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# SIMULATION MODEL OF A VERTICALLY INTEGRATED SUPPLY CHAIN: A CASE STUDY

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This paper reports on the successful development and use of simulation for the analysis of a vertically integrated supply chain. Simulation has only recently been applied to the analysis of industrial supply chains and this model differs from existing work in this area in that the manufacturing function is modelled in detail. This is contrast to the logistical models developed using simple lead times to represent manufacturing. This paper reports on the scale of system being analysed, the type of data required to populate such a model, such as product routings, standard times, work centre capacities and shift cycles and the level of detail included in the study and the performance outputs from the model. Using this model experiments were carried out to analyse the effect of stocking policies, production controls, changing demand trends and the effect of forecasting and information sharing on supply chain performance measures. One such experiment to determine the effective trade-off from operating three different finish stocking policies is outlined in detail. These experiments provide management with a useful tool for decision support in relation to both strategic and production strategies.

**Significance:** To managers this paper presents a case study on the successful use of simulation for the analysis of a supply chain. To simulation practitioners it gives details on the development of the supply chain simulation model.

**Keywords:** Supply chain simulation, Decision support systems, and Manufacturing detail.

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## 1. INTRODUCTION

Supply Chain Management (SCM) has emerged over the past 20 years, resulting from the change in market competition between isolated organisational units to more global competition between groups of organisations, driven by a sophisticated and more demanding customer. The competitiveness of products and services is no longer the responsibility of a single organisational unit, but the supply chain as a whole. Successful supply chains are ones that either have a 'productivity advantage' or a 'value advantage' or a combination of the two. In today's global markets, fierce competition caused by the introduction of products with short life cycles, and the heightened expectations of customers have forced business enterprises to invest in, and focus attention on, their supply chains, (Simchi-Levi, Kaminsky and Simchi-Levi (2000))

It can be seen throughout the literature that impressive results have been achieved using supply chain management techniques, such as those stated by Hewlett Packard, (Lee and Billington (1995)), Campbell Soup (Gachon and Fisher (1998)), IBM (Lin, Ettl, Buckley et al. (2000)) and BASF (Grupp (1998)).

It has been found, through a review of the supply chain modelling area, that there exists a vast amount of published material, which can be broadly categorised into two distinct groups. That is into analytical and simulation inventory modeling. The body of work in relation to analytical modeling is quite extensive with the first work being carried out in this area by Clark and Scarf (1960). Further extended work has been carried out in this area by Federgruen and Zipkin (1984), Rosling (1989), Axsäter (1990), Gachon (1999), Gachon and Fisher (2000), Gachon (2001), Chen (1998), Chen (1999), Gallego (1998), Chen and Song (2001) and many more. The area of supply chain simulation modeling however does not have the same levels of related published material with studies by Ingalls (1998), Feigin (1999), Ingalls and Kasales (1999), Lin et al. (2000), Bagchi, Buckley, Ettl et al. (1998), Ganeshan, Boone and Stenger (2001) and Petrovic, Roy and Petrovic (1998). Although there has been extensive work carried out on the analysis of these supply chain systems through the use of analytical techniques, it can be noted that these models are very restrictive in both size and application, often built around a single product, single time period, single product line, etc. These models are often also designed to answer one specific question using a simplified network structure. It can be seen that changes in the structure or the posing of additional questions to the model is if not impossible, very difficult. Therefore the motivation for this work is threefold:

1. The application of simulation to analyse a supply chain, a topic that is relatively new.
2. The use of supply chain simulation to analyse a Small-to-Medium (SME) enterprise as opposed to the larger scale models developed for IBM (Lin et al. (2000)), Hewlett Packard (Lee and Billington (1995)) and Compaq (Ingalls et al. (1999)).
3. Logistic supply chain models primarily use simple lead-times to represent manufacturing. However, in the case of this company the manufacturing function is an important issue, where product interaction can have significant effects on supply chain performance. Therefore, a detailed manufacturing function has been incorporated into this model.

## 2. PROBLEM FORMULATION

The organisation involved in the study is classed as a vertically integrated raw material supplier, offering a complete range of its related industries products to a global marketplace. Schary and Skjøtt-Larsen (1995) define vertical integration as "the ownership by one organization of other firms in its supply or distribution network... The totally integrated firm is completely self-sufficient. The non-integrated firm is completely dependant on market forces and other organizations for its operations." Christopher (1998) states, "Vertical integration normally implies ownership of upstream suppliers and downstream customers."

