, to investigate levels of BW across incremental changes in the demand averaging interval from 2 to 50 days. The safety stock multiplier is fixed at three (reflecting a safety stock of two times anticipated sales) and the demand average period is set at 5, 10, 20 and then 50 days, the results being displayed in Fig 45.

9.2.2 Operational Parameters.

Operational variables that may have a relationship with Bullwhip are; Order batching rules, Transit time and Capacity. These factors are subject to investigation in order to establish a relationship with Bullwhip and to identify whether they influence any effect following the application of performance measures.

Batching rules were initially investigated during the validation and verification stages and the results discussed in 9.3.2. At that stage it was clearly established that there is a significant relationship between order batching and increased levels of Bullwhip. The application of Performance Measures did not alter the levels of Bullwhip however.

Transit times however are the subject of separate experimental runs. The scheduled transit time (as defined in Chapter 7.3.3) are doubled and then trebled and levels of Bullwhip both with and without Performance metrics are recorded.

Experiment 5 is a set of simulation runs, both with and without the application of PM's, to investigate levels of BW with standard, double and treble transit times

across all modes of transport. In all cases the other variables (e.g. ROP calculation variables) are set at representative levels and the results displayed in Fig 46.

A similar set of experiments is carried out to investigate the impact of variations in Capacity (at the Manufacturer).
Experiment 6 is a set of simulation runs, both with and without the application of PM's, to investigate levels of BW with 1, 2, 3 and 4 times the standard capacity at the Manufacturers plant. In all cases the other variables (e.g. ROP calculation variables) are set at representative levels and the results displayed in Fug 47.

9.2.3 Consumer Demand

The variability of consumer demand entering into the model would intuitively have a bearing on the level of Bullwhip as 'increased levels of uncertainty lead to increased levels of dynamic behaviour' (Petrovic 2001 & Swaminathan, Smith et al. 1998). The sensitivity of this relationship, across a range of variability (from stable to volatile) is the subject of a further set of experiments where both the standard deviation of order size and frequency will be set at; 0.033, 0.133 and 0.33 to represent a range of demand profiles. A similar consideration, with and without the application of Performance Measures will be completed.
Experiment 7 is a set of simulation runs, both with and without the application of PM's, to investigate levels of BW with standard deviation of Order size and Order frequency at; 0.033, 0.133 and 0.33. In all cases the other variables (e.g. ROP calculation variables) are set at representative levels and the results displayed in Fig 48.

9.2.4 Performance Measurement Mechanisms

The sensitivity of the Performance targets themselves are the last group of identified factors that may impact the level of Bullwhip. Whether targets are challenging or modest will logically dictate the frequency of operational changes in the Supply Chain but whether such changes translate into increasing levels of Bullwhip was explored by a final set of experiments. The targets themselves are discussed later and displayed in Fig 49.

Experiment 8 is a set of simulation runs, both with and without the application of PM's, to investigate whether a modest, medium or challenging set of performance targets changes the level of dynamic behaviour experienced. In all cases the other variables (e.g. ROP calculation variables) are set at representative levels and the results displayed in Fig 50.

For all 8 experiments in a 'classical' dynamic discrete-event simulation the physical system is modelled and the target behaviour, *in this case supply chain dynamics*, is recorded for analysis and understanding. Using Simul8 the dynamic behaviour in the model can also displayed graphically in real time. for example a background level of demand variation caused simply by time delays and batching rules (Fig 41), results were also recorded on a number of Output Spread sheets for further analysis.

The simulated time period typically used was 1000 days, representing a period of over three years. In practice this actually represents a longer period (circa 10 years) as the simulation ran; 24 hours a day, seven days a week, 365 days a year. For any given simulation 1,000 days actually recorded slightly higher quantities of Bullwhip (6.99) as opposed to 3,000 days (5.2) or 5,000 (5.15). This would imply a gradual attenuation of Bullwhip for periods of 10-50 years but since in reality the commercial significance of Bullwhip would be sought before this, the period of 1000 days was considered a suitable run length and also proved to be a faster and more practicable run time.

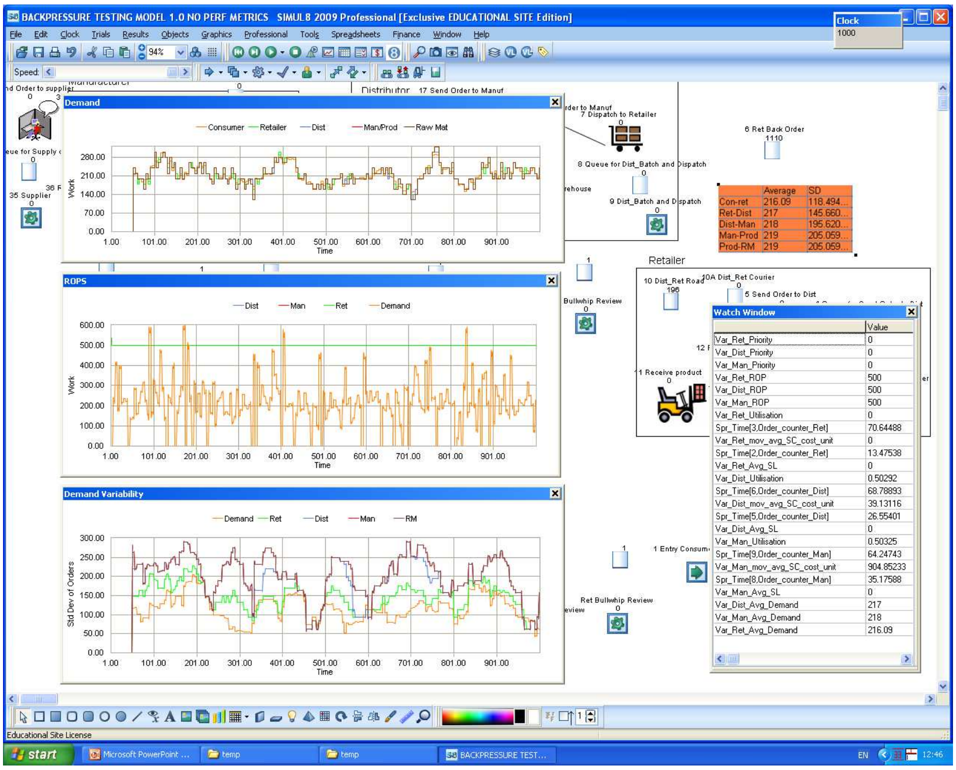

Figure 40. Validation runs. No Bullwhip, No Perf Review, ROQ=200

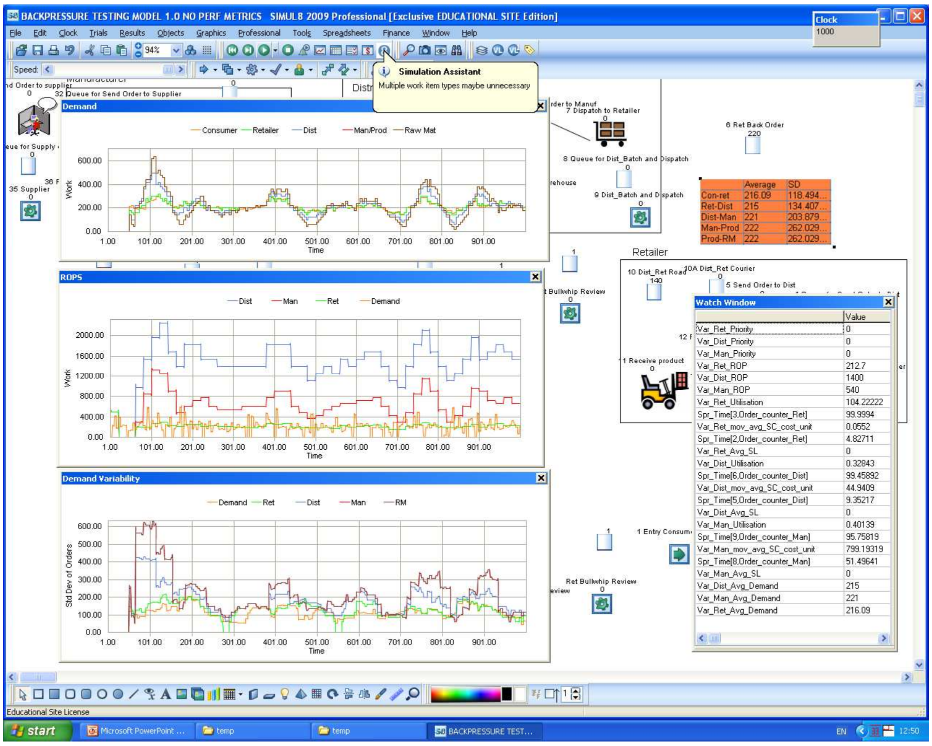

Figure 41. Validation runs. With Bullwhip, No Perf Review, ROQ=200

To test significant relationships the scenarios were repeatedly simulated and the results summarized statistically. The experiments were conducted in paired sets, all experiments being run with seven replications. Each set represented a set of conditions that could be examined with the two pairs representing ‘with’ and ‘without’ performance metrics.

The experiments in each of these groups are discussed in the following sections.

9.3 Re-Order Point Calculation Parameters

The re-ordering mechanism and consequent inventory adjustments have been attributed as the fundamental cause of Bullwhip from the outset (Forrester and Wright, 1961). The specific influence of Demand Forecasting has also been scrutinised (Lee *et al.*, 1997a. b) and a range of re-order point calculations of varying complexity have actually been used in simulations.

Two examples of such calculations which demonstrate the range of complexity are;

1. Merkuryev, Petuhova et al. (2002)

$$\mathbf{ROP = d * LT + Z * \sigma d * \sqrt{LT}}$$

Where;

d – the forecast of average weekly demand.

LT – the lead time.

Z – the safety stock factor, based on in-stock probability during the lead time;

σd – estimation of the standard deviation of the weekly demand.

2. Reiner and Fichtinger (2008)

Where a *representative* Lead Time; ‘Mean lead time’ which is composed of a variability component, a utilization component and a capacity component is calculated and fixed.

Indeed in a commercial scenario where lead times are difficult to monitor precisely, facilities may be remote and deliveries made by a range of carriers, then many organisations work could reasonably work on the assumption that the lead time is a constant and that applying a slightly higher safety stock factor to the average demand is a workable solution. Such practice calculates the 'weekly lead time demand' by multiplying the 'Contracted lead time' by the 'weekly demand', this figure is subject to a safety stock factor and the ROP is readily calculated.

On the grounds that the fundamental question of the effect of Performance Measures on variability requires the inclusion of a *representative* ROP mechanism, then the calculated average demand being multiplied by a variable input figure (Bullwhip ROP Review Multiplier) which acts as a classic safety stock multiplier has been adopted;

SET Var_Ret_ROP = Var_Ret_Bull_ROP_Multiplier*Var_Ret_Avg_Demand

When the current inventory (including in transit inventory and queued orders) is less than the current ROP then a new order is added (see 7.4). Such a mechanism assumes the Lead Time to be fixed and adjusts the ROP to take account of changes in demand levels whilst maintain a required quantity of safety stock. The three key variables in the ROP calculation are therefore;

- **Variable RET *(in this case Retailer)* Bullwhip ROP Multiplier** is an input figure on the 'Input Spread Sheet' - it is in effect a safety stock multiplier recalculating a ROP proportionally to the average calculated demand.

- **Review Interval**: The frequency with which the "Var Average Demand" and therefore a new ROP is recalculated is inversely proportional to the Review Interval – 'the longer the interval the less frequent the recalculation takes place'. This interval is also an input figure on the 'Input Spread Sheet'.

- **Demand Averaging periods**: The number of weeks across which recent Demand is averaged, for the purposes of ROP calculation, is dictated by the Average period. This period might be; 4, 12 or 52 weeks representing a month, a quarter or a year. Demand Average Period is an input figure on the 'Input spread sheet'. This period is also an input figure on the 'Input Spread Sheet'.

BW Mult	Review Interval	Avg Period	Perf Review	Con-Ret	Ret-Dist	Dist-Man	Man-Prod	Prod-RM	**Bullwhip**
10	5	4	No	118.8667	307.66	628.55	1116.64	1116.64	**9.39**
10	20	4	No	118.8667	311.09	667.98	1060.41	1060.41	**8.92**
5	20	4	No	118.8667	208.237	371.4	597.79	597.79	**5.03**
10	60	4	No	118.8667	226.91	395.61	520.22	520.22	**4.38**
5	5	4	No	118.8667	216.72	342.75	512.73	512.73	**4.31**
10	20	12	No	118.8667	182.18	299.74	498.89	498.89	**4.20**
10	60	12	No	118.8667	172.47	270.98	419.54	419.54	**3.53**
10	5	12	No	118.8667	187.81	290.93	405.86	405.86	**3.41**
5	60	4	No	118.8667	173.63	238.53	313.63	313.63	**2.64**
10	5	52	No	118.8667	160.94	214	269.87	269.87	**2.27**
10	60	52	No	118.8667	156.4	201.88	269.87	269.87	**2.27**
10	20	52	No	118.8667	158.44	205.22	260.05	260.05	**2.19**
5	5	12	No	118.8667	156.024	197.68	240.09	240.09	**2.02**
5	20	12	No	118.8667	154.47	188.35	232.65	232.65	**1.96**
5	60	12	No	118.8667	149.47	170.97	211.55	211.55	**1.78**
1	5	4	No	118.8667	146.223	166.692	197.187	197.187	**1.66**
1	20	4	No	118.8667	145.675	160.075	189.525	189.525	**1.59**
5	60	52	No	118.8667	144.57	162.32	188.32	188.32	**1.58**
5	5	52	No	118.8667	145.122	160.58	181.82	181.82	**1.53**
5	20	52	No	118.8667	146.76	162.07	179.61	179.61	**1.51**
1	60	4	No	118.8667	141.208	156.022	177.53	177.53	**1.49**
1	5	12	No	118.8667	140.925	142.333	161.462	161.462	**1.36**
1	20	12	No	118.8667	141.208	142.333	154.362	154.362	**1.30**
1	60	12	No	118.8667	136.89	138.34	154.1	154.1	**1.30**
1	5	52	No	118.8667	140.355	141.203	152.01	152.01	**1.28**
1	60	52	No	118.8667	139.496	140.64	149.08	149.08	**1.25**
1	20	52	No	118.8667	139.78	140.635	148.276	148.276	**1.25**

Figure 41. Comparison of the effect of the three ROP factors

Fig 42 shows the results of an initial investigation into the relative influence of the three ROP factors, the table was then sorted according to the level of recorded Bullwhip

Since most of the top half of the table contains simulation runs with higher BW Multiplier values, then clearly this factor must be evaluated further. Similarly the Average Period (where shorter Periods increasing the recorded level of Bullwhip) has a similar pattern of results, less clear is the Review Interval. In order to establish the impact of the application of Performance Metrics on *each factor in isolation,* three further sets of experiments were conducted. The data is presented in Appendices 6, 7 and 8 whilst the results are displayed graphically and discussed in the following sections.

