The Dynamics of Capacity Constrained Supply Chains

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Abstract

The analysis of capacity levels and there location is of vital importance in the design and management of supply chains as it is commonly believed that capacity constraints exacerbate poor customer service levels. The Inventory and Order Based Production Control System (IOBPCS), often associated with "real life" production control systems, is used as "company" building blocks for the dynamic simulation of a supply chain. Various combinations of capacity levels through the supply chain are used and results are analysed using a multi-attribute ranking technique. Production capacity constraints are implemented at each echelon in the form of a maximum order rate that can be placed on the production facilities.

A strategy of maintaining a record of unfilled orders (backlog) at the production facility highlights a number of notable dynamic characteristics over and above the normal dynamics of an unconstrained IOBPCS. There is an excess inventory build up even as production order backlog is being depleted. This is simply dealt with by effectively re-engineering the total business via integrating the company's overall inventory control policy with production. The new system is used to analyse the effect of capacity constraints within a three echelon one player supply chain. The inclusion of a non-linearity into the system leads to improved dynamic performance in some designs for the step change in sales and capacity constraint levels tested, but this does not mean improved consumer levels.

The strategy examined to improve dynamic performance is the holistic setting of system parameters to improve the non-linear systems. The future direction for research and ideas for further improvement are also presented, where the simulation results indicate the need to closely monitor appropriate system variables such as inventory levels, and to incorporate them within more robust decision rules.

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Introduction

Gaining an insight into the effects of capacity constraints in a supply chain is of increasing importance in the light of improvement practices such as Business Process Re-engineering (BPR). Advocates of BPR are taking a wider view of the business with regards to their internal and external business processes (Johansson et al 1993). The external processes include the buyer and supplier relations where there has been a movement towards reduced supplier numbers. In many cases it is becoming popular to single source for one part, or family of parts. Assessing the impact of suppliers performance is therefore ever more critical due to the larger reliance placed on this relationship and the increasing pressures to provide the optimum price/product/service mix. Downstream, intermediate business performance between your company and the final customer (consumer) is again important in the light of competing supply chains, where an optimised supply chain will be the victor in the increasingly competitive market place.

This work will predominantly examine the effect of capacity constraints within an individual echelon and then a pipeline supply chain. This is the start of a project that will eventually examine the dynamics of players within a supply chain network. The effect of capacity constraints of suppliers will be important in determining supply policy in both the short and longer term. The simulation results are therefore a beginning in highlighting some pitfalls to avoid, namely the double accounting phenomenon and points the way forward for future research.

Implementation of Capacity Constraints

The now well understood Inventory and Order Based Production Control System (IOBPCS), which is part of a generic family said to be representative of many production control systems across a spread of market sectors Edghill (1990) and Towill (1982), is used as the basic building block for this simulation work with the EXSMO simulation language used as the medium for analysis.

The capacity constraints implemented in the linear IOBPCS system are highlighted in Figure 1. There are a number of important points to be noted at this stage;

1. All the linear parts of the system are unaffected during the simulation except the clipping of the order rate into the production facility as indicated in the flow diagram in Figure 1.

2. There are a number of places for implementing a capacity constraint within the system, a limitation could be placed on the completion rate for example or simply in the order acceptance channel. However constraining the order rate being placed on the shop floor appears to be the realistic placement within the system and therefore offers maximum insight into the effect of capacity constraints in the system.

3. There is an order backlog level for the production facilities which is built up when the production facilities reaches saturation. The percentage of backlog fed back into production order rate is determined by K, the backlog feedback gain. When $K>0$ (and <1) then all backlog will eventually be worked off. This of course assumes that the average consumption is less than the capacity constraint in the system. When $K = 0$, the backlog is effectively ignored.