Due to an increase in competition in the marketplace, and a need to produce products at reduced costs in order to maximise profitability the company identified the need to carry out a systematic review of their operations. From this review, they determined that to increase their competitiveness it was necessary to carry out a Business Process Re-engineering (BPR) exercise to give them more control, insight and understanding of how their supply chain was operating. The first step in any BPR exercise is envision. The enterprise should review its current profile and develop a broad strategic vision (Changchien and Shen (2002)). After deciding on the necessity of the BPR exercise, the company set about formulating the key objectives for the process. These objectives included:

- A reduction of inventory in the entire supply chain.
- A reduction in the throughput times of parts through the overall supply chain and through each of the different processing areas.
- An increase in the quantity of orders that are delivered both on time and in full to the distributors.

After the first step of the BPR exercise had been completed and the objectives set, a team was set up of external consultants and internal experts from a number of fields to carry out the project. The team's first task was to identify the core processes, which form the building blocks for the business, followed by an analysis of the current system. Further to this a number of Key Performance Indexes (KPIs) were formulated to evaluate the system, both currently and in the future. In brief, these included:

1. On Time In Full (OTIF) – which is the percentage of orders received into finished stock that can be satisfied completely from finished stock, assuming a make-for-stock policy is being operated.
2. Velocity levels – this is the processing time of an order through a processing area.
3. Days of Inventory in Finished Stock – This is the number of days that current stock levels can satisfy, based on a rolling historical demand.

In addition to these points the system to be analysed is significantly detailed, in particular in relation to product movement through the manufacturing process, taking into account the stocking locations. The model itself consists of:

- Approximately 17,000 Order lines processed in system in one year, from 8 different distributors.
- 42 work centres, which consist of 276 machines operating on 6 different shift patterns.
- 10,000 finished stock parts of which approximately 3,000 are active at any point in time.
- 1,000 buffer stock parts from which the finished stock parts are processed from.
- Approximately 60,000 routing lines associated with the 42 work centres and all processed parts.

## 3. SYSTEM DESCRIPTION

The section of the companies supply chain structure as shown in Figure 1, can generally be regarded as an extension of the well studied serial multi-echelon supply chain, being supplied by a number of raw material suppliers and supplying a number of distributors, who in turn supply individual customers. Although there are a number of echelons prior to the bulk stock inventory location, they are not examined in this study. It is felt that this is a valid assumption, as in the real system material is always available for processing at this point due to the use of product substitutions. The possible top-level part movements and product flow are outlined in Figure 1, from *Bulk Stock* through to *Finish Stock* and ultimately to the final customers through the distributors. It can be seen that part movements can generally be categorised into three different types of flow. Two of these can be categorised as straight flow lines, where the parts take a straightforward path from *Bulk Stock* into *Buffer* Stock and through to *Finish Stock.* The third flow line is categorised as a re-entry type flow, whereby the parts move from *Bulk Stock* into *Buffer Stock* through *Bulk Processing* and then back into *Buffer Stock* through *Intermediate Processing* where the part number and properties change. These parts are then moved through *Finish Processing and into Finish Stock.*

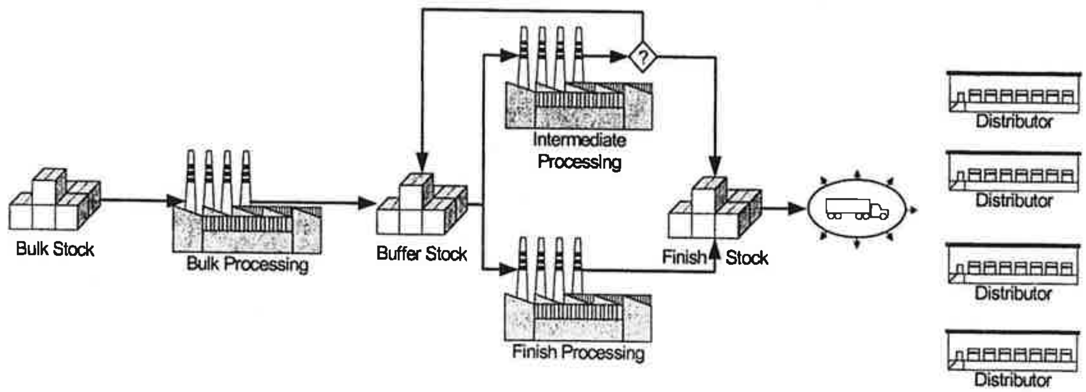


Figure 1. Supply Chain Structure

### 3.1 Supply Chain Manufacturing Function

Each of the processing areas in the supply chain analysed contain a number of work centres, which have a number of resources (direct labour and/or machine(s)) and shift cycles associated with them. Each of these work centres consists of a buffer, which feeds into a specified number of resources, which are available to complete the processing task. When the task has been completed the work order is moved to the next work centre in its product routing. For example *Product X* has a *Finish Processing* route of FC – I3 – LC – QC – PK, with associated standard processing times of 0.3, 0.2, 0.75, 0.1, 0.05 hours per part.