9.3.1 Demand Average Period.

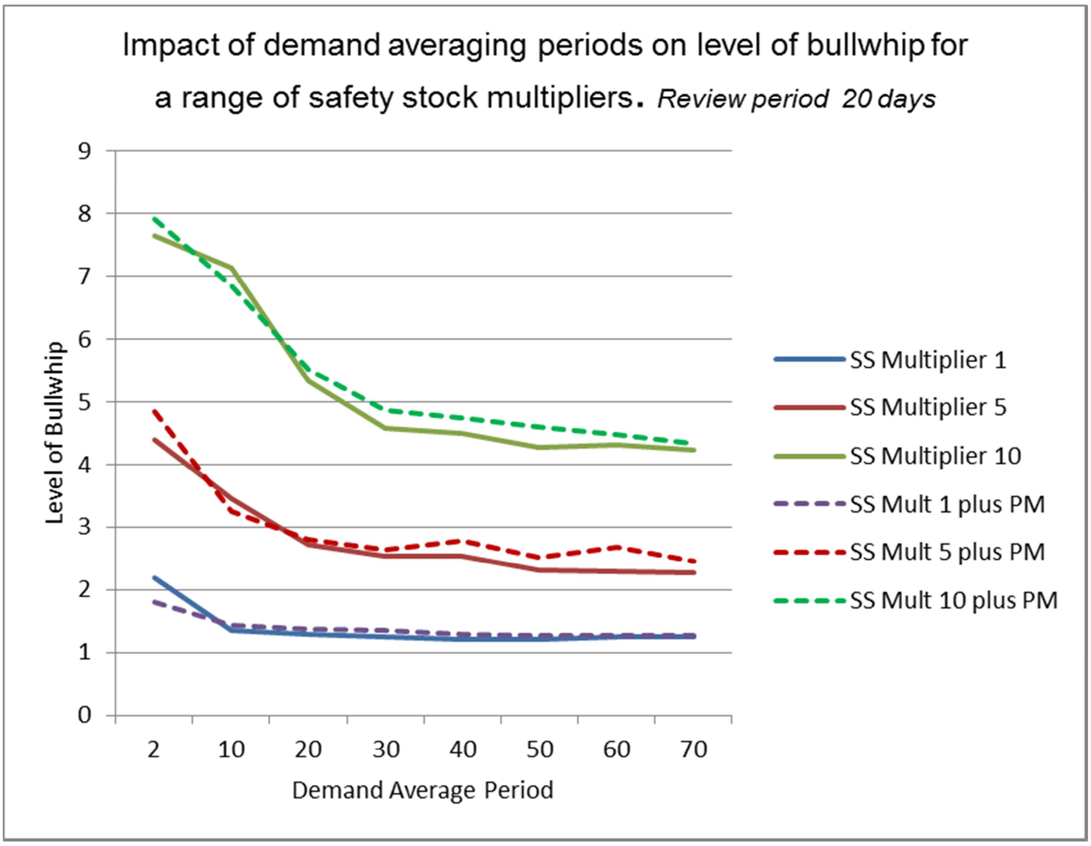

Figure 42. The impact of the Demand Average Period

If the demand is averaged across 30 days or more - the Demand Average period has little effect on the level of recorded Bullwhip in the simulation. When the Demand Average period is shorter than 30 days however its effect on Bullwhip becomes significant. Furthermore the effect is amplified by increasing the stock multiplier applied in the ROP calculation.

Across the range of Safety Stock Multipliers however, the application of Performance Measurement Systems did **not** produce a significant change in the recorded level Bullwhip.

9.3.2 Safety Stock Multiplier

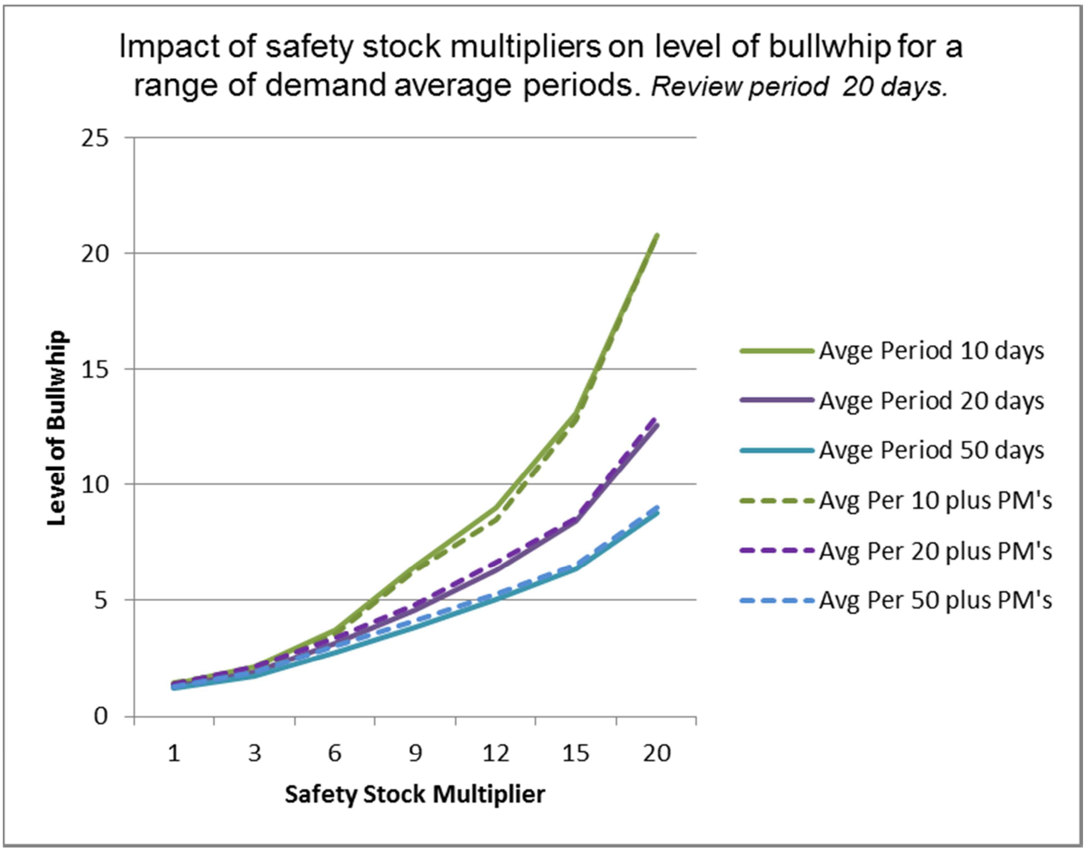

Figure 43. The impact of a Safety stock Multiplier on Bullwhip

The Safety Stock multiplier has a significant effect on the level of Bullwhip recorded in the model. Moreover the effect is greater when the Demand Average Period is also shorter *(the reciprocal finding from 9.3.1).*

Across the range of Demand Average Periods however the application of Performance Measurement Systems did **not** produce a significant change in the recorded level Bullwhip.

9.3.3 Demand Average Interval

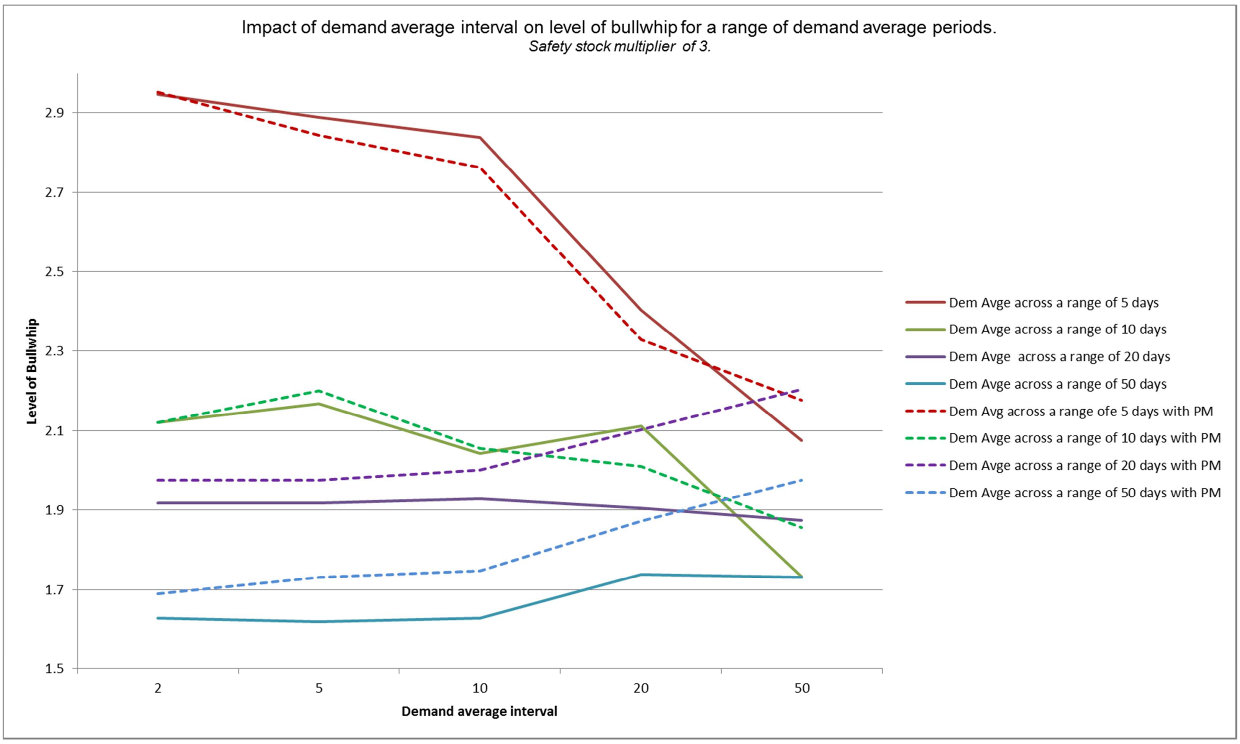

Figure 44. Impact of Demand Average Interval on Bullwhip

The Level of Bullwhip is clearly affected by the Demand Average Period, i.e. the fewer the days across which the average is taken – the greater the Bullwhip. In a given Average Period, across the range of 'demand average intervals' (the frequency this calculation takes place) of 2 to 20 days, the level of Bullwhip is relatively stable.

As the interval approaches 50 days however (where forecasts become very stable, if inaccurate) all 'demand average periods' including the relatively short 5 days period, tend to normalise towards a similar value.

Across the range of Demand Average Intervals; 2-20 days, the application of Performance Measurement Systems did not produce a significant change in the recorded level of Bullwhip. However with intervals greater than 20 days the application of PM's had a varied and interesting effect on the level of BW.

The Performance Measurement calculations within the model were set to take place continuously with Demand averaged across 20 days. In effect the application of Performance Measures effectively put a maximum Demand Average Interval of 20 days on the ROP calculation in the simulation.

The effects of imposing a secondary, variable limit on this parameter would appear to introduce a more involved even chaotic, reaction which is discussed in 10.2. Within the range of comparable settings however the application of PM's did not significantly change the level of BW.

9.4 Supply Chain Operational Parameters

Two sets of operational characteristics are identified as significant in the literature; Order batching (Lee *et al.*, 1997a. b) and Process/Transit Time (Disney *et al.*,1997b).

9.4.1 Order Batching

In the case of order batching; Fig 38 (with no order batching) and Fig 41 (Re-Order Quantity of 200) readily demonstrate its significance on Bullwhip as simply applying a ROQ at every role immediately increases dynamic behaviour by some 74%. The simulation model confirms the direct relationship between order batching and dynamic behaviour in the Supply Chain.

9.4.2 Transit Time

Transportation delays exists between the Retailer and Distributor (R-D) and Distributor and Manufacturer (D-M). Applying simulated transport delays of 100% and 200% respectively appeared to produce **no impact on the level of Bullwhip** in the model (Fig 47).

This result was pointed out as being surprising - since 'Excessive transport delays' are accepted universally as a fundamental cause of Bullwhip; *'the longer the material delivery cycle time the greater the effect'* (Disney et al., 1997b). Indeed cycle time compression is a fundamental objective of Supply Chain Management undertaken specifically to reduce Bullwhip (Geary, Disney et al. 2006).

Fig 44 demonstrated the undeniable relationship between the Safety Stock factor and Bullwhip and since Lead time acts in a similar fashion to the SS factor in the equation - then a similar relationship can be deduced.

$$\mathbf{ROP = d * LT + Z * \sigma\, d * \sqrt{LT}}$$

Run length	BW Mult	Review Interval	Avg Period	Air	sea	road	courier	Perf Review	Con-Ret	Ret-Dist	Dist-Man	Man-Prod	Prod-RM	
1000	5	20	20	1	35	3	1	No	118.494	166.55	249.27	323.32	323.32	2.728577
1000	5	20	20	2	70	6	2	No	118.494	166.5	249.27	323.32	323.32	2.728577
1000	5	20	20	3	105	9	3	No	118.494	166.5	249.27	323.32	323.32	2.728577
1000	5	20	20	1	35	3	1	yes	118.494	172	247.65	333.51	333.51	2.8145729
1000	5	20	20	2	70	6	2	yes	118.494	166.55	243.04	323.14	323.14	2.7270579
1000	5	20	20	3	105	9	3	yes	118.494	169.66	242.73	322.3	322.3	2.7199689

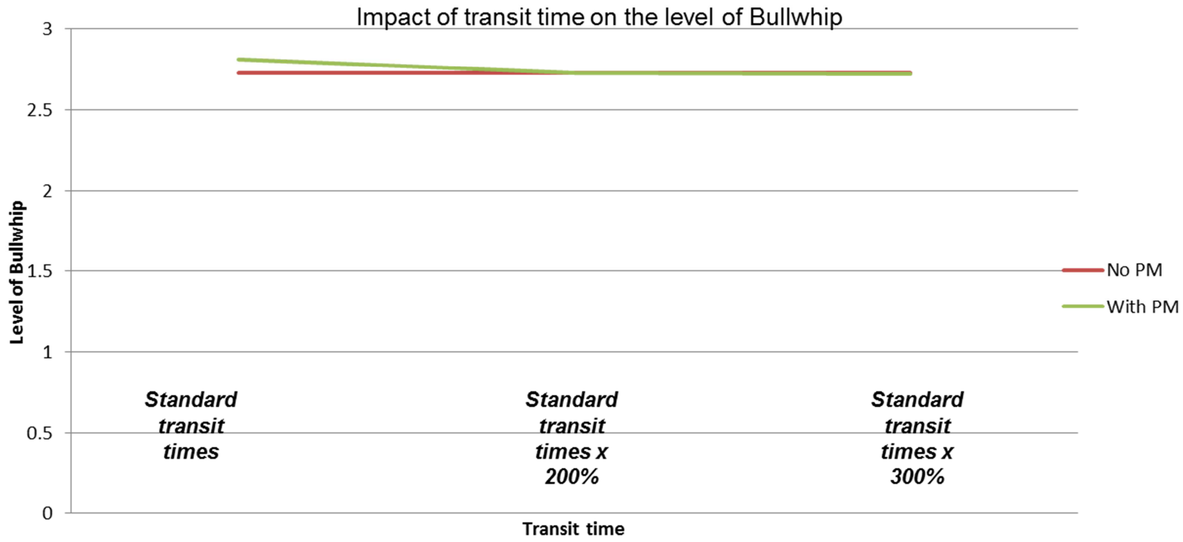

Figure 45. Impact of Transit time on Bullwhip

Model validation checks confirmed the result and a more considered investigation, lead to the re-examination of the ROP mechanism simulated within the model.