Test Structure

The structure of the tests is highlighted in Table 1. Three levels of constraints are utilised for the simulation results. A full factorial design is not carried out but a combination of the most realistic scenarios is used, with the possible exception of simulation 8 where the supply chain is highly constrained. The highest constraint levels are associated with the third echelon in the supply chain which is furthest removed from the consumer. The echelons are simply coupled through information and material pipelines. The orders passed on to the next echelon (the supplier) are simply those which the customer places on its own production facility. A one to one ratio of raw material to final product is assumed. Additionally no raw material inventory is maintained and production can continue irrespective of the supply characteristics. Poor service response can however be interpreted through the suppliers actual inventory levels and is a heavily weighted factor in the performance of the system.

Simulation Number	Echelon 1	Echelon 2	Echelon 3	M.A.U.T Placing
1	None	None	None	4
2	None	None	High	3
3	None	Medium	High	2
4	Low	Medium	High	6
5	Low	None	None	7
6	Low	Medium	None	5
7	None	Medium	None	1
8	Low	Low	Low	8

Where :
Low = New Steady State Demand + 4% (2600 units/week)
Med = New Steady State Demand + 12% (2800 units/week)
High =New Steady State Demand + 30% (3250 units/week)
Step input = Initial Steady State + 25% (2000 to 2500 units/week)

Table 1. Capacity Constraint Level Selection for Simulation Studies.

Analysing System Performance

The Multi-Attribute Utility Theory (MAUT) is used to rank the relative performance of each of the simulation results (Del Vecchio and Towill 1990). The order rate and actual inventory levels of the players in the chain are the two monitored variables of system performance. The criteria used on these variables are outlined in Figure 2, which shows the MAUT tree along with the relative weightings placed on them Actual inventory dynamics are weighted higher than the production dynamics as we are taking a predominantly customer service point of view. Supplier stock outs are not desirable, hence the peak drop in inventory is only taken when stock out occurs and the time over which this occurs.

The effect of varying the backlog feedback gain is first examined by analysing a single IOBPCS. An optimum gain is determined for subsequent analysis of a supply chain.

Varying the Backlog Feedback Gain

Determining the effect of the feedback backlog gain is shown in Figure 3 where the effects on Actual Inventory and Order Rates are shown with K = 100%,10%,5%,2%& 0%. With all backlog being fed back significant dynamics are present in the system. Actual inventory levels rise to over 450% of the desired inventory at week 42 for K=100%. This occurs while production is working at maximum

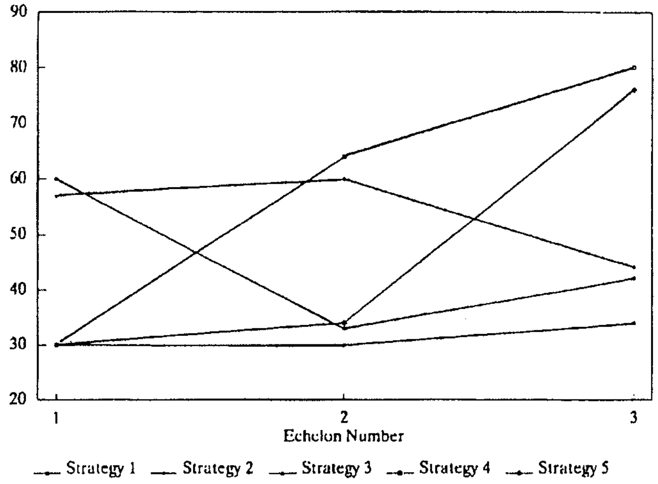

Figure 7. MAUT Ranking for Individual Echelons for Improvement Strategy Simulations