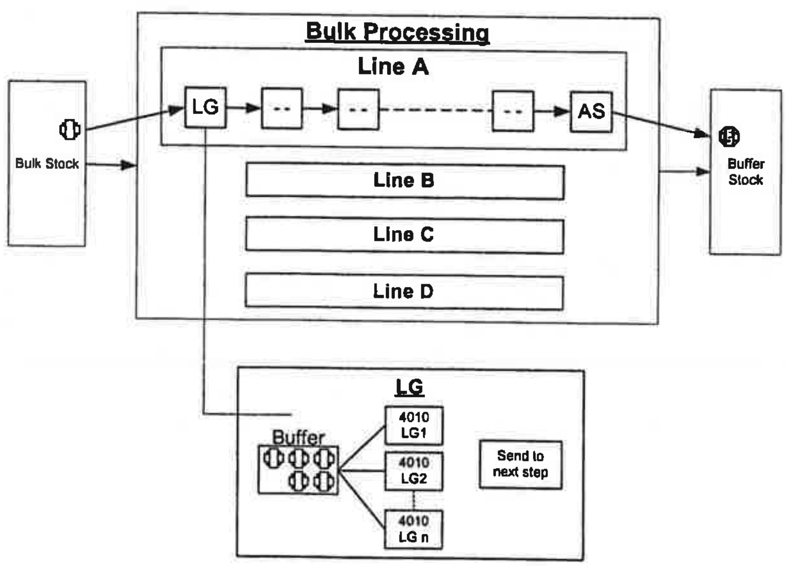


Figure 2: Supply Chain Manufacturing Function

Figure 2 outlines the level of detail associated with the work centres in Bulk Processing Line A. When a work order is triggered from buffer stock requesting a quantity of a certain product to be processed, the process to produce that part, the parent material and the routing to process the part are identified. Then the required quantity of the parent material (taking into account the potential yield losses throughout the process) is removed from bulk stock and sent to the first work centre on its operations list (route). The material enters the buffer area of this work centre and waits, until the required machine or group of machines become available to process the part. The buffers work on a first in, first out basis. After the material has been processed on the machine(s), it then moves on to the next work centre on its operations list until it has reached its last operation and into a stock location.

### 3.2 Supply Chain Process Flow

Figure 3 presents a schematic of the product flow and work order generation of the supply chain as described in Figure 1. The work order generation is based on the $(R, nQ)$ inventory control policy. An $(R, nQ)$ policy operates as follows: whenever the inventory position (= inventory on-hand + orders outstanding – backorders) is at or below $R$, order $nQ$ units where $n$ is the minimum integer required to increase the inventory position to above $R$. $R$ is the *reorder point* and $Q$ the *base order quantity*. The process begins when distributor demand is received into finished stock. From this point demand is satisfied whenever possible from existing stock. When demand is not satisfied, work orders are sent to the relevant upstream echelon. Then depending on material availability, these work orders are either placed in the relevant processing queue immediately, or further work orders are placed further upstream and the waiting work order is recorded and processed as soon as material becomes available. There is one added complexity in this process in that certain products use substitute parent material when there is insufficient outlined parent material, if there is a substitute material available. Otherwise as before a work order for the original outlined parent material is sent upstream.

