SUPPLY CHAIN SIMULATION: EXPERIENCES FROM TWO CASE STUDIES

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ABSTRACT

Analysing supply chains utilising discrete event simulation allows the analyst to take on a dynamic approach to system analysis. This paper outlines the research area of supply chain simulation and reports on two case studies from the Swedish electronics industry. Starting with a descriptive case study of a company's transition into supply chain management, the case continues to study how the level of detail in simulation models affects the simulation results and also to analyse the upstream supply chain of the same company. In the other case study, a supply chain is analysed using two different approaches. First, the interaction between quality, cost, and lead-time is evaluated using simulation. Second, screening and robust optimisation is applied to the same simulation models.

INTRODUCTION

One of the research topics covered by Production Economics is supply chain management. Supply chain management incorporates the use of analysis tools such as system dynamics, optimisation, and simulation. Theoretical models of the supply chain behaviour can be created by observing the supply chain's historical data or by collecting new data. Experiments that study the supply chain behaviour are useful in order to find causal effects and to test different or even extreme scenarios. Causal effects are however difficult to find if they are separated in time and space and extreme scenarios are hard to control in a supply chain. An alternative to conducting experiments in the system is of course to use a model of the system for experimentation.

Many of the supply chain models found in the literature are models that are used for optimisation. These models are used to answer questions about plant location, product mix, technology choice, means of distribution, inventory planning and control, vendor choice, configuration, and reverse logistics; see Goetschalckx *et al.* (2002) and Shapiro (2001) for extensive work on supply chain optimisation models. Optimisation models consider the supply chain at specific instances in time and do not take on a dynamic view like in simulation. Optimisation models often lack the estimate of the variability or robustness of a solution in a stochastic environment. Metrics such as lead-time variability, percent of on-time delivery and so on, are hard to obtain in using an optimisation model. In a recent literature review, Goetschalckx *et al.* (2002) examine seven different modelling approaches for global logistics systems using mathematical programming. Only one model in the review utilised stochastic lead-times and only a few included other stochastic characteristics. Stochastic characteristics are an important factor of supply chains. Especially a stochastic demand is regarded as having great impact on financial performance (Chwif *et al.* 2002).

Bekker and Saayman (1999) distinguish between time based and non-time based modelling techniques in logistics. They define time based as time driven and characterise simulation as a time-based technique. The advantage of time-based techniques, such as simulation, is the ability to include the stochastic nature of a system over time, while the non-time based techniques, such as optimisation often exclude this behaviour.
There is a methodological and practical difference in the way optimisation and simulation finds optimal solutions. In optimisation, the solution is dependent on the scenario that defines the experimental domain (cf. Zeigler *et al.* 2000). The optimal solution is only valid for that scenario and will become invalid if the scenario changes. In simulation it is possible to experiment with a set of scenarios in order to find a robust solution. The robust solution is not optimal but minimises/maximises the objective function that is subject to a set of scenarios. This solution is not as sensitive for environmental changes as the optimal solution obtained through optimisation.

Simulation in supply chain management offers a complement to the more prevailing modelling using optimisation models since simulation is more suited for representing random effects and predicting the dynamic behaviour of supply chains. This paper outlines the research area of supply chain simulation and reports on two case studies from the Swedish electronics industry. Starting with a descriptive case study of one company's transition into supply chain management, the case continues to study how the level of detail in simulation models affects the simulation results and also to analyse

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the upstream supply chain of the same company. In the other case study, a supply chain is analysed using two different approaches.

SUPPLY CHAIN SIMULATION

Forrester (1961) developed industrial dynamics (also known as systems dynamics) as a tool for systems analysis. Thus, systems dynamics have been used for supply chain simulation in over 40 years (Towill 1996). Later, supply chain simulation developed to include other simulation methodologies as well such as discrete event simulation.

Supply chain simulation defined as the use of simulation methodology, incorporating discrete event simulation technology, to analyse and solve problems found relevant to supply chain management.

The main reasons to use discrete event simulation for supply chain management related problems are (i) the possibility to include dynamics and (ii) the simplicity of modelling. Discrete event simulation is suited for these kinds of studies where time-dependant relations are analysed. Simulation also has a capability of capturing uncertainty and complexity that is well suited for supply chain analysis (Jain *et al.* 2001). Manivannan (1998) provides different examples of supply chain simulation including warehousing and distribution systems and trucking operations, among others. In another example of supply chain simulation, Bhaskaran (1998) provides a technique to analyse supply chain instability and inventory levels. Simulation is used to link the dynamic behaviour of a supply chain with the cost calculations possible in a mathematical programming model.