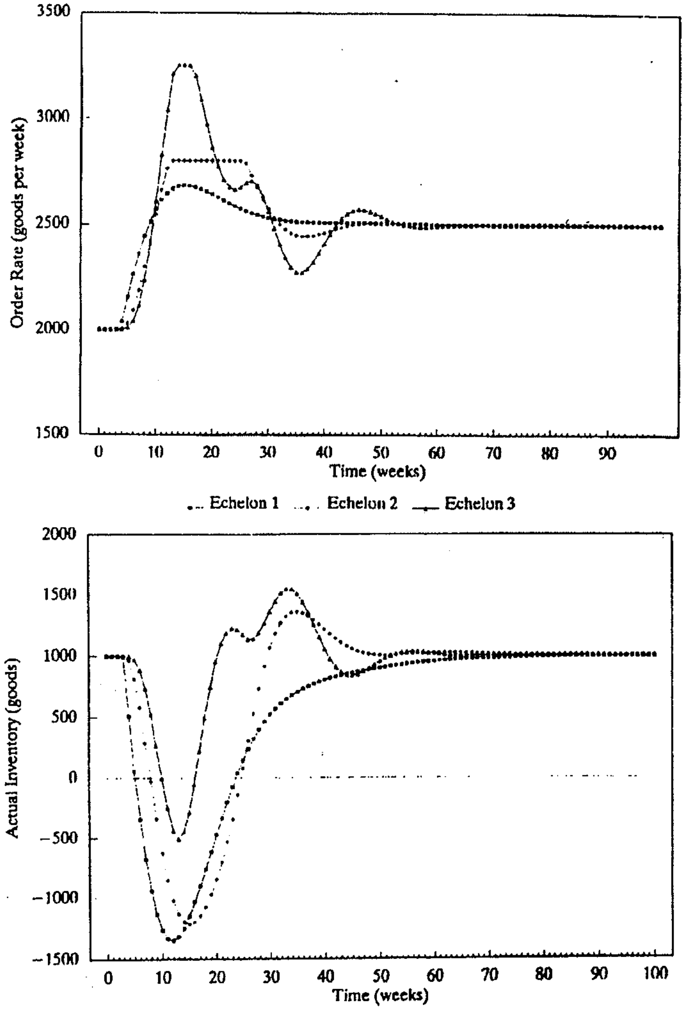

Figure 8. Dynamics of a Constrained Supply Chain with a 25% Reduction in Production Time Constant (Tp)

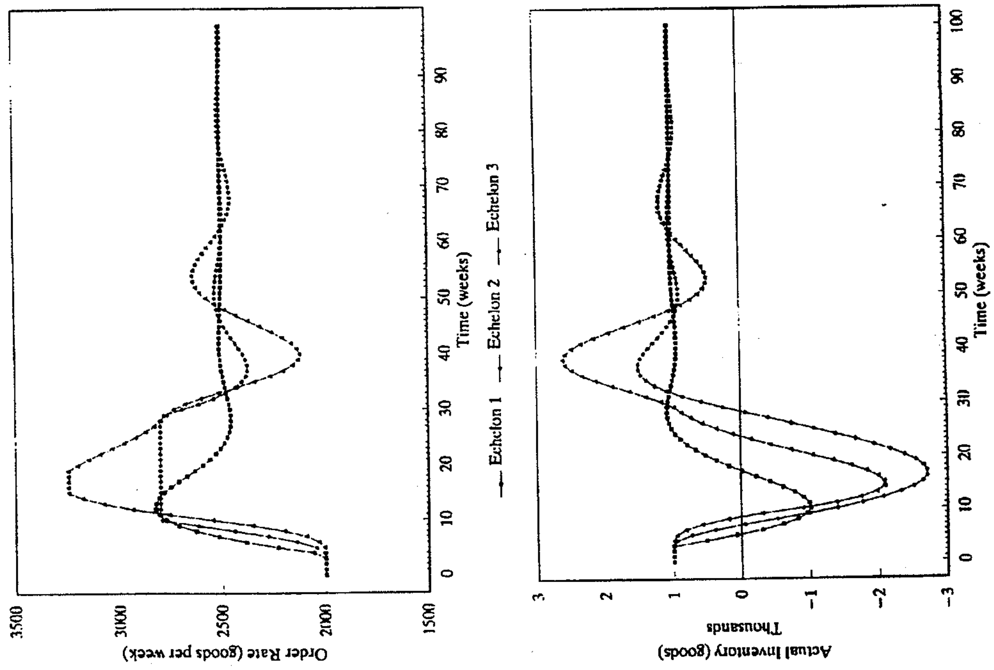

Figure 5. Dynamics of a Constrained Supply Chain (Simulation Number 3) for a Step Input