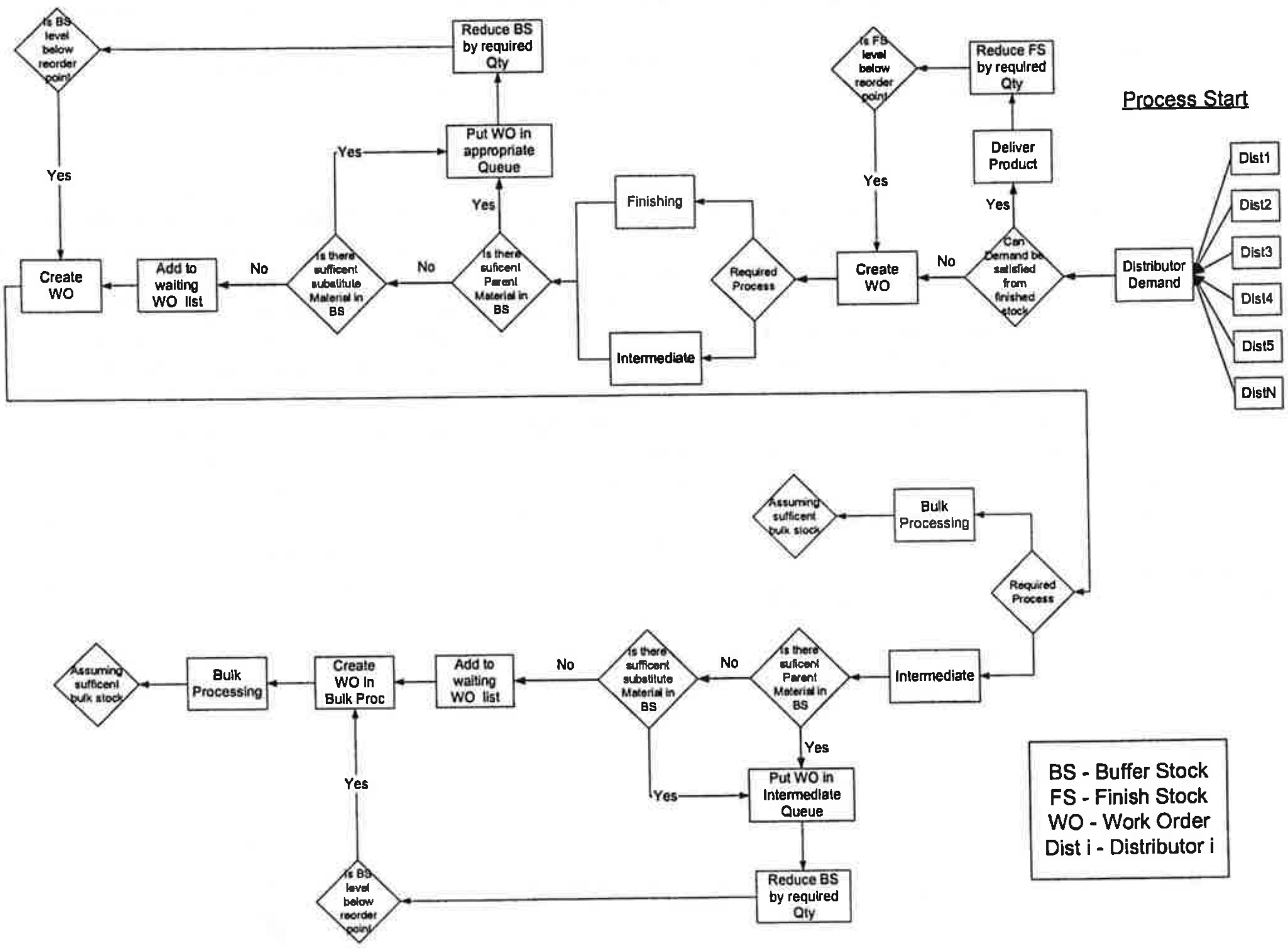


Figure 3: Product Flow and Work Order Generation with Substitution

## 4. MODEL DESCRIPTION

It can be noted from the general overview of the company, the issues the company would like to have analysed and the level of detail incorporated in the supply chain that it would not be possible to model this system accurately and efficiently using analytical techniques. Therefore the use of simulation was decided upon as a viable process for analysing the supply chain.

### 4.1 Model Assumptions

A number of key simplifying assumptions, which were regarded as necessary and justified prior to the development of the simulation model were outlined as follows:

- The use of a single processor in each work centre, with a suitably adjusted processing time as opposed to splitting batches across a number of machines, to eliminate the need for batch splitting in work centres, which in turn reduces the number of entities in the model at any one time, thus speeding up the processing time of the model.
- Substitution is used across all products in the company when necessary, but there is no formal procedure for it. Therefore a number of substitution tables were developed for products with high demand to incorporate the concept into the model.
- Daily demand for a specific product is sent into the model as a consolidated work order, i.e. if two distributors order the same product on the same date the two orders are consolidated and the work order is given the earliest distributor required date as the due date for the entire work order. This is the case in the actual system most of the time but not all the time.
- Demand is only satisfied when the entire order can be fulfilled.
- It is assumed that there will be an infinite stock of material in bulk stock, which is the most upstream stage in the model currently being analysed.
- Individual set-up times are not used, as these are relatively small in comparison with the processing times. Where set-up times are significant they are included in the standard times used.