SET Var_Ret_ROP = Var_Ret_Bull_ROP_Multiplier*Var_Ret_Avg_Demand

Whilst the simulated ROP mechanism is valid for the purpose of testing the effects of applying Performance Measures, it does not explicitly consider the average lead time of orders in the calculation of the ROP. The quantity of orders in transit is included in the average demand function, but the time these orders have taken is not a function in the ROP calculation and consequently, changes in transit time do not induce changes in the ROP and the subsequent level of Bullwhip.

One very positive consequence of this observation however, is that a new degree of clarity can be brought to our understanding of the relationship between Lead Time and Bullwhip. ***Increasing transit time in itself does not increase Bullwhip; rather it is the role transit time plays in the reorder point calculation that changes the level of dynamic behaviour.*** *If the adopted ROP calculation does not consider lead time, then changes in transit time do not affect the level of Bullwhip.*

It is worth reiterating here that the Lead Time associated with individual orders is captured in this model and used in the Performance Measurement function (see section 7.6).

Capacity constraints are not identified in the literature as a significant factor and the model similarly displayed no change in the Bullwhip with variation in capacity. Applying a Performance Measurement System does however marginally increase the level of dynamic behaviour (Fig 46) however this is attributed to the Performance Metric engaging more frequently the secondary production capacity, but the fundamental principle; ‘no relationship between capacity and Bullwhip’ is evident.

Run length	BW Mult	Review Interval	Man Capacity stations	Perf Review	Con-Ret	Ret-Dist	Dist-Man	Man-Prod	Prod-RM	
1000	5	20	27	No	118.494	166.55	249.27	323.32	323.32	2.728577
1000	5	20	54	No	118.494	166.55	249.27	323.32	323.32	2.728577
1000	5	20	81	No	118.494	166.55	249.27	323.32	323.32	2.728577
1000	5	20	108	No	118.494	166.54	249.27	323.32	323.32	2.728577
5000	5	20	27	No	118	146	185	225	323.14	2.7270579
5000	5	20	81	No	118	146	185	225	333.51	2.8145729
5000	5	20	81	yes	119	148	194	242	333.51	2.8145729
1000	5	20	27	yes	118.494	172	247	333	333	2.8102689
1000	5	20	54	yes	118.494	178	254	344	344	2.9031006
1000	5	20	81	yes	118.494	170.8	250	337	337	2.8440259
1000	5	20	108	yes	118.494	172	250	341	341	2.8777828

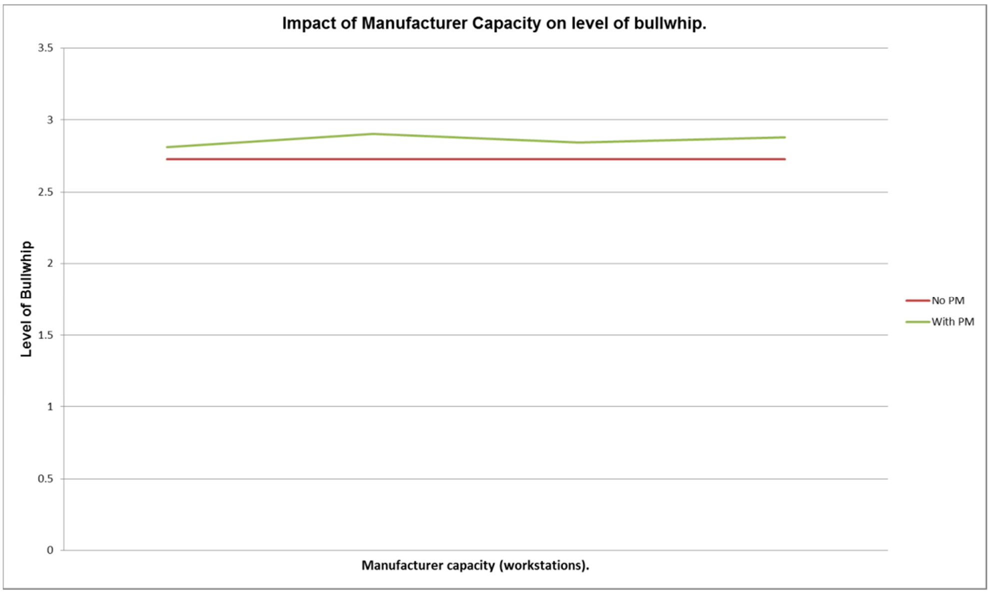

Figure 46. Impact of Capacity on Bullwhip.

9.5 Consumer Demand Parameters

The variation in demand adopted in the model was developed and used in previous work considering SC dynamics and the Lean/Agile debate (Taylor, Love et al. 2008) where standard deviation of demand values of 0.033, 0.133 and 0.33 were used to represent a range of demand profiles.

Across this identified range of Demand the application of a Performance Measurement Systems did **not** produce a significant change in the recorded level Bullwhip. In both cases, with and without Performance Measures (Fig 48), the demand averaging mechanisms in the ROP's dampen the levels of dynamic behaviour suffered in the SC. When demand variation exceeds a standard deviation of 0.33 and approaches a value of 1 then far greater levels of Bullwhip are incurred. At these higher levels of demand volatility the application of PM's appears to marginally increase the level of Bullwhip, however this reaction at the extreme is discussed in section 10.2 .

Run length	BW Mult	Review Interval	Avg Period	interval	std dev	cons order size	std dev	Perf Review	Con-Ret	Ret-Dist	Dist-Man	Man-Prod	Prod-RM	
1000	5	20	20	5	0.165	200	6.6	No	15.63	99.12	167.56	233.13	233.13	14.91555
1000	5	20	20	5	0.665	200	26.6	No	63	122.29	187.56	267.65	267.65	4.248413
1000	5	20	20	5	1.6	200	66	No	121.52	174.8	252.47	336.13	336.13	2.766047
1000	5	20	20	5	5	200	200	No	289	347.7	446.96	568.6	568.6	1.967474
1000	5	20	20	5	0.165	200	6.6	yes	15.6	115.94	201.8	275.06	275.06	17.63205
1000	5	20	20	5	0.665	200	26.6	yes	63	124.8	206.93	281.97	281.97	4.475714
1000	5	20	20	5	1.6	200	66	yes	121.52	184.85	262.14	350.76	350.76	2.886438
1000	5	20	20	5	5	200	200	yes	289	353	444.7	557.8	557.8	1.930104

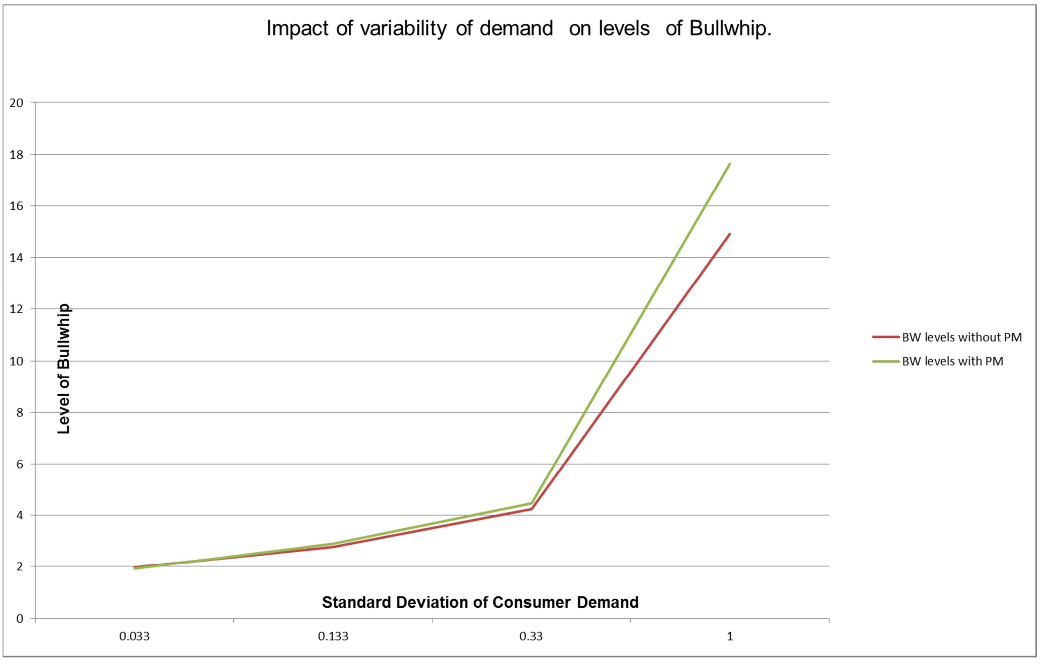

Figure 47. Impact of Demand variation on Bullwhip

9.6 Performance Metric Calculation Parameters

Two distinct options were considered for establishing performance targets; those obtained from industry/the SCC directly and those derived via an intimate knowledge of the model and its parameters. Various extreme values for performance targets were applied during the validation process. However it became apparent that since the model data was derived and extrapolated from a variety of previously published sources (rather than a single commercial source) appropriate PM targets would not be found externally.

A set of targets was established, *across all five* aspects of performance, based upon the metric output during steady state (Fig 49). Low performance metric targets were the 'mean plus 10%', 'Normal' and 'High' are displayed below. The different levels of Bullwhip witnessed with or without, the application of SC performance measures, could then be established.

		Man	Dist	Ret
Low	Utilisation	0.3	0.3	0.3
	Flexibility	38	67	71
	Cost	1750	113	48
	Responsiveness	69	3	2
	Reliability	0.71	0.71	0.71
Norm	Utilisation	0.4	0.4	0.4
	Flexibility	34	62	65
	Cost	1400	90	38
	Responsiveness	55	2	1
	Reliability	0.95	0.95	0.95
High	Utilisation	0.5	0.5	0.5
	Flexibility	30	57	60
	Cost	1050	68	29
	Responsiveness	41	1	1
	Reliability	0.99	0.99	0.99

Figure 48. Performance metric targets

A sequence of performance priorities was programmed into the model (Fig 35) representing a logical interpretation of typical SCC members' strategic priorities. In all cases the model produced a complete set of results, demonstrating all five priorities as being dominant at some point in the run, when performance targets were applied (Fig 36).

The effect of the sequence of performance priorities is clearly a matter of interest, a priority that dominated operational settings could for example represent a predefined preference/strategic objective and could be best simulated via both the following;

- Applying the more demanding target to this aspect and the Normal value to the remaining four.
- Ensuring this metric was the final aspect of performance considered in the 'Performance Review' elements in the model.

However it was considered that this preliminary work should first establish the effect of applying a representative set of SC Performance Measures. Opportunities for expanding the work to investigate competitive priorities supported by local targets are discussed later in 10.5.

The level of Bullwhip demonstrated within the model across a range of Performance Metric targets is displayed in Fig 50. Whilst Bullwhip is influenced by the multiplier used in the ROP mechanism, it is evident that varying the target levels of the metrics themselves does not bring about any significant change in the level of Bullwhip.

		bw mult	rev per	interval							
	1000	1	20	10	No	118.494	134.41	142.5	160.5	160.5	1.354499
No PM's	1000	9	20	10	No	118.494	226.45	413.56	770.2	770.2	6.499907
	1000	20	20	10	No	118.494	410.54	1028.1	2463.5	2463.5	20.79008
	1000	1	20	10	Yes	118.494	137.37	154.67	159.24	159.24	1.343866
Low	1000	9	20	10	Yes	118.494	226.45	423.64	736.26	736.26	6.213479
	1000	20	20	10	Yes	118.494	408.82	1033.77	2460	2460	20.76054
	1000	1	20	10	Yes	118.494	138.82	158.52	171.4	171.4	1.446487
Norm	1000	9	20	10	Yes	118.494	226.45	413.56	748.87	748.87	6.319898
	1000	20	20	10	Yes	118.494	408.83	1030.46	2459.95	2459.95	20.76012
	1000	1	20	10	Yes	118.494	144.5	163.5	176.03	176.03	1.48556
High	1000	9	20	10	Yes	118.494	228.2	398.4	722.72	722.72	6.099212
	1000	20	20	10	Yes	118.494	408.83	984.6	2460	2460	20.76054

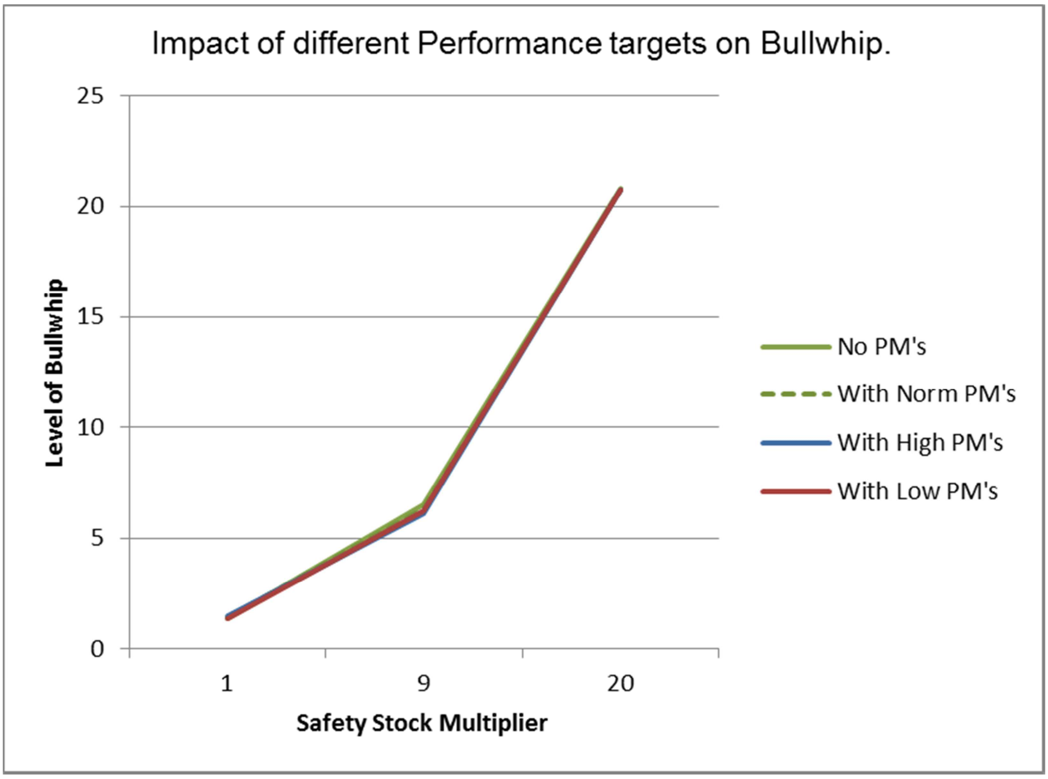

Figure 49. The effect of varying the performance targets on Bullwhip

9.7 Conclusions

- Within the ROP calculation two variables; 'demand average period' and 'safety stock multiplier' showed a significant positive relationship with Bullwhip. The 'demand average interval' however showed far lower correlation across the 2-20 day range of ROP calculations.