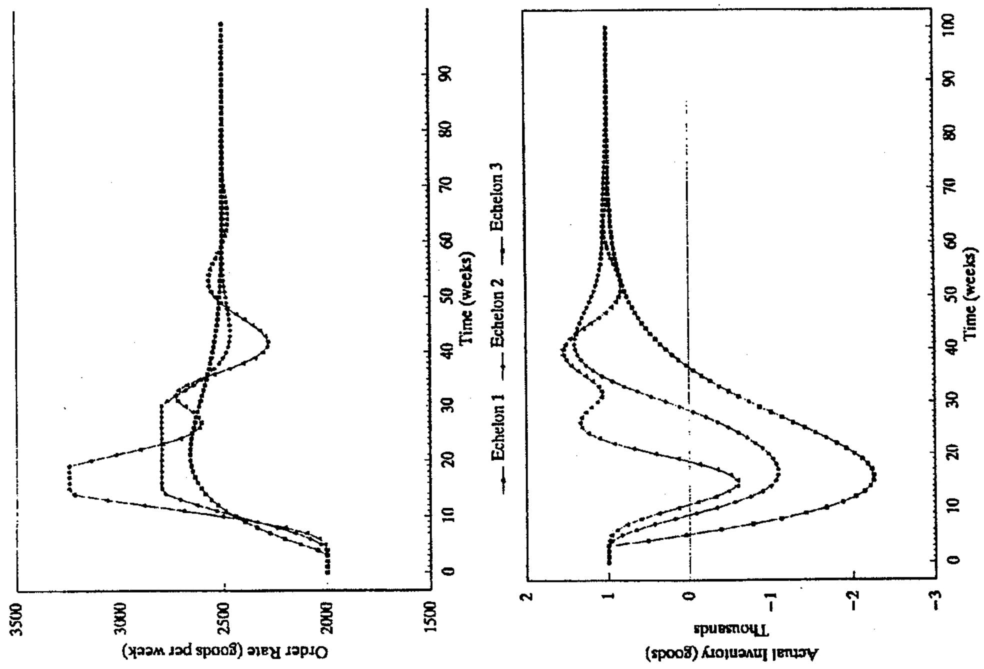

Figure 6. Dynamics of a Constrained Supply Chain with Improved Parameter Settings