Jain *et al.* (2001) point out the model's level of detail as being one of the major difficulties in supply chain simulation. It is not uncommon to simulate at a level of detail that does not match the objective of the analysis. The choice of the level of detail is therefore an important issue in supply chain models. The model must also be credible in order for the results to be useful. Validation of a supply chain model can be a difficult task because of lack of data and lack of system experts. Manivannan (1998) points out the complex nature of supply chains as one of the main obstacles in supply chain simulation. Other modelling challenges that Manivannan highlights are the missing support for logistic processes in simulation software and unfamiliarity to simulation in the logistics industry. The wide use of optimisation methods in logistics and the fact that many problems have a closed-form solution are other challenges for supply chain simulation.

Banks *et al.* (2002) discuss what makes supply chain simulation different from other simulation applications. One major difference from e.g. simulation of manufacturing systems is that supply chain models contain information flows together with the flow of materials. The importance of handling different levels of detail is made apparent in the case of supply chain simulation. Different actors in the supply chain store data in different ways, which makes data collection harder. It is therefore difficult to model the whole supply chain at the same (desired) level of detail. The difficulty with different levels of detail together with the size of supply chain models tend to make the model building process take a longer time in supply chain simulation. To experiment with supply chain simulation models often include a large number of alternative scenarios demanding efficient experimental planning. Validation is another field where supply chain simulation meets difficulties. Subjective methods such as walkthroughs are hard to accomplish on the supply chain level. Sub-model validation is a way around the problem with huge systems since the problem is to get system experts with detailed knowledge about the *whole* supply chain.

CASE STUDY I: SUPPLY CHAIN TRANSITION AND MODELLING

The first case study concerns a company in the mobile communications industry. Olhager et al. (2002) deals with the impact of supply chains on operations management at the case company. It specifically deals with the transition of one of the plants from being a production unit to the role of a supply unit in a supply chain. This change has had a large impact on many factors related to supply chain structure and flexibility, reengineering of the information flow, the management of the supply process, and on performance measurement.

The role in the supply chain emphasises that a proactive approach for the operations at the supply units is necessary. Before introducing new technology, new solutions, and new supply paths, these must be tested, debugged, and corrected. This calls for simulation approaches especially with respect to new supply chain or supply network structures.

The change experienced at the case company has also been a change towards mass customisation. When mapping this move relative the product-process matrix by Hayes and Wheelwright (1984) and product profiling by Hill (1995) a misalignment between markets and manufacturing is seemingly appearing. However, the line flow process with a short set-up time is able to accommodate multiple product variants. Total product volumes are high and increasing. Consequently, rate-based and JIT/pull approaches can be utilised even though products are built to order. The role of the operations manager in the supply chain setting is to build structures and to empower the organisation. Flexibility must be built into these structures. The delivery team managing the order process embodies this empowerment.

For the same case company, Persson (2002) investigates how the choice of level of detail influences the outcome of a simulation study. To investigate the impact of a varying level of detail, a part of the manufacturing system is modelled using three different levels of detail.

The first model is built at a high level of detail containing all elements in the system. The second model contains aggregations of some of the processes in the system and the third model consists only of the main process. The experiments with the models aims at finding differences between the three models' outputs that originates from the choice of the level of detail. The results show that there are significant differences between the models.

The credibility of the results clearly depends on how a study is carried out. In simulation, this is done in the activities of validation and verification. The models outputs show great differences although the models are validated and verified. Essentially this difference in modelling originates from the chosen level of detail. Validation of simulation models must therefore include all simulation outputs used in a study. Output data must also be analysed using aggregates instead of single outputs.

Following the same case study, the analysis in Persson (2003) focuses on the supply chain's dynamic behaviour. The case company defines three different upstream routes for supply of electronic components and mechanical parts for mobile communications manufacturing. The first route concerns traditional purchasing, where components are shipped to the manufacturing plant and delivered into stock. This concept is here called direct supply, DS. The second route includes the use of vendor-managed inventory, VMI, at the manufacturer's plant. The components are called off when they are needed in production. The third route is a supply logistics centre, SLC, run by a third party. At the SLC components are held in stock by the company's suppliers and shipped in sets to the manufacturing plant at predefined time intervals. In this case, the SLC supplies two manufacturing plants with around the clock shipments.