- Increasing transit/lead time *in itself* did not increase the level of Bullwhip. This initially appears counterintuitive as Process Time has been identified (see Chapter 2.2) as a cause of Bullwhip (Disney, Naim et al. 1997). The experiments conducted in Chapter 8 however demonstrate that **'it is the role transit time plays in the reorder point calculation'** that changes the level of Bullwhip rather than lead time itself. Since Lead time acts in a similar fashion to the SS factor in the equation;

  $$\mathbf{ROP = d * LT + Z * \sigma d * \sqrt{LT}}$$

  Then it can be said that where the ROP is calculated as a function of the average demand during lead time, then Lead time does indeed have a positive correlation with Bullwhip.

- Examining the objective question however, when experimenting across a range of realistic ROP variables, *the application of a representative Performance Measurement Systems does* **not** *produce a significant change in measured level of Bullwhip.*

10. CONCLUSIONS AND FURTHER WORK

This study is an investigation into the effect of applying a Supply Chain Performance metric framework on the level of dynamic behaviour in the Supply Chain. It uses a dynamic discrete event simulation model, programmed in the simulation software SIMUL8, of a classic Beer Game design. Uniquely within the model there exist elective mechanisms for calculating SC performance across the five SCOR aspects of performance. In each role these measures can be compared to a set of predefined targets and appropriate operational responses made during the simulation run. These operational responses influence; production capacity, transport routes and ROP calculations and ultimately the degree of dynamic behaviour (Bullwhip effect) in the Supply Chain is quantified using the ratio of the standard deviation of upstream/downstream demand, for each role and for the Supply Chain as a whole.

Experimental areas of particular interest, along with their associated variables, were categorised into four identified functional groups;

- ROP Calculation
- Operational Parameters
- Consumer Demand
- Performance Measurement Mechanisms

A set of simulation configurations and runs were undertaken in order to understand the significant factors and relationships influencing Bullwhip and the impact of a Performance Measurement system on it. In all cases where appropriate, simulation runs were conducted both with and without the application of performance measures.
Conclusions drawn from the results of these sets of simulation runs are laid out in the following chapter.

10.1 The significance of Re-Order Point

In a typical Supply Chain, where Consumer demand information is not shared and Supply Chain Planning is not centralised, there are a number of sequenced and iterative calculations of the Reorder Point within each role. The Re-Order Point calculation establishes the stock level at which demand is placed with upstream roles (suppliers) and since the measure of Bullwhip adopted in this model is the variation of 'demand made' relative the variation of 'demand received', then an understanding the ROP mechanism is fundamental to understanding any changes in dynamic behaviour. Classically the Re-Order Point calculation is expressed as follows;

$$\mathbf{ROP = d * LT + Z * \sigma\, d * \sqrt{LT}}$$

Where;

d – the forecast of average weekly demand.

LT – the lead time.

Z – the safety stock factor, based on in-stock probability during the lead time;

σd – estimation of the standard deviation of the weekly demand.

(Merkuryev, Petuhova et al. 2002)

In most commercial settings some form of averaging is applied to demand in order to facilitate forecasting and order generation. Smoothing the demand forecast has direct benefits to Supply Chains as failure to control schedule instability results in high average inventory (Bhaskaran 1998). Numerous authors (Metters 1997; Chen, Drezner et al. 1998; Dejonckheere, Disney et al. 2003; Chatfield, Kim et al. 2004; Zhang 2004) have researched the demand forecasting mechanism and its consequences on system dynamics. Their studies differed in method but between them they examined the forecasting methods of; moving average, simple exponential smoothing and double exponential smoothing. Notably their results all conclude that the number of observations used in moving average should be **high** in order to lower the bullwhip effect.

In this work all the key parameters of the ROP have been investigated across a range of values both with and without the application of Performance Measures.

Key parameters identified are;

- Demand averaging mechanism *(demand average period 9.1.1 & demand average frequency/interval 9.1.3)*
- Safety Stock Multiplier *(9.1.2)*
- Lead Time (*transport between roles 9.2.2 and production capacity constraints*)

Whilst the first two factors did show significant correlation with Bullwhip the Lead time did not, this in itself was contrary to the literature; “Because the amount of safety stock contributes to the bullwhip effect, it is intuitive that, when the lead times between the resupply of items along the supply chain are longer, the fluctuation is even more significant” (Lee, 1997).

Through experimentation however it was established that increasing transit time *in itself* does not increase Bullwhip; rather ***it is the role transit time plays in the reorder point calculation that changes the level of dynamic behaviour***. If the adopted ROP calculation does not consider lead time, then changes in transit time do not affect the level of Bullwhip. That such an realisation was not an initial objective of the work (see 1.5.1) does not diminish from the increase in clarity that it brings to the field in general.

In terms of the initial objectives of the work however; the experiments showed ***no significant change in level of dynamic behaviour displayed as a result of applying Performance Measures.***

10.2 The Nature of Dynamics in the Supply Chain

Wilding (1998) wrote on the causes of dynamic behaviour experienced within supply chains where he indicated three interacting yet independent effects (Fig 51);

- Deterministic chaos is generated by fixed rules that make system behaviour predictable, but in practice the non-linear effects of many causes, delays and batching rules make the system less predictable.

- Parallel interactions occur between different channels of the same tier in a supply network, two Distributors exchanging products for example.

- Demand amplification, changes in demand being amplified as they pass back up the supply chain through successive organisations.

Figure 50. The SC Complexity triangle. Wilding, 1998

The combination of these effects can significantly increase the degree of uncertainty within a supply chain system. The "supply chain complexity triangle" results because each source of uncertainty can act as a stimulus for one of the other sources of behaviour to occur.

A paradox identified with the “supply chain complexity triangle” is that methods to reduce the magnitude of one effect may result in an increase in magnitude of other sources of uncertainty.
For example; a supplier lead-time is reduced on the basis that this is known to reduce the degree of amplification generated within supply chains (Forrester and Wright 1961). However the reduction in lead-time also reduces the prediction horizon of the data series, reducing the forecast stability and increasing in the degree of chaos. This demonstrates the trade-off between amplification and chaos on one side of the complexity triangle.

Wilding’s work could be interpreted here as follows;

- Amplification is represented by the ROP mechanism.
- Deterministic chaos is represented as the situations in Extremes of Demand Average Interval (9.2.3) and Extremes of Demand Variability (9.4) where multiple deterministic inputs into the model bring about a seemingly dynamic but in effect chaotic output.
- Parallel interactions (multiple routes/products which are not represented in this/Beer game model).

For example; in this case the application of Performance Measures (see section 9.4) in situations of extreme demand variation (standard deviations of between 0.5 and 1 for both size and frequency) there was a 15% increase in the level of Bullwhip. An organisation faced with such volatile demand may dramatically increase ROP. However the existing tight performance targets ‘high service’ and ‘low cost’ etc. now force it to fluctuate capacity and modes of transport on a daily basis thus exhibiting almost chaotic behaviour. The role of deterministic chaos and parallel interactions on performance metrics are obviously an opportunity for further study.

10.3 Performance Objectives and Bullwhip

One original feature of the model developed in this work was the optional application of operational responses in light of the calculated SCOR metrics when compared to a set of targets. It has been seen (Ch 9 and 10.1) that the application of a representation of a SCPM system does not influence the level of Bullwhip in the Supply Chain. That is not to say that the numerous responses made by the roles in the model did not change (ideally improve) various and multiple aspects of the organisation's performance.

Fig 52 and Fig 53 demonstrate the difference in measured performance for two identical simulation runs with and without the Performance Measures. Displayed in the 'watch-windows' are the final values following a run of 1000 days. Note that the 'performance priority' for the various roles has changed (many times throughout the ocurse of the run) and its final value is different for all three roles. The priority is not established when the PM's are switched off, however all the metric values are still calculated and displayed.

In this example the measured BW with and without PM is 2.82 and 2.72 respectively. Whilst this difference in the level of Bullwhip may not be significant, the different recorded scores across the five dimensions of Performance leads to another important dimension for discussion.

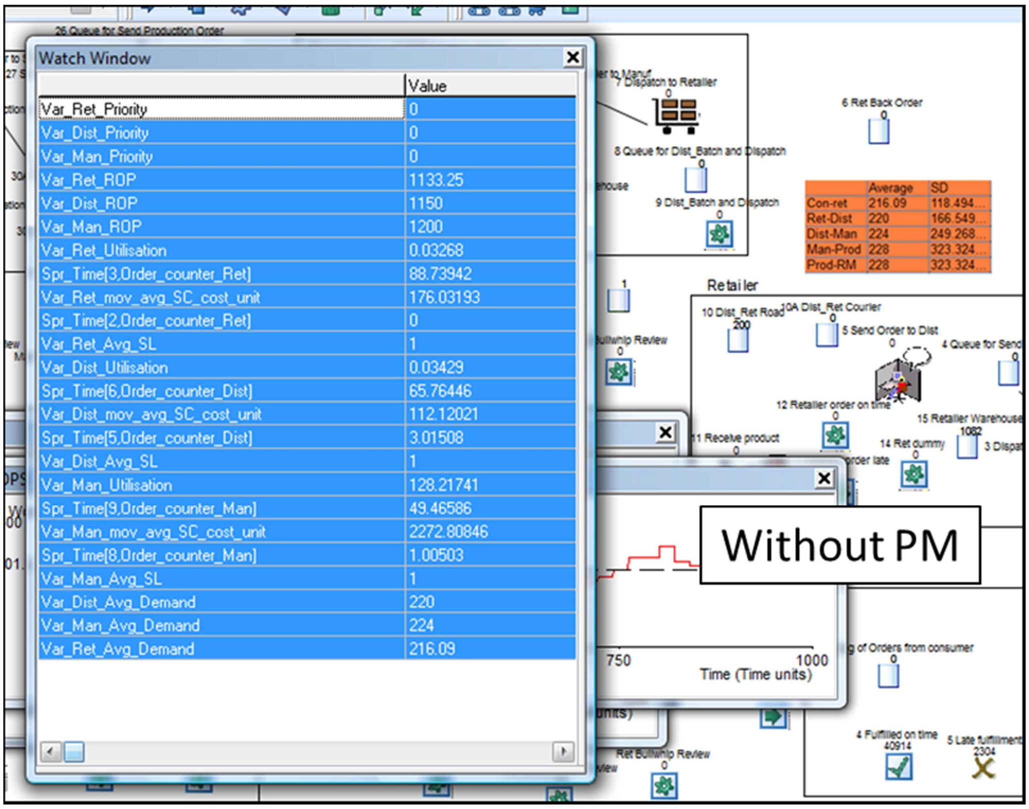

Figure 51. Example of SC performance Without applying Operational responses

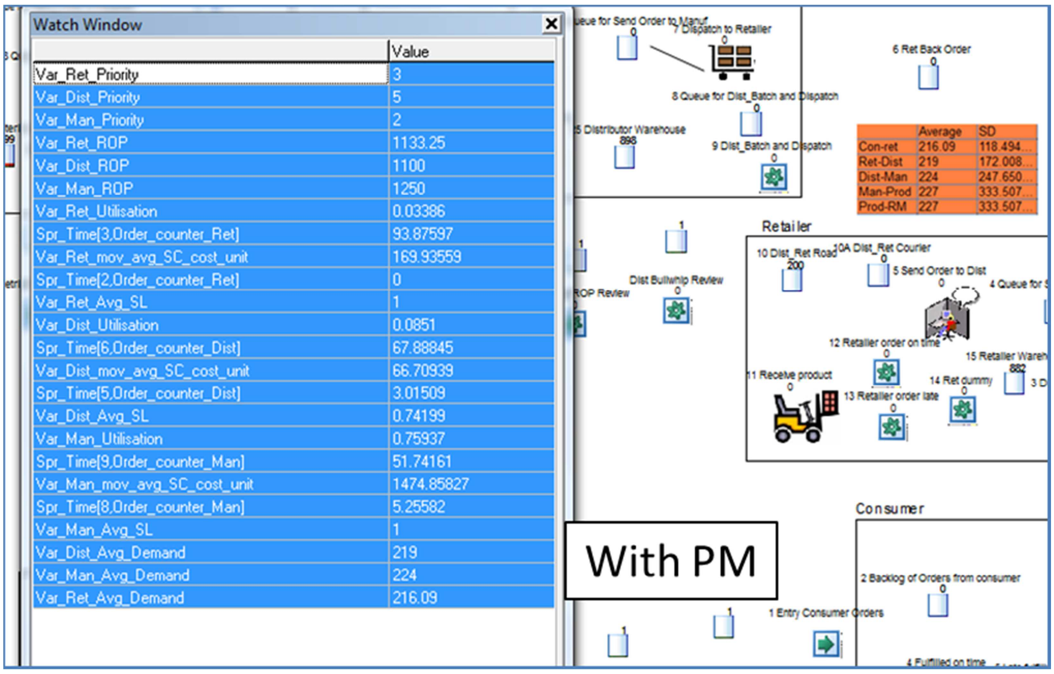

Figure 52. Example of SC performance With applying Operational responses

Note that the Retailer and the Manufacturer achieve identical levels of delivery service (1 being 100%) but following with the application of PM's - at lower Supply Chain cost. At this point in the run Average Service Level is not quite as high for the Distributor, where service is only 74%, but again at lower (in this case significantly lower) Supply Chain cost.