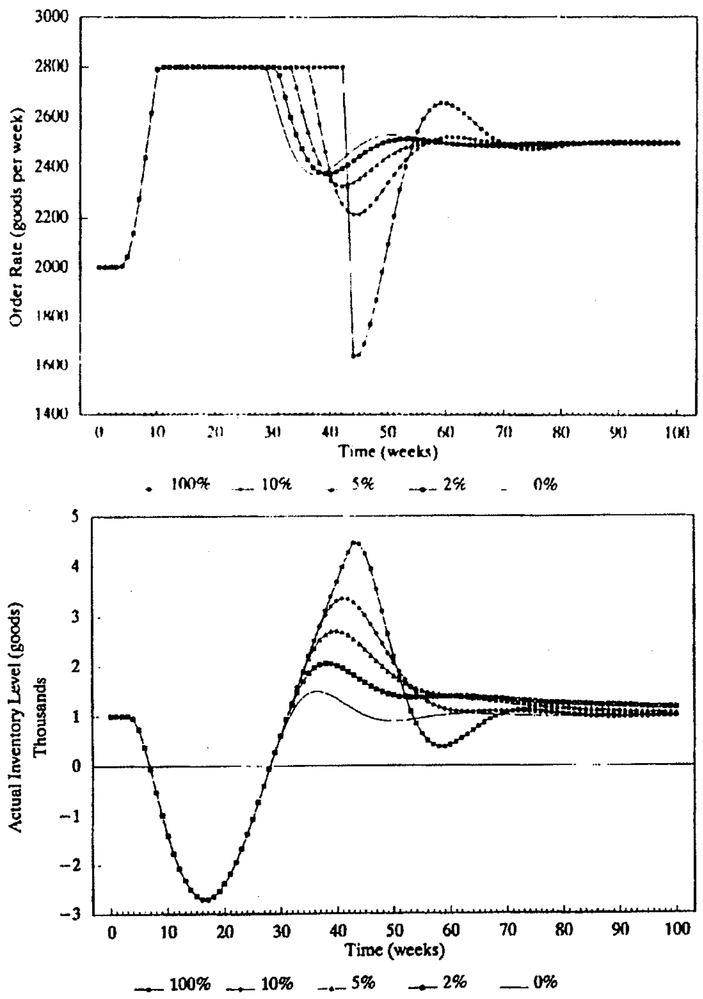

Figure 3. Effect of Feedback Backlog Gain on the Dynamics for an IOBPCS system to a Step Input

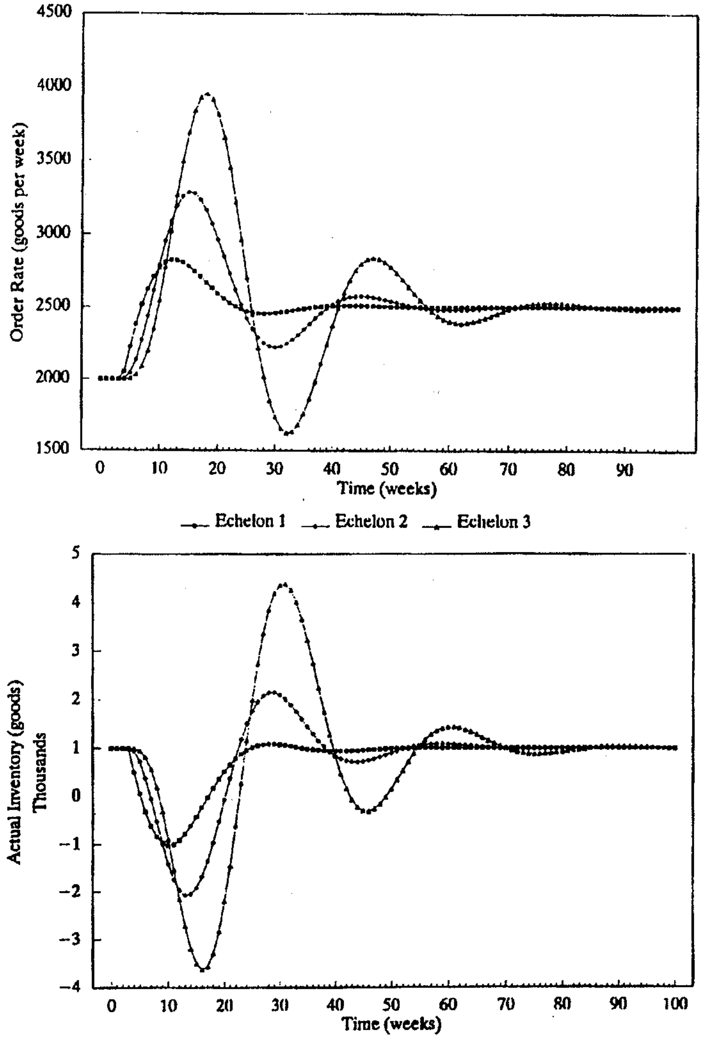

Figure 4. Dynamics of an Unconstrained Supply Chain (Simulation Number 1) for a Step Input