Persson (2003) analyses the sensitivity of the three supply routes with respect to cost, lead-time, and lead-time variability. The results of the study indicate that the influence from a decreasing yield in the manufacturing process can be limited to the inventory at the manufacturing line and the use of an SLC relaxes the supplier from influences of manufacturing process yield. Managerial implications of the findings in this study are both specific and general. In the specific situation of the case company, the model provides useful data on the concepts of the different supply routes. The SLC concept is supported by the simulation results since it provides a buffer towards the suppliers of the SLC products. Thereby, the effect of yield level on supply is reduced. The company predefine the choice of supply route for each product in this study. In general, products that use the VMI and direct supply routes are characterised by the level of co-operation with the suppliers. Suppliers with high volume standardised products use the VMI mode while more customised products, such as integrated circuits, make use of the direct supply route. Products that are assembled late in the process and that have a high degree of customisation make use of the SLC concept. The SLC provides opportunities for co-ordination of supply to the manufacturing line and quality tests at the SLC. While relaxing the suppliers from the changes in yield, no increase in work in process can be detected. However, the transportation cost with hourly transports between the SLC and the manufacturing plant can not be neglected.

In more general terms, the model shows that the supply chain under the influence of fluctuating demand due to the changing process yield can handle most of the fluctuations in all investigated supply routes. However, the route that takes care of the fluctuations in the most effective way is the longest route, i.e. the route that contains the most intermediate inventory. In the case of the SLC route, the supply chain is expanded with an extra inventory holding stage compared with the DS and VMI routes. Therefore, the fluctuating demand of supply is limited to the manufacturing line. This means that the concept of a third party solution for the SLC provides the company with an independent upstream time buffer. This can be seen in Figure 1, the closer the inventory is stored to the manufacturing line, the more influenced by changing yields it gets.

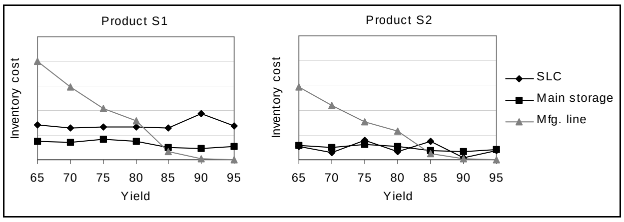

Figure 1: Inventory cost for the two products that utilise the SLC concept

Olhager et al. (2002) describes the transformation process from production units to demand-driven supply units. The transformation included a change in material supply routes. Vendor-managed inventory was already in use at the company and the benefits of that system was incorporated in supply logistics centres (SLC). The SLC concept is supported by the results in Persson (2003). The results of the simulation study show that the SLC provides a buffer towards the supply unit, such that environmental disturbances such as yield changes have little effect on the supply from the SLC. At the same time the SLC concept can incorporate the use of VMI and direct supply to supply the SLC. As the results from this case study the case company points out the advantage with having a single global provider for the SLC instead of local providers. This allows for materials to be re-routed between the SLCs as the demands for specific components change with the product mixes at different supply units. The SLC handles material used for packaging and mechanical components used in assembly.

CASE STUDY II: SUPPLY CHAIN SIMULATION ANALYSIS

In the second case study, Persson and Olhager (2002) reports on a supply chain simulation analysis. The purpose of this paper is twofold. First, alternative supply chain designs with respect to quality (product yield is equal to quality in this case), lead times and costs are evaluated. Second, the interrelationships among these and other parameters are analysed. The study concerns three different instances of the same supply chain, the old, the current, and the next generation supply chain design.

The results in terms of performance measures such as total cost, inventory holding, quality, lead-time, and lead-time variability shows some interesting interactions. Lead-time variability increases between the old and the current supply chain, even though lead times are reduced. However, for the next generation supply chain design, both lead-times and lead-time variability are expected to reduce considerably, thereby providing both shorter and more reliable lead times. The other performance measures improve with an improvement of quality and supply chain structures. The model capturing the relationships among total cost, quality and lead-time, indicates that total cost increases more than linearly with lead-time, see Figure 2. Also, the level of non-linearity increases with reduced quality levels. Consequently, low quality in supply chains with long lead-times is devastating to supply chain performance. Inversely, good quality and short lead-times in integrated and synchronised supply chains will lead to superior performance. The payoff in terms of total cost is more than proportional to the improvements in quality and lead-times, the latter largely a result of improved supply chain designs.

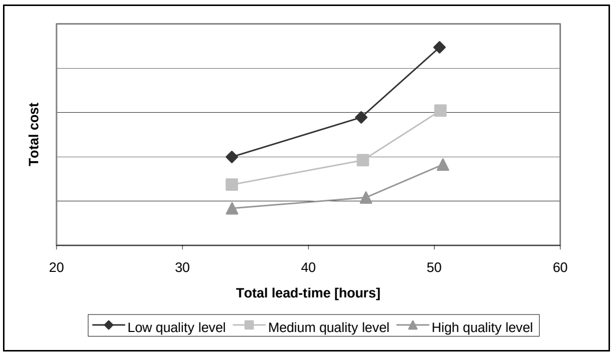

Figure 2: Relationship between total cost, lead-time, and quality level (cost levels are confidential)

To capture the influence of different yield levels on lead-time, the use of "scrap-inflated" lead-times as a performance measure is introduced in Persson and Olhager (2002). When a product is scrapped its lead-time is added to the next product that is entered into the simulation model, thereby adding to the lead-time calculations. These lead-times get shorter as the yield level (or quality level) improves. Scrap-inflated lead-times correspond to the time that capital is tied up in work in process, and, therefore, provide a better interpretation in terms of time for work-in-process inventories. Lead-times that ignore the scrap effect would underestimate the true work in process levels.