### 4.2 Model Development

The simulation package chosen for the study was eM-Plant (www.tecnomatix.com). There were a number of reasons for this choice. The first being the fact that this package is object orientated, which allows for easy replication of objects (such as work centres, etc.). The second reason is its ability to use an ODBC link (Open Database Connectivity Link) to connect the simulation model directly to an information database, and the third main reason was the flexibility offered by eM-Plant in relation to its programming language (Sim Talk) to customise objects to realistically resemble the existing physical supply chain. This was especially useful when modeling the manufacturing function and for examining the effect of these functions on the overall supply chain performance.

The simulation model itself is connected to a number of database tables (Figure 4), which are stored in MS Access, by means of an ODBC link between MS Access and eM-Plant. This link enables easy transfer of data from the real system into the simulation model and can be set up to continually update and maintain the information in the model. The databases, which are used in the model, contain information on the individual distributors demand, the product routes for parts as they flow through the system with associated standard times, the processes that produce different products and associated yield factors, the output from these processes and the overall bills of material. Similarly, results are extracted from the model to Microsoft Excel using ActiveX controls.

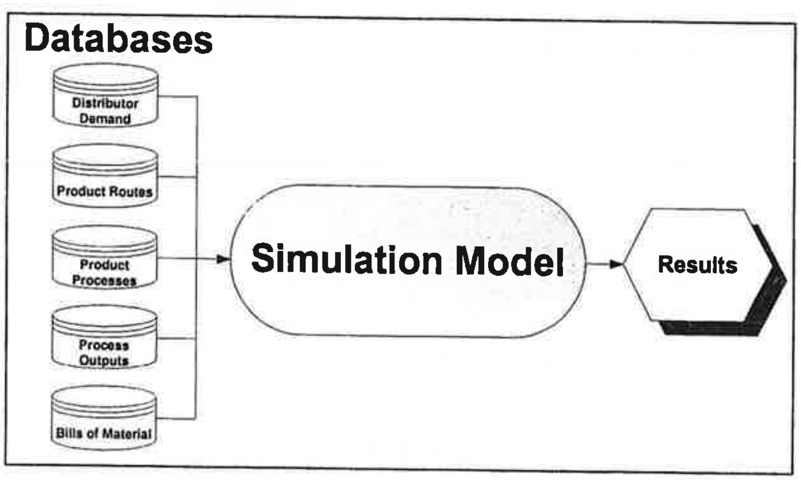


**Figure 4: Simulation model database integration**

## 4.3 Modelling Objects

The following section briefly presents details of the supply chain model, in relation to the overall structure (see Figure 5), development and operation of the model, which should aid the practitioner in such studies. The steps used for model development are those as described for building a sound simulation model in Law and Kelton (2000). The model itself consists of a number of key object classes, which include:

- Distributor Objects – These objects store demand information relevant to each distributor in the model, such as demand items, quantities, order dates and so on. This information is imported into the model using the above-described ODBC link to the distributor demand database.
- Demand Object – This object is used to consolidate demand orders for all the distributors periodically. This object controls the movement of material to and from finished stock.
- Stock Objects – These objects control the inventory points in the model, of which there are three. These objects keep track of the inventory position of each item in the system and generate production orders according to a (*R*, *nQ*) inventory control policy for each product as mentioned previously. These objects are linked to the information databases, which include the product routings, product processes, process outputs and the bills of material. It is these objects that control the production orders moving through the system.
- Processing Objects – These objects control the actual movement and processing of material between the stocking locations. Each processing centres controls the work centres associated with that area. When an order arrives into a processing centre, parent material is requested from the relevant stocking location. If no parent material is available, then relevant substitute materials are searched for and assigned to the order if present, else the order is put on hold and an order for parent material is sent to the relevant upstream echelon. Each processing object also contains information on process outputs and yields and controls these parameters as the model is operating.
- Work Centres – The work centres contain the controlling mechanism for the processing of work orders as they move through the supply chain model. They consist of a buffer object, which holds the work orders waiting processing and a single processing unit to process the work orders. When the work order enters the processor the processing time is calculated as the ((Work Order Standard Time * Work Order Qty) / (Servers)), which is equivalent to splitting the batch equally over each machine. When the part has been processed it is then sent to its next operation on its production route. If this operation is the last operation on its route, it is either sent to the appropriate stocking location, where it is either placed in stock, transferred to the customer or a combination of the two.
- Shift Cycles – The shift cycles control the operation time of each work centre in the model and currently there are six different shifts controlling the different work centres.
- Model Outputs – In the model the statistics module accumulates and calculates weekly the output parameters for each simulation run and the excel module transfers the models output from the format present in eM-Plant to Microsoft Excel for further analysis. The statistics module calculates the stock levels throughout the model, the work centre utilisations and the KPIs, which include the Days of Inventory, the velocity levels and the OTIF product percentages. This information is then exported to Excel, for run time reviews.