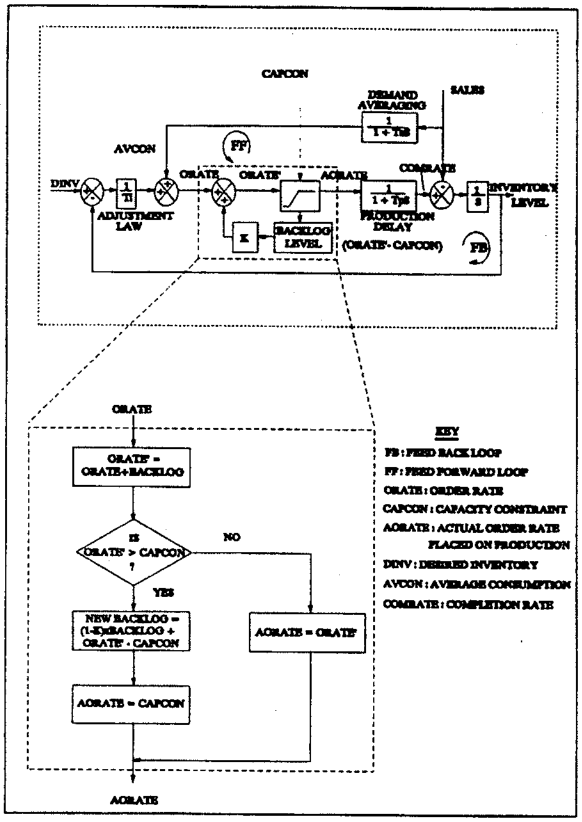

Figure 1. Flow Diagram of Capacity Constraint Decision Rule Within an IOBPCS.

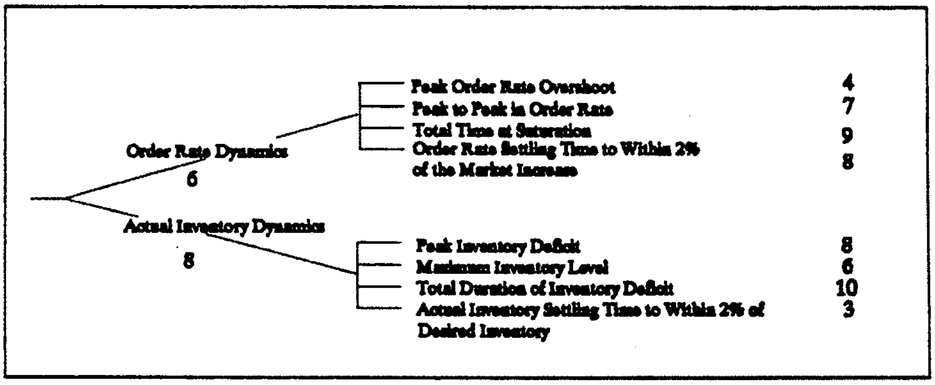

Figure 2. The Multi-Attribute Decision Tree with Applied Weightings

Stevens, G. Integrating the Supply Chain, 1985. International Journal of Physical Distribution an Materials Management, Vol. 19 No. 8 pp. 3-5.

Towill, D. R. 1981. Coefficient Plane Modelling for Control System Analysis and Design, Chichest Research Studies Press (John Wiley & Son Ltd).

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dynamically adjusting the inventory recovery time Ti when stocks are running low. This may result in more frequent operation at capacity but will result in improved customer service levels, which is an important variable to monitor.

The limiting factor of time invariant capacity constraint levels is not realistic. Longer term expansion of capacity may also be built into the simulation especially if significant market growth scenarios are to be examined. Long term, high amplitude sinusoidal input analysis on time invariant capacity constrained supply chains has been performed which adds weigh to this argument (Evans 1992).

A solution to the problem of supply chain dynamics is through differentiating between real and perceived orders. This can be effectively performed in reality through an effective Information Technology strategy assuming suitable organisational and cultural changes have taken place (Evans et al 1993). For the simulation model this simply involves the inclusion of additional feedforward loops in the model.

The Effects of Capacity Constraints in the supply chain

For an individual echelon at capacity the inventory deficit and the length of time at stock out increases, although capacity constraints do not always degrade the performance of the ***whole*** system for a step input. This is highlighted when echelon 1 is operating at capacity, in general the subsequent echelons improve their dynamic performance, and as the MAUT analysis shows can produce the "best" system. However echelon 1 at capacity results in poor customer service levels. This presents a dilemma, an improved supply chain designed to meet the MAUT framework will in fact result in a poorly performing supply chain from the consumers point of view. However if the steady state initial stock levels over the whole system could be set to avoid any stock out in the chain a constrained supply chain is desired. However there is a trade off. Higher stocks would be required in the front of the chain where two problems are found. Firstly high value has been added to the product and secondly front of chain players tend to hold significant political weight. These companies would prefer to see high stocks at the back of the chain.