Kleijnen, Bettonvil, and Persson (2003) expands the analysis of Persson and Olhager (2002) by including screening and robust optimisation. In the paper, the three alternative designs from Persson and Olhager (2002) are subject to a screening process using sequential bifurcation. This group screening strategy is previously used for deterministic simulations. The number of experimental factors is reduced from 92 factors to 11 in the most extreme case. This is achieved in only 42 simulations (including mirror observations of each run)

An experimental design is also applied to the important factors in the model in order to find a robust optimal solution for the case company. The factors are divided into two groups, one consisting of all controllable factors and one consisting of all environmental factors. The case company can directly control controllable factors while the environmental factors are outside of control and can be considered as disturbances. In the experimental design, a central composite design for the controllable factors is crossed with a Latin hypercube sampling design for the environmental factors.

The results show that all of the controllable factors, that are important according to the screening process, show significant effects in the regression analysis. As was suspected, several two-way factor interactions also show significant effects. Most interesting is the presence of interactions between the controllable and environmental factors. These interactions indicate that the case company can counteract eventual changes in environmental factors by changing their controllable factors.

The next generation supply chain design, the design with the shortest lead-time and lowest cost, proves also to be the structure with the most robust solution. The variability of lead-time and cost are smallest for the next generation supply chain design compared with the other two.

The simulation studies of the second case company focuses on performance measures such as quality (in terms of yield), lead times and costs. Costs include costs for work in process levels, rework time, and scrap. The study shows how these performance measures are interlinked with each other. The studies show that the performance measures improve with improved quality and improved supply chain designs. The model capturing the relationships among cost, quality and lead-time, indicate that cost increases more than linearly with lead-time. Also, the non-linearity increases with worse quality. Consequently, bad quality in long lead-time supply chains is devastating to supply chain performance. Inversely, better quality and shorter lead-times in integrated and synchronised supply chains will lead to superior performance, see Figure 2.

The screening used in the second case study shows that demand, yield and transportation time are the most important input variables in the simulation models. In the context of supply chain management this means that product quality, in terms of yield, and supply chain design, in terms of transportation times, are important parameters in the studied supply chain designs. Demand is the single most important input variable in all the investigated models and is, of course, crucial to any supply chain. The results of the experiments, designed to find two-way interactions and quadratic effects, shows that two-way interactions exists between factors that can be controlled by the case company and factors describing the surrounding environmental disturbances. Disturbances such as low yield levels affects both the overall supply chain cost and the lead-time in this particular supply chain setting. Decreasing the transportation time in the supply chain can, however, counteract these disturbances. The optimal setting found through the experiments, suggest that the shortest supply chain design (the next generation supply chain) is the one with lowest cost, see Figure 3. The shortest supply chain will also provide the most robust solution since both the standard error and average of the weekly costs are minimised.

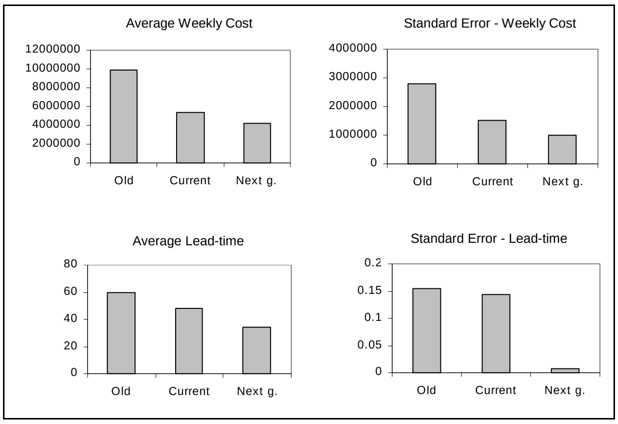

Figure 3: Optimal solutions for the three supply chain designs

CONCLUSION

The two reported case studies highlights the usability of simulation for research related to supply chain management. The first case study reports both on the implications of a transition of the company to become a supply unit in a supply chain and on methodological impacts of simulation for supply chain related research questions. The second case study further expands the methodological development in screening and simulation output analysis. Together, these two case studies provides a balanced picture of both insights in supply chain management and in simulation methodology.

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