	No PM	With PM
Retailer Utilisation	0.032	0.034
Retailer Supply Chain Cost	176	169.9
Retailer Average Service Level	1	1
Distributor Utilisation	0.034	0.085
Distributor Supply Chain Cost	112.12	66.71
Distributor Average Service Level	1	0.74
Manufacturer Utilisation	128	0.76
Manufacturer Supply Chain Cost	2272	1475
Manufacturer Average Service Level	1	1

Reducing costs is one of the five, Level 1, objectives of the SCOR model and indeed of Supply Chain Management. In this example the application of Performance Measures can be seen to achieve this objective and reduce Supply Chain cost. 'Reducing Bullwhip' (demand variation) however is not one of the SCOR metrics. This leads to the question; if 'Demand Stability' or 'Demand Forecast Stability' were a SCOR metric, would it deliver improvement (reducing Bullwhip) as part of a set of six or more objectives. A modified research objective therefore might be; 'Are performance measurement systems incomplete in that they would benefit from the inclusion of an operational stability measure/objective. If reducing BW was a stated priority in a Performance Metric system would it have an impact on the level of dynamic behaviour and would it come at the detriment of other objectives?

This study of the impact of Performance Measures on Bullwhip makes an assumption *(based on the literature!)* that reducing demand variability is a key objective of SCM and that increasing variability is a backward step. It would be interesting to consider the converse of this and explore whether Bullwhip reducing activities negatively affect other aspects of Supply Chain Performance. Some references hint at this counter relationship; "*Dampening of the order variability decreases the bullwhip effect and the average on-hand inventory but with the problem of a decreasing service level*" (Jammernegg and Reiner 2007).

Certain metrics related to stability are present in SCOR. For example Forecast Accuracy is specified in the majority of the SCOR Planning Processes; P1.1, P2.1, P3.1 and P4.1 (see Appendix 1). However because accurate forecasts are not as great a priority as service, cost etc, they do not feature in the SCOR Level 1 metrics. The complexity of a model that incorporated every SCOR metrics would be a daunting prospect. If such a model was designed then the challenge would be how a suitable hierarchy of priorities could be established in order allow a single metric to influence operational priority, frequently enough in order to drive performance. Placing the challenges involved in simulation modelling aside, the fact remains that SCOR (nor any other model identified in the literature) explicitly or implicitly monitors and drives reductions in Bullwhip.

This study can conclude however that the application of a representative and widely acclaimed Supply Chain performance measurement system (the SCOR model) does NOT alter the levels of Bullwhip experienced in the Supply Chain. The key significant feature of this work however, is that there is now a tested and validated method of investigating the level of effect of the application of Performance Measurement Systems on dynamic behaviour in supply chains. The method can now be adopted to facilitate different Performance Measurement systems and explore questions such as "If Bullwhip reduction was an explicit objective in a Performance Measurement system what are the consequences to local and Supply Chain performance?

10.4 Further opportunities with the work

- The success of a Supply Chain is a complex and multi-dimensional question, one that lends itself to Performance Metric Systems. Various Supply Chain Objectives could be tested, including the objective of reducing demand variability, through the use of different objective performance metrics and justified responses.

- This model uses representative data from a number of published sources since no such commercial data was readily available across the range of aspects of performance in a suitable Supply Chain. There is a significant precedent for this approach as the first studies of Bullwhip (Forrester and Wright 1961) were conducted on the basis of theoretical system dynamics models and not on any study of commercial data. Suitable sources of commercial data could be sourced however, in order to build an extremely realistic simulation of a supply chain.

- Primarily a more complex model could be developed, acknowledging that most companies find themselves not supplying a single product but a range (Fransoo and Wouters 2000) and existing in a supply Web rather than the single supply chain. Performance targets could be selected according to the ABC product classification which might vary from 99 per cent for "A" products to 97.5 per cent for "B" products and 95 per cent for "C" products (Disney, Naim et al. 1997).

  This more complex model offers possibilities to study the impact of parallel interactions discussed above.

- More industrially focused models may deliver opportunities to study the relative impact of Performance Measures within or indeed between different industries/sectors. Published simulations, for example seasonality in clothing (Al-Zubaidi and Tyler 2004) where a subroutine to imitate management behaviour near the end of sales season have been incorporated, add embellishments and local adaptations that, *along with local/specific objectives and performance targets*, would offer the opportunity to calculate specific relationships now that the fundamental principles have been established. In the wider context however, there is the opportunity to experiment with any number of industries/sectors, in a range of economic environments with organisations adopting different objectives.

- Supplier selection practices and resultant performance priorities, based on a firm's position on the supply chain could be explored. Criteria used by component suppliers and end-product manufacturers can vary (Choi and Hartley 1996) and the priority sequence of performance criteria could vary between different industries, geographical locations or even strategic objectives ‘lean/agile’ etc.

- Detailed use of the SCC benchmarked metrics, to deliver specific target levels for the different aspects of performance, might facilitate the development of more complex models with sets of critical performance targets within each aspect of performance (Fig 44).

Figure 53. Phased SCOR Performance targets. Source SCOR Manual 6.1

10.3 Footnote

Exploration of the levels of dynamic behaviour within supply chains as a direct consequence of the ever increasing application of Performance Measurement systems is a valid and necessary subject for research. This work has established the fundamental mechanism between the two very widely explored, but largely independent, fields of study and points the way for further work. It is appropriate that the final word should echo one of the founders in the field;

More comprehensive models are opening the door to a new understanding - the future will no doubt show that we now know only a fragment of what we need to learn (Forrester 1968).

11. REFERENCES

Abernathy, F. H., J. T. Dunlop, et al. (2000). "Control your inventory in a world of lean retailing." Harvard business review 78(6): 169.

Al-Zubaidi, H. and D. Tyler (2004). "A simulation model of quick response replenishment of seasonal clothing." International Journal of Retail & Distribution Management 32(6): 320-327.

Anderson, E. G., C. H. Fine, et al. (2000). "Upstream volatility in the supply chain: The machine tool industry as a case study." Production and Operations Management 9(3): 239-261.

Angerhofer, B. J. and M. C. Angelides (2000). System dynamics modelling in supply chain management: research review, Society for Computer Simulation International San Diego, CA, USA.

Balci, O. (1998). "Verification, validation, and testing." Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice: 335-393.

Banks, J. and C. O. Malave (1984). "The simulation of inventory systems: An overview." Simulation 42(6): 283.

Barla, S. B. (2003). "A case study of supplier selection for lean supply by using a mathematical model." Logistics Information Management 16(6): 451.

Barnett, M. (2003). "Modeling & Simulation in Business Process Management." BP Trends Newsletter, White Papers & Technical Briefs.

Beamon, B. M. (1998). "Supply chain design and analysis: models and methods." International Journal of Production Economics 55(3): 281-294.

Beamon, B. M. (1999). "Measuring supply chain performance." International Journal of Operations and Production Management 19: 275-292.

Beamon, B. M. and T. M. Ware (1998). "A process quality model for the analysis, improvement and control of supply chain systems." Management 28(9/10): 704-715.

Bechtel, C. and J. Jayaram (1997). "Supply chain management: a strategic perspective." International Journal of Logistics Management 8: 15-34.

Bhaskaran, S. (1998). "Simulation Analysis of a Manufacturing Supply Chain*." Decision Sciences 29(3): 633-657.

Bolstorff, P. and R. Rosenbaum (2007). "Supply chain excellence: a handbook for dramatic improvement using the SCOR model."

Boughton, D. K. a. N. (2001). "New paradigms in planning and control across manufacturing supply chains." International Journal of Operations & Production Management 21(5/6): 582-593.

Braglia, M. and A. Petroni (2000). "A quality assurance-oriented methodology for handling trade-offs in supplier selection." International Journal of Physical Distribution and Logistics Management 30(1/2): 96-111.

Brewer, P. C. and T. W. Speh (2000). "Using the balanced scorecard to measure supply chain performance." Journal of Business Logistics 21(1): 75-94.

Bullinger, H. J., M. Kuhner, et al. (2002). "Analysing supply chain performance using a balanced measurement method." International Journal of Production Research 40(15): 3533-3543.

Burbidge, J. L. (1981). "Britain’s counter productive plants." Management Today November: 86–90.

Cachon, G. P. and M. A. Lariviere (2001). "Contracting to assure supply: How to share demand forecasts in a supply chain." Management Science: 629-646.

Cachon, G. r. P. and M. Fisher (2000). "Supply Chain Inventory Management and the Value of Shared Information." Management Science 46(8): 1032-1048.

Cagliano, R., F. Caniato, et al. (2004). "Lean, agile and traditional supply: how do they impact manufacturing performance?" Journal of Purchasing and Supply Management 10(4-5): 151-164.

Camerinelli, E. and A. Cantuon (2006). "Measuring the Value of the Supply Chain: A Framework." Supply Chain Practice 8(2): 40-59.

Campbell, A., M. Goold, et al. (1995). "Corporate strategy: the quest for parenting advantage." Harvard business review 73: 120-120.

Carter, M. F. (1986). Designing flexibility into automated manufacturing systems.

Çebi, F. and D. Bayraktar (2003). "An integrated approach for supplier selection." Logistics Information Management 16(6): 395-400.

Chan, F. T. S., H. J. Qi, et al. (2003). "A conceptual model of performance measurement for supply chains." Management decision 41(7): 635-642.

Chan, F. T. S., N. K. H. Tang, et al. (2002). "A simulation approach in supply chain management." Integrated Manufacturing Systems 13(2): 117.

Chang, Y. and H. Makatsoris (2001). "Supply chain modeling using simulation." International Journal of simulation 2(1): 24-30.

Chatfield, D. C., J. G. Kim, et al. (2004). "The bullwhip effect—impact of stochastic lead time, information quality, and information sharing: A simulation study." Production and Operations Management 13(4): 340-353.

Chen, E., Z. Drezner, et al. (1998). The bullwhip effect: Managerial insight's on the impact of/oivrasthig and information on variability in a supply chain, New york: Kluwer/Academic Press.

Chen, F., Z. Drezner, et al. (2000). "Quantifying the bullwhip effect in a simple supply chain: The impact of forecasting, lead times, and information." Management Science: 436-443.

Chen, F. and R. Samroengraja (2000). "The stationary beer game." Production and Operations Management 9(1): 19-30.

Childerhouse, P. and D. Towill (2000). "Engineering supply chains to match customer requirements." Logistics Information Management 13(6): 337-345.

Choi, T. Y. and J. L. Hartley (1996). "An exploration of supplier selection practices across the supply chain." Journal of Operations Management 14(4): 333-343.

Chow, G., T. D. Heaver, et al. (1994). "Logistics Performance." International Journal of Physical Distribution & Logistics Management 24(1): 17-28.

Christopher, M. (1999). "Logistics and Supply Chain Management: Strategies for reducing cost and improving service." International Journal of Logistics Research and Applications 2(1): 103-104.

Council, S. C. (2005). "Supply-Chain Operations Reference Model: SCOR Version 7.0 Overview." URL: www. supply-chain. org., Stand 9.

Croom, S., P. Romano, et al. (2000). "Supply chain management: an analytical framework for critical literature review." European Journal of Purchasing and Supply Management 6(1): 67-83.

D'Souza, D. E. and F. P. Williams (2000). "Toward a taxonomy of manufacturing flexibility dimensions." Journal of Operations Management 18(5): 577-593.

Das, S. K. and L. Abdel-Malek (2003). "Modeling the flexibility of order quantities and lead-times in supply chains." International Journal of Production Economics 85(2): 171-181.

De Boer, L., E. Labro, et al. (2001). "A review of methods supporting supplier selection." European Journal of Purchasing and Supply Management 7(2): 75-89.

Dejonckheere, J., S. M. Disney, et al. (2003). "Measuring and avoiding the bullwhip effect: A control theoretic approach." European Journal of Operational Research 147(3): 567-590.

Ding, H., L. Benyoucef, et al. (2004). "A simulation-optimization methodology for supplier selection problem." Int. J. Computer Integrated Manufacturing 18(2-3): 210-224.

Disney, S. M., P. Childerhouse, et al. (1997). The development of supply chain structures in the automotive aftermarket sector.

Disney, S. M., M. M. Naim, et al. (1997). "Dynamic simulation modelling for lean logistics." International Journal of Physical Distribution and Logistics Management 27: 174-196.

Disney, S. M. and D. R. Towill (2003). "The effect of vendor managed inventory (VMI) dynamics on the Bullwhip Effect in supply chains." International Journal of Production Economics 85(2): 199-215.

Disney, S. M. and D. R. Towill (2003). "On the bullwhip and inventory variance produced by an ordering policy." Omega 31(3): 157-167.

Easton, L., D. J. Murphy, et al. (2002). "Purchasing performance evaluation: with data envelopment analysis." European Journal of Purchasing and Supply Management 8(3): 123-134.

Fearne, A. and D. Hughes (1999). "Success factors in the fresh produce supply chain: insights from the UK." Supply Chain Management: An International Journal 4(3): 120-128.

Fisher, M. L. (1997). "What is the right supply chain for your product?" Harvard business review 75: 105-117.

Forrester, J. W. (1968). "Industrial dynamics-after the first decade." Management Science: 398-415.

Forrester, J. W. and J. Wright (1961). Industrial dynamics, MIT press Cambridge, MA.

Fransoo, J. C. and M. J. F. Wouters (2000). "Measuring the bullwhip effect in the supply chain." Supply Chain Management: An International Journal 5(2): 78-89.

Garland, C., T. D. Heaver, et al. (1994). "Logistics performance: definition and measurement." International Journal of Physical Distribution and Logistics Management 24(1): 17–28.

Geary, S., S. M. Disney, et al. (2006). "On bullwhip in supply chains—historical review, present practice and expected future impact." International Journal of Production Economics 101(1): 2-18.

Gerwin, D. (1993). "Manufacturing flexibility: a strategic perspective." Management Science: 395-410.

Glaser-Segura, D. and H. Cirtita (2007). "Supply Chain Performance Metrics: A Confluence of Foci and Methodology Maturation." Forthcoming Cerca con Google.
Group, G. T. (2007). 31/05/2007. from http://www10.mcadcafe.com/link/display_detail.php?link_id=19620#.