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Improvement Strategy	Echelon 1	Echelon 2	Echelon 3	M.A.U.T Placing
1	Nominal	Nominal	Nominal	4
2	Fast	Fast	Fast	2
3	Pessimistic	Pessimistic	Pessimistic	5
4	Pessimistic	Nominal	Fast	1
5	Pessimistic	Pessimistic	Nominal	3

Where	Ta	Ti	Tp	Natural Frequency Rad/wk	Damping ratio ς
Fast	4	2	4	0.35	0.35
Nominal	8	4	4	0.25	0.5
Pessimistic	10	12	4	0.14	0.87

Table 2. Improvement Strategies via Supply Chain Redesign for Simulation 3.

The constraints used in simulation number 3 will be used throughout for the improvement strategie Again a MAUT analysis was carried out comparing only the improvement designs, with Ta and being adjusted in line with Table 2 which also show the MAUT results.

From the MAUT analysis the original system (simulation number 3) was ranked fourth. The bett designs with a pessimistic first echelon produce a slow reacting first echelon which translates in poor inventory performance. Echelon 2 at nominal followed by a fast echelon 3 results in the "be improvement design". Improvement strategy 2 provides relatively good dynamic performance f echelons 1 and 2 but echelon 3 suffers significant dynamic problems and the MAUT ranks this supp chain system low. The MAUT weightings for each echelon is highlighted in Figure 7. The tot system performance is the sum of these weights, i.e. an equal weighting is placed on each echelon.

It is interesting to note that the highest ranked system in the improvement strategies also correspon with the best IOBPCS descriptions (pessimistic, nominal or fast) for the linear system simulated Del Vecchio (1990). It should be noted however, that different system parameters and performan measurements were used.

Practitioners have long been calling for lead time reductions in all business operations. Therefo reducing Tp as a trial for the simulation was carried out for case 3 with a 25% reduction througho the supply chain. The results are shown in Figure 8 . Not surprisingly the benefits are significant a are evident when compared with Figures 5 and 6. Significantly less time is spent at saturation, wi improved inventory characteristics and reduced settling times.

The next step

This analysis is the first step to fully understanding the consequences of adding non-linearities into IOBPCS and subsequently an IOBPCS based supply chain. Counteracting the effects have in t work looked to eliminate the double accounting phenomenon, i.e. to ensure an integrated inte company.

Additional analysis is required through different inputs into the system. For example periodic inp into a real supply chain are common occurrences with difficulties being posed at around the natu frequency of the system as highlighted by Evans (1992) and Towill (1994).

This further analysis with tightly constrained supply chains may require a redesigned system reduce the probability of hitting the capacity constraint level. As in hard system design the next s must be an examination of counteracting the non-linearity with another non-linearity in the syst the obvious step being the creation of a rapid inner loop in the system. This is effectiv opportunity to utilise the excess capacity. However, as the simulations highlight this increase in consumer demand sends echelon 3 into saturation.

System Analysis

The MAUT ranking of these simulations are shown in Table 1. The most notable fact is that the unconstrained case is not the highest ranked (best) system in the simulations performed. Constrained supply chains do in fact produce improved system performance for a step input into the system. Simulations 2,3 and 7 are ranked higher than the unconstrained system, simulation number 1. These all have a first echelon with no capacity constraint restriction. An examination of Figures 4 and 5 help to explain how constraints improve dynamic performance in these cases. Echelon 3's order rate is significantly lower when Echelon 2 saturates (although 3 saturates the order rate would only have climbed another 42 units - results from Simulation number 7 and not shown). That is the "demand amplification" is significantly reduced in the constrained systems 2,3 and 7. Echelon 2 saturating at 12% above the new market steady state is, in this case, desirable.