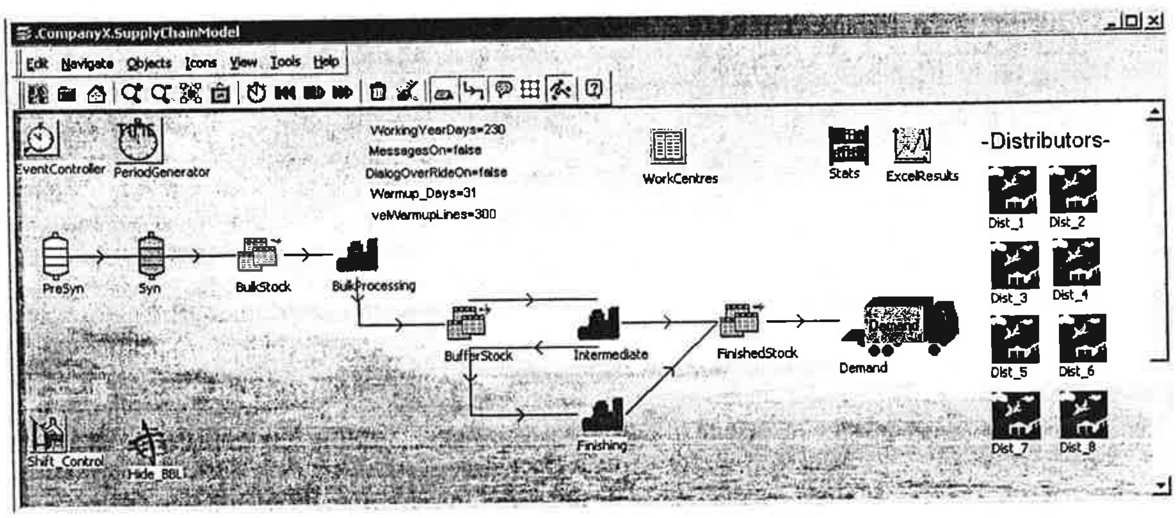


Figure 5: Supply Chain Simulation Model

## 5. VALIDATION

As the model was being developed it was continually validated to ensure that each module in the system operated as was expected. After these modules were amalgamated to create the supply chain model, the entire system was validated as a unit to ensure the output from the model and the model itself presented an accurate representation of the system being studied. In order to ensure the validity of the model a number of steps and techniques were used, which include:

<u>Collection of high-quality information and data on the system.</u>

This was aided by the fact that an existing Business Process Re-Engineering (BPR) exercise was being carried out within the organisation, thus presenting large quantities of information from the system on which an abstraction of the model could be formulated.

<u>Interaction with the supply chain manager on a regular basis.</u>

Interaction with the supply chain manager on a regular basis was a key function to the successful completion of a valid simulation model. Initially this consisted of a number of meetings in conjunction with the other subject matter experts to determine the information required to build the model in a credible fashion and to determine the questions, which the simulation model was required to answer. After the model was verified further consultation was carried out with the supply chain manager to analyse the outputs from the model in order to determine out of character data, to highlight discrepancies in the model structure. This process was carried out iteratively with 4 revisions of the model.

<u>Maintenance of an assumptions document and performance of a structured walk-through.</u>

A document was maintained with each assumption of the model, for example – demand is only satisfied when an entire order can be fulfilled. After the initial model iterations had been completed, a final walk-through was carried out, including the modeller and a simulation expert who was familiar with the structure of the system being modelled in order to validate the logic of the simulation model in relation to the interaction of the different sections of the model and the logic of the model code itself.