Gunasekaran, A., C. Patel, et al. (2001). "Performance measures and metrics in a supply chain environment." International Journal of Operations and Production Management 21(1/2): 71-87.

Hermann, C. F. (1967). "Validation problems in games and simulations with special reference to models of international politics." Behavioral science 12(3): 216.

Hines, P., M. Holweg, et al. (2000). "Waves, beaches, breakwaters and rip currents: a three-dimensional view of supply chain dynamics." International Journal of Physical Distribution and Logistics Management 30(9/10): 827-846.

Holmberg, S. (2000). "A systems perspective on supply chain measurements." International Journal of Physical Distribution and Logistics Management 30(9/10): 847-868.

Holmström, J. (1997). "Product range management: a case study of supply chain operations in the European grocery industry." Supply Chain Management: An International Journal 2(3): 107-115.

Holweg, M. and J. Bicheno (2002). "Supply chain simulation–a tool for education, enhancement and endeavour." International Journal of Production Economics 78(2): 163-175.

Holweg, M., S. Disney, et al. (2005). "Supply chain collaboration: making sense of the strategy continuum." European Management Journal 23(2): 170-181.

Houlihan, J. B. (1985). "International supply chain management." The International Executive 27(3).

Huan, S. H., S. K. Sheoran, et al. (2004). "A review and analysis of supply chain operations reference (SCOR) model." Supply Chain Management: An International Journal 9(1): 23-29.

Huang, Z. and A. Gangopadhyay (2004). "A simulation study of supply chain management to measure the impact of information sharing." Information Resources Management Journal 17(3): 20-31.

Hwarng, H. B. and N. Xie (2008). "Understanding supply chain dynamics: A chaos perspective." European Journal of Operational Research 184(3): 1163-1178.

Jack, E. P. and A. Raturi (2002). "Sources of volume flexibility and their impact on performance." Journal of Operations Management 20(5): 519-548.

Jacobs, F. R. (2000). "Playing the beer distribution game over the internet." Production and Operations Management 9(1): 31-39.

Jain, S., R. W. Workman, et al. (2001). Development of a high-level supply chain simulation model.

Jammernegg, W. and G. Reiner (2007). "Performance improvement of supply chain processes by coordinated inventory and capacity management." International Journal of Production Economics 108(1-2): 183-190.

Jeffrey, A., F. Jerry, et al. (2005). Combining hands-on, spreadsheet and discrete event simulation to teach supply chain management. Proceedings of the 37th conference on Winter simulation. Orlando, Florida, Winter Simulation Conference.

Kamann, D. J. F. and E. F. Bakker (2004). "Changing supplier selection and relationship practices: a contagion process." Journal of Purchasing and Supply Management 10(2): 55-64.

Kaplan, R. S. and D. P. Norton (1996). The balanced scorecard: Translating strategy into action, Harvard Business School Press.

Kasi, V. (2005). Systemic assessment of SCOR for modeling supply chains.

Kleijnen, J. P. C. (2003). Supply chain simulation: a survey, Tilburg University.

Labarthe, O., B. Espinasse, et al. (2007). "Toward a methodological framework for agent-based modelling and simulation of supply chains in a mass customization context." Simulation Modelling Practice and Theory 15(2): 113-136.

Lambert, D. M. and T. L. Pohlen (2001). "Supply chain metrics." International Journal of Logistics Management 12(1): 1-20.

Lapide, L. (1999). "New developments in business forecasting." Journal of Business Forecasting Methods and Systems 18: 12-14.

Lee, H. L. and C. Billington (1992). "Managing supply chain inventory: pitfalls and opportunities." Sloan management review 33(3): 65-73.

Lee, H. L., V. Padmanabhan, et al. (1997). "The bullwhip effect in supply chains." Sloan management review 38: 93-102.

Lee, H. L., V. Padmanabhan, et al. (1997). "Information distortion in a supply chain: the bullwhip effect." Management Science: 546-558.

Love, D. M. (1980). Aspects of Design for a Spare Parts Provisioning System, University of Aston in Birmingham.

Lowson, R. (2001). "Analysing the effectiveness of European retail sourcing strategies." European Management Journal 19(5): 543-551.

Maskell, B. H. (1991). Performance measurement for world class manufacturing: A model for American companies, Productivity Press.

Mason-Jones, R., M. M. Naim, et al. (1997). "The impact of pipeline control on supply chain dynamics." International Journal of Logistics Management 8: 47-62.

Mason-Jones, R. and D. R. Towill (1997). "Information enrichment: designing the supply chain for competitive advantage." Supply Chain Management: An International Journal 2(4): 137-148.

Mason, G. M. S. (2009). "An integrated supply chain model with dynamic flow and replenishment requirements." Journal of Simulation: 84-94.

McCullen, P. and D. Towill (2001). "Achieving lean supply through agile manufacturing." Integrated Manufacturing Systems 12(6/7): 524-533.

McCullen, P. and D. Towill (2002). "Diagnosis and reduction of bullwhip in supply chains." Supply Chain Management: An International Journal 7(3): 164-179.

Meixell, M. J. and V. B. Gargeya (2005). "Global supply chain design: A literature review and critique." Transportation Research Part E 41(6): 531-550.

Mentzer, J. T., W. DeWitt, et al. (2001). "Defining supply chain management." Journal of Business Logistics 22(2): 1-26.

Merkuryev, Y. A., J. J. Petuhova, et al. (2002). Simulation-based analysis of the bullwhip effect under different information sharing strategies.

Metters, R. (1997). "Quantifying the bullwhip effect in supply chains." Journal of Operations Management 15(2): 89-100.

Mihram, G. A. (1972). "Some Practical Aspects of the Verification and Validation of Simulation Models." Operational Research Quarterly (1970-1977) 23(1): 17-29.

Miragliotta, G. (2006). "Layers and mechanisms: A new taxonomy for the bullwhip effect." International Journal of Production Economics 104(2): 365-381.

Mitchell, T. W. (1924). "Competitive illusion as a cause of business cycles." The Quarterly Journal of Economics: 631-652.

Morash, E. A. (2002). "Supply chain strategies, capabilities, and performance." Transportation journal 41(1): 37-54.

Mummalaneni, V., K. M. Dubas, et al. (1996). "Chinese purchasing managers' preferences and trade-offs in supplier selection and performance evaluation." Industrial Marketing Management 25(2): 115-124.

Narasimhan, R., S. Talluri, et al. (2001). "Supplier evaluation and rationalization via data envelopment analysis: an empirical examination." The Journal of Supply Chain Management 37(3): 28-37.

Neely, A., M. Gregory, et al. (1995). "Performance measurement system design." International Journal of Operations and Production Management 15(4): 80-116.

New, S. J. and R. Westbrook (2004). Understanding supply chains: concepts, critiques, and futures, Oxford University Press, USA.

Olhager, J. (1993). "Manufacturing flexibility and profitability." International Journal of Production Economics 30(31): 67-78.

Paik, S. K. and P. K. Bagchi (2007). "Understanding the causes of the bullwhip effect in a supply chain." International Journal of Retail & Distribution Management 35(4): 308-324.

Persson, F. and J. Olhager (2002). "Performance simulation of supply chain designs." International Journal of Production Economics 77(3): 231-245.

Persson, F. A., J. (2007). "The development of a dynamic supply chain analysis tool - Integration of SCOR and discrete event simulation." International Journal of Production Economics doi:10.1016/j.ijpe.2006.12.064.

Petrovic, D. (2001). "Simulation of supply chain behaviour and performance in an uncertain environment." International Journal of Production Economics 71(1-3): 429-438.

Rafele, C. (2004). "Logistic service measurement: a reference framework." Journal of Manufacturing Technology Management 15(3): 280-290.

Raghunathan, S. (2001). "Information sharing in a supply chain: A note on its value when demand is nonstationary." Management Science: 605-610.

Reiner, G. and J. Fichtinger (2008). "Demand forecasting for supply processes in consideration of pricing and market information." International Journal of Production Economics.

Riddalls, C. E., S. Bennett, et al. (2000). "Modelling the dynamics of supply chains." International Journal of Systems Science 31(8): 969-976.

Sargent, R. G. (2004). Validation and verification of simulation models.

Schmenner, R. W. (2001). "Looking ahead by looking back: swift, even flow in the history of manufacturing." Production and Operations Management 10(1): 87-96.

Schmitz, J. and K. W. Platts (2003). "Roles of supplier performance measurement: indication from a study in the automotive industry." Management decision 41(8): 711-721.

Schneiderman, A. M. (1996). "Metrics for the order fulfillment process (part 1)." Journal of Cost Management 10: 30-42.

Schunk, D. and B. Plott (2000). Using simulation to analyze supply chains, Society for Computer Simulation International San Diego, CA, USA.

Seidmann, A. (1995). "Electronic data interchange: Competitive externalities and strategic implementation policies." Management Science: 401-418.

Sethi, A. K. and S. P. Sethi (1990). "Flexibility in manufacturing: a survey." International Journal of Flexible Manufacturing Systems 2(4): 289-328.

Shepherd, C. and H. Gunter (2006). "Measuring supply chain performance: current research and future directions." International Journal of Productivity and Performance Management 55(3/4): 242.

Slack, N., S. Chambers, et al. (2007). Operations management, Prentice Hall.

Stainer, A. (1997). "Logistics-a productivity and performance perspective." Supply Chain Management: An International Journal 2(2): 53–62.

Stank, T. P., S. B. Keller, et al. (2001). "Supply chain collaboration and logistical service performance." Journal of Business Logistics 22(1): 29-48.

Stephens, S. (2001). "Supply Chain Council & Supply Chain Operations Reference (SCOR) Model Overview." Supply Chain Council, Inc., Pittsburgh, USA [http://www. supplychain. org/].

Stephens, S. (2001). "Supply chain operations reference model version 5.0: a new tool to improve supply chain efficiency and achieve best practice." Information Systems Frontiers 3(4): 471-476.

Sterman, J. D. (1989). "Modeling managerial behavior: misperceptions of feedback in a dynamic decision making experiment." Management Science: 321-339.

Stewart, G. (1995). "Supply chain performance benchmarking study reveals keys to supply chain excellence." Logistics Information Management 8(2): 38-44.

Stewart, G. (1997). "Supply-chain operations reference model (SCOR): the first cross-industry framework for integrated supply-chain management." Logistics Information Management 10: 62-67.

Stone, J. and D. Love (2007). "Modelling the relationship between local logistics management decisions and overall supply chain performance: a research agenda." International Journal of Business Performance Management 9(2): 240-252.

Sun, H. X. and Y. T. Ren (2005). The impact of forecasting methods on bullwhip effect in supply chain management.

Swaminathan, J. M., S. F. Smith, et al. (1998). "Modeling Supply Chain Dynamics: A Multiagent Approach*." Decision Sciences 29(3): 607-632.

Tan, K. C. (2001). "A framework of supply chain management literature." European Journal of Purchasing and Supply Management 7(1): 39-48.

Taylor, D. G., D. M. Love, et al. (2008). "Determining inventory service support levels in multi-national companies." International Journal of Production Economics 116(1): 1-11.

Taylor, D. H. (2000). "Demand amplification: has it got us beat?" International Journal of Physical Distribution and Logistics Management 30(6): 515-533.

Terzi, S. and S. Cavalieri (2004). "Simulation in the supply chain context: a survey." Computers in industry 53(1): 3-16.

Torres, O. A. C. and F. A. V. Morán (2006). The Bullwhip Effect in Supply Chains: A Review of Methods, Components, and Cases, Palgrave Macmillan.

Towill, D. and M. Naim (1993). "Partnership sourcing smooths supply chain dynamics." Purchasing and Supply Management: 38-38.

Towill, D. R. (1996). "Industrial dynamics modelling of supply chains." International Journal of Physical Distribution and Logistics Management 26: 23-42.

Towill, D. R. (1997). "FORRIDGE-Principles of good practice in material flow." Production Planning and Control 8(7): 622-632.

Towill, D. R., M. M. Naim, et al. (1992). "Industrial dynamics simulation models in the design of supply chains." International Journal of Physical Distribution and Logistics Management 22: 3-3.

Towill, D. R., L. Zhou, et al. (2007). "Reducing the bullwhip effect: Looking through the appropriate lens." International Journal of Production Economics 108(1-2): 444-453.

Ulrich, K. T. and S. Pearson (1998). "Assessing the importance of design through product archaeology." Management Science: 352-369.

Upton, D. M. (1994). "The management of manufacturing flexibility." California Management Review 36: 72-72.

Van Ackere, A., E. R. Larsen, et al. (1993). "Systems thinking and business process redesign: an application to the beer game." European Management Journal 11: 412-412.

Van der Zee, D. J. and J. Van der Vorst (2005). "A Modeling Framework for Supply Chain Simulation: Opportunities for Improved Decision Making*." Decision Sciences 36(1): 65-95.

van Hoek, R. I. (1998). "Measuring the unmeasurable–measuring and improving performance in the supply chain." Supply Chain Management: An International Journal 3(4): 187-192.

Van Hoek, R. I. (2001). "The contribution of performance measurement to the expansion of third party logistics alliances in the supply chain." International Journal of Operations and Production Management 21(1/2): 15-29.

Van Landeghem, R. and K. Persoons (2001). "Benchmarking of logistical operations based on a causal model." International Journal of Operations and Production Management 21(1/2): 254-266.

Venkateswaran, J., Y. J. Son, et al. (2002). Investigation of influence of modeling fidelities on supply chain dynamics.

Verma, R. and M. E. Pullman (1998). "An analysis of the supplier selection process." Omega 26(6): 739-750.

Vickery, S., R. Calantone, et al. (1999). "Supply chain flexibility: an empirical study." The Journal of Supply Chain Management 35(3): 16-24.

Wang, G., S. H. Huang, et al. (2004). "Product-driven supply chain selection using integrated multi-criteria decision-making methodology." International Journal of Production Economics 91(1): 1-16.

Warburton, R. D. H. (2004). "An exact analytical solution to the production inventory control problem." International Journal of Production Economics 92(1): 81-96.

Webster, M. and E. Lane (2002). "Supply system structure, management and performance: a conceptual model." International Journal of Management Reviews 4: 353-369.

Wilding, R. (1998). "The supply chain complexity triangle: uncertainty generation in the supply chain." International Journal of Physical Distribution and Logistics Management 28: 599-616.

Wilson, E. J. (1994). "The relative importance of supplier selection criteria: a review and update." The Journal of Supply Chain Management 30(3): 34-41.

Workgroup, N. (1992). "Performance indicators in logistics." Logistics Information Management 5(3): 35–40.

Zeng, A. Z. (2003). "Global sourcing: process and design for efficient management." Supply Chain Management: An International Journal 8(4): 367-379.

Zhang, X. (2004). "The impact of forecasting methods on the bullwhip effect." International Journal of Production Economics 88(1): 15-27.

12. APPENDICIES

Appendix 1 SCOR Level 2 PLAN metrics

Process Category		Reliability	Responsiveness	Flexibility	Cost	Assets
P1 Plan SC						
Identify, Prioritize and Aggregate Supply Chain	P1.1	Forecast Accuracy	Intra-Manufacturing Replan		Supply-Chain Finance Costs	
					Forecasting and Demand MIS Costs	
Identify, Prioritize and Aggregate Supply Chain Resources	P1.2			Cumulative Source/Make Cycle Times	Planning Costs as a % of Total Supply Chain Costs	Inventory Days of Supply
				Intra-Manufacturing Replan Cycle Time	Supply Chain Finance Costs	Inventory Turns
					Product Data (MIS) Management Costs	Return On Assets
					Manage Finished Goods Data (MIS)	Cash-to-Cash Cycle Time
Balance Supply-Chain Resources with Supply-Chain Requirements	P1.3	Delivery Performance to customer request date	Order Fulfillment Lead Time	Supply Chain Response Time	Total Supply-Chain Costs	Inventory days of Supply
		Fill Rate		Production Flexibility	Value Added Productivity	Asset Turns
		Perfect Order Fulfillment				Cash-to-Cash Cycle Time
Establish and Communicate Supply Chain Plans	P1.4	Perfect Order Fulfillment		Cumulative Source/Make Cycle Time	Supply Chain Finance Costs	Inventory Days of Supply (Inventory Turns)
		On-time Delivery		Total Supply Chain Response Time	Inventory Carrying Costs	Return on Assets
						Cash-to-Cash Cycle time
P2 Plan Source						
Identify, Prioritize, and Aggregate Product Requirements	P2.1	Forecast Accuracy				
Identify, Assess, and Aggregate Product Resources	P2.2					
Balance Product Resources with Product Requirements	P2.3	Supplier on-time Delivery Performance				
Establish Sourcing Plans	P2.4	Supplier on-time Delivery Performance				
		Supplier Fill Rate				
P3 Plan Make						
Identify, Prioritize, and Aggregate Production Requirements	P3.1	Forecast Accuracy				
Identify, Assess, and Aggregate Production Resources	P3.2					
Balance Production Resources with Product Creation Requirements	P3.3			Cumulative Make Cycle Time		Total WIP Inventory DOS
Establish Production Plans	P3.4	Production Plan Adherence		Cumulative Make Cycle Time		Total WIP Inventory DOS
P4 Plan Deliver						
Utilize Current Label *(demand sources)*	P4.1	Forecast Accuracy	In-Stock Position (Inventory)	Order Management Cycle Time		
		Sales Floor Error Rates On Shelf Locations		% Overtime Labor		
		Shelf SKU Accuracy				
Identify, Assess, and Aggregate Delivery Resources	P4.2	Forecast Accuracy		Order Management Cycle Time		
Balance Delivery Resources with Delivery Requirements	P4.3	Delivery Performance to Customer Request Date				
Establish Delivery Plans	P4.4	Delivery Performance to Customer Request Date				Finished Goods Inventory Days of Supply
		Fill Rate				

Appendix 2 SCOR Level 2 SOURCE metrics

Process Category		Reliability	Responsiveness	Flexibility	Cost	Assets
Identify Sources of Supply	S3.1	% Potential suppliers selected which become qualified	Source Identification Cycle Time	Time and/or Cost reduction related to Source Identification	Product Process Engineering as a % of Product Acquisition Costs	Value of assets provided by service provider (cost avoidance)
		% Qualified suppliers which meet defined requirements	Source Qualification Cycle Time			
Select Final Supplier(s) and Negotiate	S3.2	% Supplier contracts negotiated meeting target terms and conditions for quality, delivery, flexibility and cost	Source Selection Cycle Time	% Single and/or Sole Source Selections	Sourcing Costs as a % of Product Acquisitions Costs	
Schedule Product Deliveries	S1.1, S2.1, S3.3	% Schedules Generated within Supplier's Lead Time	Average Release Cycle of Changes	Average Days per Schedule Change	Product Management and Planning Costs as a % of Product Acquisitions Costs	Capacity Utilization
		% Schedules Changed within Supplier's Lead		Average Days per Engineering Change		
Receive Product	S1.2, S2.2, S3.4	% Orders/ lines received damage free	Receiving Cycle Time	% Receipts Received without Item and Quantity Verification	Receiving costs as a % of Product Acquisition Costs	
		% Orders/ lines received complete				
		% Orders/ lines received on-time to demand requirement				
		% Orders/ lines received with correct shipping documents				
Verify Product	S1.3, S2.3, S3.5	% Orders / line received defect free	Verification Cycle Time	% Receipts Received Without Quality Verification	Verification costs as a % of Product Acquisition Costs	
Transfer Product	S1.4, S2.4, S3.6	% Product transferred damage free	Transfer Cycle Time	Time and Cost Reduction related to Expediting the Transfer Process.	Transfer & Product storage costs as a % of Product Acquisition Costs	Inventory DOS
		% Product transferred complete				
		% Product transferred on-time to demand requirement				
		% Product transferred without transaction errors				
Authorize Supplier Payment	S1.5, S2.5	% Invoices processed without issues and/or errors	Payment Cycle Time.	% Invoice Receipts and Payments Generated via EDI.	Cost per invoice.	

Appendix 3 SCOR Level 2 MAKE metrics

Process Category		Reliability	Responsiveness	Flexibility	Cost	Assets
Finalize Production Engineering	M3.1	Deliver to commit date variance	Production Engineering Cycle time		ECO cost	Capacity Utilization
		Number of ECOs				
Schedule Production Activities	M1.1, M2.1, M3.2	Schedule achievement	Customer Signature/Authorization to Order Receipt Time	Schedule Interval	WIP inventory days of supply	Capacity utilization
		Percent of orders scheduled to customer request date		Upside Production Flexibility	Scheduled resource costs	
		Schedule achievement		Downside Production Flexibility	Plant level order management costs	
Issue Material	M1.2, M2.2, M3.3	Inventory accuracy	Sourced/in-process product requisition cycle time		Inventory obsolescence	Cash-to-cash cycle time
Issue Sourced/In-Process Product		Out of stock occurrences			Inventory days supply - sourced product, in-process product	
		% Parts received at point of use				
Produce and Test	M1.3, M2.3, M3.4	Fill rates	Total build cycle time	Intra-Manufacturing Re-Plan Cycle	Total Production Employment	Capacity utilization
		Ratio of actual to theoretical cycle time	Product/Grade Changeover Time		Value Added Productivity	Asset Turns
		Warranty and returns	Intra-Production Re-Plan Cycle		Warranty Costs	
		Yields	Ratio Of Actual To Theoretical Cycle Time			
		Yield variability				
		Scrap expense				
		In-process failure rates				
Package	M1.4, M2.4, M3.5	Warranty costs	Package cycle time		Packaging cost	Asset turns
		Yield			Scrap packaging expense	Capacity utilization
					Warranty costs	
Stage Finished Product	M1.5, M2.5, M3.6	Staging time			Inventory Carrying Cost	Inventory days supply-plant FG
Release Finished Product to deliver	M1.6, M2.6, M3.7	% Release errors	Quarantine or Hold time		Release cost per unit	
			Release process cycle time			

Appendix 4 SCOR Level 2 DELIVER metrics

Process Category		Reliability	Responsiveness	Flexibility	Cost	Assets
Process Inquiry & Quote	D1.1, D2.1	# Of Call backs as % of total inquiries	Customer Signature/Authorization to Order Receipt Time		Order Management Costs-Not company specific	
Obtain and Respond to Request for Proposal (RFP) / Request for Quote (RFQ)	D3.1					
Negotiate & Receive Contract	D3.2		Customer Signature/Authorization to Order Receipt Time	Upside Order Flexibility	Create Customer Order Costs	
				Downside Order Flexibility		
Receive, Enter & Validate Order	D1.2, D2.2	Perfect Order Fulfillment	Order Receipt to Order Entry Complete Time	Upside Order Flexibility	Create Customer Order Costs	
Enter Order, Commit Resources & Launch Program	D3.3		Customer Signature/Authorization to Order Receipt Time	Downside Order Flexibility	Order Entry and Maintenance Costs	
					Order Fulfillment Costs	
Reserve Inventory & Determine Delivery Date	D1.3, D2.3	Delivery Performance To Customer Commit Date	Order Receipt to Order Entry Complete Time		Finished Goods Inventory Days of Supply	Finished Goods Inventory Carry Cost
					Order Fulfillment Costs	Capacity Utilization
Consolidate Orders	D1.4, D2.4	Order Consolidation Profile	Order Entry Complete to Order Ready for Shipment Time		Transportation Costs	
			Order Entry Complete to Start Manufacture Time		Distribution Costs	
Schedule Installation	D3.4		Order Entry Complete to Start Manufacture Time	Upside Order Flexibility	Order Fulfillment Costs	
				Downside Order Flexibility		
Plan & Build Loads	D1.5, 2.5, D3.5	None	Order Entry Complete to Start Manufacture Time	Upside Shipment Flexibility	Transportation Costs	
				Downside Shipment Flexibility	Distribution Costs	
Route Shipments	D1.6, D2.6, D3.6		Order Entry Complete to Order Ready for Shipment Time		Transportation Costs	
					Distribution Costs	
Select Carriers & Rate Shipments	D1.7, D2.7		Carrier Quote Response Time		Transportation Costs	
			Order Entry Complete to Start Manufacture Time		Distribution Costs	
Receive Product at Warehouse	D1.8	Incoming Material Quality	Dock To Stock Cycle Time	Upside Delivery Flexibility	Distribution Costs	Finished Goods Inventory Days of Supply
				Downside Delivery Flexibility	Incoming Material Costs	Inventory Obsolescence as a % of Total Inventory
					Product Acquisition Costs	End-of-Life Inventory
Pick Staged Product	D1.9, D2.8, D3.7	On Time In Full	Complete Manufacture to Order Ready for Shipment Time	Upside Delivery Flexibility	Distribution Costs	Finished Goods Inventory Days of Supply
		Documentation	Order Entry Complete Time to Order Ready for Shipment Time	Downside Delivery Flexibility		
		Fill Rates				
Load Vehicle, Generate Shipping Documentation, Verify Credit, & Ship Product	D1.10, D2.9, D3.8	Delivery Performance to Customer Commit Date	Complete Manufacture to Order Ready for Shipment Time	Upside Shipment Flexibility	Transportation Costs	Field Finished Goods Inventory Days of Supply
		Delivery Performance to Customer Request Date	Order Ready for Shipment to Customer Receipt of Order Time	Downside Shipment Flexibility		
		Perfect Order Fulfillment	Order Entry Complete to Order Ready for Shipment Time			
Receive & Verify Product at Customer Site	D1.11, D2.10, D3.9	Perfect Order Fulfillment	Customer Receipt of Order to Installation Complete	Upside Shipment Flexibility		
			Order Ready for Shipment to Customer Receipt of Order Time	Downside Shipment Flexibility		
Test & Install Product	D2.11, D3.10	% Faultless Installations	Customer Receipt of Order to Installation Complete	Upside Installation Flexibility	Installation Costs	Field Finished Goods Inventory Days of Supply
			Installation Cycle Time (Measured in Days)	Downside Installation Flexibility		
Invoice & Receive Payment	D1.13, D2.12, D3.11	% Of Faultless Invoices	Deliver Cycle Time	Upside Delivery Flexibility	Customer Invoicing/Accounting Costs	Days Sales Outstanding
			Days Sales Outstanding	Downside Delivery Flexibility		

Appendix 5 SCOR performance priority setting

Stone, James

From: Caspar Hunsche [chunsche@supply-chain.org]
Sent: 27 March 2009 03:53
To: Stone, James
Subject: Re: SCC Contact Form (Non-Member)

Dear James,

I am not sure I can answer your question as it appears rather theoretic in nature. (Sorry if I am misinterpreting it).

The SCC and it's members consider the prioritization of the 5 performance attributes as an important first step in understanding supply chain performance. A well performing supply chain provides the capabilities to support the product strategy. A supply chain that services products that are considered high quality maybe configured differently than the low cost volume products. A company that needs to fulfill it's customer orders fast may lead to a different configuration than a supply chain that needs to be focused on it's assets.

Our members generally acknowledge that their is no justification to be best in class for all attributes as the cost and effort to achieve this does not warrant the result. Our implementation training materials (based on Bolstorff's Suply Chain Excellence book) emphasize the prioritization of 1 attribute to Superior performance (90 percentile), 2 attributes to advatage (70 percentile) and 2 parity (50 percentile).

Regarding your comment about certain attributes being antagonistic. Yes, attributes may be in theory antagonistic, but sometimes one improvement program support multiple attributes. For example: on a project I worked on the finding was that every touch (shipping, receiving) of a certain product line cause 1% of the goods to be damaged. By shipping directly from the regional warehouse we reduced the number of touches by 2 (as no receiving or shipping was required at the store) resulted in lower shipping cost (Cost metric) AND a 3% improvement of defect free/damage free deliveries (Reliability metric).

I hope this answers your questions.