<u>Validation of components in the model by use of quantitative techniques.</u>

In order to assess the validity of the model in relation to extreme data sets, sensitivity analyses were carried out, where demand was increased dramatically and capacity was decreased and the results reviewed, to determine there reaction in relation to the limits of the model.

<u>Validation of the output from the overall simulation model.</u>

Where possible the output of the simulation model has been directly compared to the expected or historical results from the actual system. However the performance measures being used have only been recently introduced into the organisation as part of the BPR exercise. Therefore, to a large extent the overall output from the simulation model was validated by visual analyses of the model and it's results, by the supply chain manager and subject matter experts within the organisation.

<u>Animation.</u>

Animation was used to follow material flow throughout the system in order to assess material movement and process outputs.

Using these steps, and to the satisfaction of the organisation it was concluded that the model is in fact an accurate representation of the actual system being studied. The model itself produces some useful model parameters for analysis, which give a good indication of the level of performance of the system under different operating conditions with which decision-making can be aided particularly at managerial level.

This case study demonstrates that it is possible to develop detailed models of systems with high degrees of complexity. In summary the model contains:

- 17,000 Order lines processed in model, from 8 different distributors.
- 42 work centres, which consist of 276 machines operating on 6 different shift patterns.
- 10,000 finished stock parts of which approximately 3,000 are active at any point in time.
- 1,000 buffer stock parts from which the finished stock parts are processed from.
- Approximately 60,000 routing lines associated with the 42 work centres and all processed parts.

In addition to these points the model itself keeps track of all these products and their interactions as they are processed throughout the system, which includes such things as recording parts that have to wait on stock in such a way to mimic reality, only releasing these parts to the shop floor as material becomes available. Reviewing such areas in more detail the following were identified as the significant inputs used in the model, which affect the overall performance of the supply chain:

- Demand quantities.
- Number of individual parts ordered and order frequency.
- Planning lead-times and safety stock levels used in stock holding and ordering policies.
- Standard run times.

- Yield rates.
- Bills of material.
- Number of work centres and machines in each work centre.
- Product routings.
- Shift cycles.
- Product substitution rules.

One of the major obstacles encountered while carrying out this study was the poor quality of information obtained from the company due to poor information storage standards, which required significant resources to correct. However, for such a system as examined here with good quality information and an experienced simulation model developer, including time to collect information and gain familiarity with the system, an estimate for model development would be between 3 and 6 months. With the advent of improved computing power, the running time of such detailed models is not restrictive. It was found using a standard Dell Latitude D800, with 256MB DIMM 266 MHz DDR SDRAM memory and 1.3GHz Pentium M processor, that it took 3 minutes 17 seconds to complete one run of the model for one year. It also takes a further 3 to 4 minutes to extract model results to Excel depending on the quantity of results obtained. However, these run times assume the model has been populated with the product structures, processes, distributor demands, standard times and production rules, which can take up to 30 minutes in this particular model, due to the large quantity of data being transferred between the information databases and the simulation model itself using the ODBC link in both. However, it is not necessary to import this information every time the model is executed and can be updated periodically through an automated report procedure if required.

## 6. EXPERIMENTS

The previous sections outlined the system being modelled, the model description and its validation. Using this model experiments were carried out to analyse the effect of stocking policies, production controls, changing demand trends and the effect of forecasting and information sharing on supply chain performance measures. For the purpose of this paper, one such experiment on the systems stocking policies is outlined in more detail.

### 6.1 Experimental Design

This experiment was carried out to determine the trade-off from differing stocking policies. The experiment was carried out keeping all variables in the model constant with the exception of the stocking policies for each finished stock product. A constant demand set was used for each run of the experiment. The experiment itself was run under three different conditions:

- All products are MFS (All products are stored in Finished Stock), which was current practice.
- Limit MTO (selected products are stored in Finish Stock as determined by stocking policy rules, set out by the company, based on a four constraints, which include the following product analysis, (1) Pareto, (2) Volatility, (3) Peaky Demand and (4) a Declining Demand), which is the policy being analysed.
- All products are MTO (only excess produce is stored in Finish Stock), which can be used as a benchmark for the other two policies.

Using the demand set supplied there are approximately 3,000 stocked products under MFS, 220 under a Limited MTO and 0 on a MTO stocking policy. The purpose of the experiment is to determine the effect of each scenario on the percentage of products that are both On Time and In Full (OTIF), the average days of inventory held in finished stock and the quantity of finished stock held. Although there are many products in the system they can be categorised into 8 different product families, but for this analysis only the top 3 families are analysed. These families have been categorised as families A, B and C. Each of these families have been further divided into Rnds and Segs, because although they use the same parent material they have different processing routes through the supply chain.

### 6.2 Experimental Results

The results of this experiment are presented in Table 1. It can be seen from these, that the change in stocking policy from All MFS, through a limited MTO to All MTO, caused a reduction in the OTIF%. It can be seen that the overall OTIF% drops from an average of 93.02% to 88.08%, if the stocking policy is to be changed from All MFS to a limited number of products manufactured as MTO, with the B Seg being affected most dropping from 70.4% to 43.8%. There is significant reduction, in the range of 15 to 25 days in the average days of inventory in finished stock across each product family as the stocking policy moves from all items MFS to limited MTO. Also, there is a significant drop in the quantity of finished stock held as the model stocking policy changes from all items MFS to limited MTO, with an average reduction of 24,000 products.

It was clear to see from the experiment that there was a significant difference in the results obtained under these three policies in relation to the OTIF percentages, the average days of inventory in finished stock for each product family and the average finish stock levels. As an example of this view Table 2 for product family A. It can be seen from this table that the OTIF percentages was 97.97% for A Rnds, with an average of 38 days inventory being held in finished stock for product family A, while having an average of 32,509 items stored in finished stock across all products while using a MFS stocking policy. When the stocking policy was changed to a limit on MTO products the OTIF percentages fell to 93.83% for A Rnds with an average of 14 days inventory being held in finished stock for product family A, while having an average of 13,267 items stored in finished stock across all products.

**Table 1: Experimental results for (A.) OTIF%, (B.) Finished Stock, (C.) Average Days of Inventory in Stock**

| | All MFS | Limit MTO | All MTO |
|---|---|---|---|
| A Rnd | 98.0 | 93.8 | 88.1 |
| A Seg | 93.1 | 90.8 | 90.9 |
| B Rnd | 89.9 | 79.1 | 78.0 |
| B Seg | 70.4 | 48.8 | 37.6 |
| C Rnd | 99.3 | 98.1 | 98.1 |
| C Seg | 84.9 | 85.3 | 81.4 |
| Totals | 93.02 | 88.08 | 84.93 |

(a.)

| WEEK | All MFS | Limit MTO | All MTO |
|---|---|---|---|
| 1 | 35472 | 14879 | 5661 |
| 13 | 31869 | 13191 | 4819 |
| 26 | 32405 | 13099 | 4570 |
| 39 | 31028 | 12378 | 4296 |
| 52 | 31769 | 12788 | 4264 |

(b.)

| | A | | | B | | | C | | |
|---|---|---|---|---|---|---|---|---|---|
| WEEK | All MFS | Limit MTO | All MTO | All MFS | Limit MTO | All MTO | All MFS | Limit MTO | All MTO |
| 1 | 30 | 4 | 1 | 30 | 13 | 0 | 30 | 3 | 1 |
| 13 | 35 | 12 | 9 | 29 | 14 | 1 | 38 | 12 | 10 |
| 26 | 39 | 14 | 11 | 36 | 19 | 6 | 42 | 15 | 12 |
| 39 | 37 | 14 | 11 | 21 | 8 | 4 | 35 | 13 | 13 |
| 52 | 37 | 15 | 11 | 37 | 20 | 7 | 44 | 17 | 15 |

(c.)

**Table 2: Results Summarised**

| | OTIF% for A Rnds | Avg Days In Finished Stock for A | Total FREs |
|---|---|---|---|
| All MTO | 88.14 | 11 | 4722 |
| limit MTO | 93.83 | 14 | 13267 |
| All MFS | 97.97 | 38 | 32509 |

# 7. CONCLUSIONS

This paper reported on the successful development and use of simulation for analysing supply chains. This case study differs significantly from previous studies in that it models in detail the manufacturing function, which is a key element for company studied. The model developed was large and contained significant levels of detail, emphasising the ability to rapidly develop such models. However caution must be exercised by the practitioner in relation to poor quality information, as this can require significant resources to correct and can severely hamper model development. For managers, it can be seen that extensive experimentation can be carried out on such models helping them to understand the effects of parameter changes on overall supply chain performance indices. These models produce useful results for determining both strategic and production strategies. In this case the trade-off between carrying stock and servicing customers is presented, providing critical decision support to an organisation.

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