Regards,
Caspar

Caspar Hunsche
Chief Technology Officer

Supply Chain Council, Inc. T 202 540 9002
1331 H Street, NW F 202 540 9027
Suite 500 chunsche@supply-chain.org
Washington DC 20005 www.supply-chain.org

Begin forwarded message:

From: info@supply-chain.org
Date: March 20, 2009 8:11:27 AM CDT
To: info@supply-chain.org

1

Appendix 6 Run; Impact of demand averaging periods on level of bullwhip for a range of safety stock multipliers

Run length	BW Mult	Review Interval	Avg Period	Perf Review	Con-Ret	Ret-Dist	Dist-Man	Man-Prod	Prod-RM	Bullwhip
1000	1	20	2	No	118.494	155.227	205.951	260.712	260.712	2.200213
1000	1	20	10	No	118.494	134.407	142.497	160.498	160.498	1.354482
1000	1	20	20	No	118.494	135.894	142.497	152.799	152.799	1.289508
1000	1	20	30	No	118.494	129.843	136.738	147.443	147.443	1.244308
5000	1	20	40	No	118.494	128.285	133.766	143.295	143.295	1.209302
5000	1	20	50	No	118.494	128.285	133.766	143.295	143.295	1.209302
5000	1	20	60	No	118.494	131.382	138.2	148.8009	148.8009	1.255767
5000	1	20	70	No	118.494	131.382	138.2	148.8009	148.8009	1.255767
5000	1	20	80	No	118.494	135.894	143.901	155.408	155.408	1.311526
5000	1	20	90	No	118.494	131.382	135.26	143.295	143.295	1.209302
5000	5	20	2	No	118.494	239.259	409.711	520.838	520.838	4.39548
5000	5	20	10	No	118.494	177.078	276.501	411.058	411.058	3.46902
5000	5	20	20	No	118.494	166.549	249.268	323.324	323.324	2.728611
5000	5	20	30	No	118.494	165.338	224.669	302.113	302.113	2.549606
5000	5	20	40	No	118.494	159.143	221.97	300.78	300.78	2.538356
5000	5	20	50	No	118.494	154.01	205.02	274.21	274.21	2.314126
5000	5	20	60	No	118.494	160.4	209.87	272.74	272.74	2.30172
5000	5	20	70	No	118.494	153.48	205.25	270.45	270.45	2.282394
5000	5	20	80	No	118.494	172.01	231.04	293.95	293.95	2.480716
5000	5	20	90	No	118.494	150.84	211.99	272.67	272.67	2.301129
5000	10	20	2	No	118.494	401.023	627.362	905.76	905.76	7.643931
5000	10	20	10	No	118.494	236.651	451.66	846.02	846.02	7.139771
5000	10	20	20	No	118.494	238.03	404.22	633.31	633.31	5.344659
5000	10	20	30	No	118.494	222.65	367.94	542.73	542.73	4.580232
5000	10	20	40	No	118.494	225.01	369.22	533.08	533.08	4.498793
5000	10	20	50	No	118.494	218.66	360.41	506.41	506.11	4.271187
5000	10	20	60	No	118.494	217.74	358.73	511.92	511.92	4.320219
5000	10	20	70	No	118.494	214.96	355.35	500.69	500.69	4.225446
5000	10	20	80	No	118.494	226.79	366.49	519.72	519.72	4.386045
5000	10	20	90	No	118.494	193.29	325.84	476.96	476.96	2.467588
	BW Mult	Review Interval	Avg Period							
1000	1	20	2	Yes	118.494	155.77	188.02	214.56	214.56	1.810725
1000	1	20	10	Yes	118.494	138.82	158.52	171.4	171.4	1.446487
1000	1	20	20	Yes	118.494	140.86	152.62	162.28	162.28	1.369521
1000	1	20	30	Yes	118.494	137.37	149.38	160.5	160.5	1.354499
5000	1	20	40	Yes	118.494	137.35	143.9	152.8	152.8	1.289517
5000	1	20	50	Yes	118.494	134.41	141.1	150.15	150.15	1.267153
5000	1	20	60	Yes	118.494	132.9	141.1	151.5	151.5	1.278546
5000	1	20	70	Yes	118.494	132.9	141.1	151.5	151.5	1.278546
5000	1	20	80	Yes	118.494				0	0
5000	1	20	90	Yes	118.494				0	0
5000	5	20	2	Yes	118.494	242.6	431.01	575.05	575.05	4.852988
5000	5	20	10	Yes	118.494	183.86	269.42	384.46	384.46	3.244552
5000	5	20	20	Yes	118.494	172	247.65	333.51	333.51	2.814573
5000	5	20	30	Yes	118.494	168.95	239.07	312.11	312.11	2.633973
5000	5	20	40	Yes	118.494	167.27	248.65	330.64	330.64	2.790352
5000	5	20	50	Yes	118.494	159.9	227	298.95	298.95	2.522913
5000	5	20	60	Yes	118.494	169.6	249	317.9	317.9	2.682836
5000	5	20	70	Yes	118.494	156.08	217	290.08	290.08	2.448056
5000	5	20	80	Yes	118.494				0	0
5000	5	20	90	Yes	118.494				0	0
5000	10	20	2	Yes	118.494	425.65	615.03	938.01	938.01	7.916097
5000	10	20	10	Yes	118.494	244.69	449.28	812.86	812.86	6.859925
5000	10	20	20	Yes	118.494	244.7	423	654.37	654.37	5.522389
5000	10	20	30	Yes	118.494	231.18	400.56	576.2	576.2	4.862693
5000	10	20	40	Yes	118.494	239.4	399.22	561.76	561.76	4.740831
5000	10	20	50	Yes	118.494	223.21	386.08	545.53	545.53	4.603862
5000	10	20	60	Yes	118.494	222.31	377.66	531.35	531.35	4.484193
5000	10	20	70	Yes	118.494	218.32	371.76	514.05	514.05	4.338194
5000	10	20	80	Yes	118.494				0	0
5000	10	20	90	Yes	118.494				0	0

Appendix 7 Run; Impact of safety stock multipliers on level of bullwhip for a range of demand average periods

Run length	BW Mult	Review Interval	Avg Period	Perf Review	Con-Ret	Ret-Dist	Dist-Man	Man-Prod	Prod-RM	
1000	1	20	2	No	118.494	155.227	205.95	260.71	260.71	2.200196
1000	3	20	2	No	118.494	185.06	283.27	413.83	413.83	3.492413
1000	6	20	2	No	118.494	270.34	469.07	569.43	569.43	4.80556
1000	9	20	2	No	118.494	372.58	593.2	849.34	849.34	7.167789
1000	12	20	2	No	118.494	466.4	709.28	974.81	974.81	8.226661
1000	15	20	2	No	118.494	560.49	847.76	1133.87	1133.87	9.569008
1000	20	20	2	No	118.494	679.81	999.29	1527.95	1527.95	12.89475
1000	1	20	5	No	118.494	134.41	142.5	160.5	160.5	1.354499
1000	3	20	5	No	118.494	159.38	211.24	284.82	284.82	2.403666
1000	6	20	5	No	118.494	202.89	379.86	623.1	623.1	5.258494
1000	9	20	5	No	118.494	271.19	605.65	1107.03	1107.03	9.342498
1000	12	20	5	No	118.494	333.12	802.25	1568.71	1568.71	13.23873
1000	15	20	5	No	118.494	384.86	956.92	1947.32	1947.32	16.43391
1000	20	20	5	No	118.494	477.6	1442.15	3415	3415	28.82002
1000	1	20	10	No	118.494	134.41	142.5	160.5	160.5	1.354499
1000	3	20	10	No	118.494	164.35	197.47	250.26	250.26	2.112006
1000	6	20	10	No	118.494	185.29	280.21	442.97	442.97	3.738333
1000	9	20	10	No	118.494	226.45	413.56	770.2	770.2	6.499907
1000	12	20	10	No	118.494	271.26	541.61	1065	1065	8.987797
1000	15	20	10	No	118.494	317.08	701.39	1550.1	1550.1	13.08168
1000	20	20	10	No	118.494	410.54	1028.1	2463.5	2463.5	20.79008
1000	1	20	20	No	118.494	135.89	142.5	152.8	152.8	1.289517
1000	3	20	20	No	118.494	152.95	184.85	225.77	225.77	1.905329
1000	6	20	20	No	118.494	184.2	272.94	376.23	376.23	3.175097
1000	9	20	20	No	118.494	214.6	356.86	541.31	541.31	4.568248
1000	12	20	20	No	118.494	259.9	466.05	751.32	751.32	6.340574
1000	15	20	20	No	118.494	311.33	588.41	998.98	998.98	8.430638
1000	20	20	20	No	118.494	398.53	810.53	1486.93	1486.93	12.54857
1000	1	20	50	No	118.494	128.29	133.77	143.3	143.3	1.209344
1000	3	20	50	No	118.494	141.46	172.7	206.04	206.04	1.738822
1000	6	20	50	No	118.494	162.14	242.5	325.22	325.22	2.744612
1000	9	20	50	No	118.494	199.05	323.57	453.68	453.68	3.828717
1000	12	20	50	No	118.494	242.83	417.6	600.84	600.84	5.070636
1000	15	20	50	No	118.494	277.17	500.35	754.06	754.06	6.363698
1000	20	20	50	No	118.494	350.02	670.22	1041.83	1041.83	8.79226
	BW Mult	Review Interval	Avg Period							
1000	1	20	5	Yes	118.494	138.82	152.05	174.88	174.88	1.475855
1000	3	20	5	Yes	118.494	165.57	219.64	275.93	275.93	2.328641
1000	6	20	5	Yes	118.494	210.67	397.76	642.37	642.37	5.421118
1000	9	20	5	Yes	118.494	272.39	624.5	1144.96	1144.96	9.662599
1000	12	20	5	Yes	118.494	339.1	817.03	1693.9	1693.9	14.29524
1000	15	20	5	Yes	118.494	390.39	941.54	1551.22	1551.22	13.09113
1000	20	20	5	Yes	118.494	483.74	1413.03	1691.65	1691.65	14.27625
1000	1	20	10	Yes	118.494	138.82	158.52	171.4	171.4	1.446487
1000	3	20	10	Yes	118.494	163.85	201.1	238.08	238.08	2.009216
1000	6	20	10	Yes	118.494	191.68	281.19	424.75	424.75	3.58457
1000	9	20	10	Yes	118.494	226.45	413.56	748.87	748.87	6.319898
1000	12	20	10	Yes	118.494	278.31	539.61	1009.24	1009.24	8.517225
1000	15	20	10	Yes	118.494	319.61	697.2	1514.9	1514.9	12.78461
1000	20	20	10	Yes	118.494	408.83	1030.46	2459.95	2459.95	20.76012
1000	1	20	20	Yes	118.494	140.87	152.61	162.28	162.28	1.369521
1000	3	20	20	Yes	118.494	152.95	200.5	249.14	249.14	2.102554
1000	6	20	20	Yes	118.494	194.8	288.94	399.72	399.72	3.373335
1000	9	20	20	Yes	118.494	221.06	375.34	572.81	572.81	4.834084
1000	12	20	20	Yes	118.494	273.95	494.14	788.55	788.55	6.654767
1000	15	20	20	Yes	118.494	326.24	596.71	1014.58	1014.58	8.56229
1000	20	20	20	Yes	118.494	409.32	807.49	1538.62	1538.62	12.98479
1000	1	20	50	Yes	118.494	134.41	141.08	150.15	150.15	1.267153
1000	3	20	50	Yes	118.494	146.23	189.15	221.82	221.82	1.871994
1000	6	20	50	Yes	118.494	174.79	267.92	358.13	358.13	3.022347
1000	9	20	50	Yes	118.494	202.06	345.41	487.43	487.43	4.113542
1000	12	20	50	Yes	118.494	244.48	430.17	625.82	625.82	5.281449
1000	15	20	50	Yes	118.494	282.66	524.86	774.31	774.31	6.534592
1000	20	20	50	Yes	118.494	359.47	706.24	1067.7	1067.7	9.010583

Appendix 8 Run; Impact of demand average interval on level of bullwhip for a range of demand average periods

Run length	BW Mult	Review Interval	Avg Period	Perf Review	Con-Ret	Ret-Dist	Dist-Man	Man-Prod	Prod-RM	
1000	3	2	5	No	118.494	117.96	260.34	349.24	349.24	2.947322
1000	3	5	5	No	118.494	117.96	261.112	342.26	342.26	2.888416
1000	3	10	5	No	118.494	172.7	240.6	336.34	336.34	2.838456
1000	3	20	5	No	118.494	159.38	211.24	284.82	284.82	2.403666
1000	3	50	5	No	118.494	155.02	191.9	245.89	245.89	2.075126
1000	3	2	10	No	118.494	155.02	204.66	251.23	251.23	2.120192
1000	3	5	10	No	118.494	155.02	206.61	256.77	256.77	2.166945
1000	3	10	10	No	118.494	155.02	194.6	241.93	241.93	2.041707
1000	3	20	10	No	118.494	164.35	197.47	250.26	250.26	2.112006
1000	3	50	10	No	118.494	146.23	173.64	205.25	205.25	1.732155
1000	3	2	20	No	118.494	155.02	183.32	227.19	227.19	1.917312
1000	3	5	20	No	118.494	155.02	186.58	227.19	227.19	1.917312
1000	3	10	20	No	118.494	150.3	185.94	228.42	228.42	1.927693
1000	3	20	20	No	118.494	152.95	184.85	225.77	225.77	1.905329
1000	3	50	20	No	118.494	155.02	183.97	222	222	1.873513
1000	3	2	50	No	118.494	135.66	160.64	192.94	192.94	1.628268
1000	3	5	50	No	118.494	135.66	160.64	191.89	191.89	1.619407
1000	3	10	50	No	118.494	137.13	160.64	192.94	192.94	1.628268
1000	3	20	50	No	118.494	141.46	172.7	206.04	206.04	1.738822
1000	3	50	50	No	118.494	148.4	173.86	205.06	205.06	1.730552
	BW Mult	Review Interval	Avg Period							
	3	2	5	Yes	118.494	179.08	263.41	349.82	349.82	2.952217
	3	5	5	Yes	118.494	179.08	259.57	336.94	336.94	2.84352
	3	10	5	Yes	118.494	178.42	249.62	327.25	327.25	2.761743
	3	20	5	Yes	118.494	165.568	219.64	275.93	275.93	2.328641
	3	50	5	Yes	118.494	172.22	204.66	258.02	258.02	2.177494
	3	2	10	Yes	118.494	155.02	204.66	251.23	251.23	2.120192
	3	5	10	Yes	118.494	156.31	209.51	260.65	260.65	2.199689
	3	10	10	Yes	118.494	155.02	201.69	243.59	243.59	2.055716
	3	20	10	Yes	118.494	163.85	201.1	238.08	238.08	2.009216
	3	50	10	Yes	118.494	157.6	193.36	220	220	1.856634
	3	2	20	Yes	118.494	165.07	191.9	234.16	234.16	1.976134
	3	5	20	Yes	118.494	157.6	195.01	234.16	234.16	1.976134
	3	10	20	Yes	118.494	151.63	195.43	237.06	237.06	2.000608
	3	20	20	Yes	118.494	152.95	200.5	249.14	249.14	2.102554
	3	50	20	Yes	118.494	166.28	217.43	261.11	261.11	2.203571
	3	2	50	Yes	118.494	145.66	169.17	200.1	200.1	1.688693
	3	5	50	Yes	118.494	149.74	179.55	205.06	205.06	1.730552
	3	10	50	Yes	118.494	140.03	179.55	207.01	207.01	1.747008
	3	20	50	Yes	118.494	146.23	189.15	221.82	221.82	1.871994
	3	50	50	Yes	118.494	161.37	200.5	234.16	234.16	1.976134