Limiting the orders into the system can be too restrictive as is the case with simulation numbers 4,5,6 and 8. In comparison with the top four simulations the MAUT results are poor. For example the order rate dynamics take longer to settle when compared with an unconstrained supply chain but peak to peak order rate fluctuations through these supply chains are lower. The major differentiating factor between a system with a first echelon at saturation and one with no constraint is in the inventory dynamics. A constrained first echelon leads to significant time at negative inventory but the peak inventory drops for the subsequent echelons are not as large. Due to the high weighting in the MAUT analysis this time at negative inventory is significant for echelon 1. However as the inventory drops are less pronounced, to obtain a 100% product availability record for the whole system the steady state desired inventories should be set at 1200, 1500 and 2100 for simulation 4 as opposed to 1100 2100 and 3700 for echelons 1,2 and 3 respectively for simulation 1. This would results in lower ***overall*** supply chain stocks.

Simulation 8 is an extreme example of a highly constrained supply chain at just 4% above the new steady state market demand, it is not surprisingly the poorest design.

System Improvement Strategies

Although the step response analysis has shown some improvement in the system with capacity constraints, there is always pressure to improve system performance further. The general procedure undertaken in hard systems design (Towill 1981) is to monitor the saturating variable in the system, in this case the order rate.

Given that the capacity constraint levels and production time constants are time invariant the only changes that can be made are in the linear part of the system. In this case the adjustable parameters are those set by management, namely Ti, the inventory recovery time and the smoothing time constant, Ta.

The improvement ideas are taken from a linear analysis of a three echelon supply chain (Towill and Del Vecchio 1994) and a series of IOBPCS designs in varying configurations through the supply chain is used as highlighted in Table 2. A "Fast" design responds rapidly to market situations and conversely the "Slow" design responds slowly to market changes. The "Nominal" design has been described as a good robust design and lies in the middle of the other two designs in terms of dynamic characteristics.

capacity to remove the backlog! The system eventually returns to operating in the linear regio where the excessive stock level is counteracted through a significant order rate drop. Thi phenomenon is termed the post saturation order rate drop (Evans 1992). The system dynamics are their best when backlog is not fed back at all, i.e. K = 0. This can be explained through the doubl accounting phenomenon.

The Double Accounting Phenomenon

Maintaining a production order backlog when the factory is operating at capacity within the IOBPC decision rule is inefficient. The IOBPCS system records unfulfilled orders through a reduction i actual inventory level. This level being calculated from actual customer order rates. Recordir unfulfilled orders due to saturation (reaching capacity) has therefore an inherent risk that is shown i the dynamics of actual inventory during a step input. Initially the IOBPCS system moves to elimina the low stocks through increasing the order rate to the production facility, which will quickly t working at capacity. Backlogs then rise to a significant level during the simulation period. Both tl reduction in actual inventory and the order rate backlog have to be worked off, with disastroı consequences. Even after actual inventory has recovered, the order backlog dominates the productic order pattern. Stocks in the warehouse grow significantly, while production are working hard eliminate their order backlog. The backlog orders are effectively false orders that are alrea accounted for in the low actual inventory stocks. The dynamic problems are therefore seen to ari directly from double accounting the orders.

This is an example of a poorly integrated company where production and inventory management a not effectively communicating. Only one level should be recorded due to saturation either at tl production or inventory control level, but not both. A lack of internal integration is often seen industrial situations and commonly highlighted in literature. However Stevens (1985) outlines th internal integration is a prerequisite to an effective supply chain management program. An integrat company will therefore be assumed and a zero backlog feedback gain is therefore used in subsequent simulation studies.

Simulation Studies

The dynamic performance for the unconstrained supply chain (Ta = 8, Ti = 4, Tp = 4 for all echelor is shown in Figure 4 via the order rate and actual inventory dynamics. The well known dema amplification problem is clearly shown in the order rate dynamics as orders are passed along t chain. As an example of how the system dynamics change with capacity constraints included shown in Figure 5 which shows the results of simulation number 3 as indicated in Table 1.

A notable characteristic of a constrained supply chain is the effect on a supplier when the custome no longer working at capacity, i.e. the non-linear system reverts to the linear case. Echelon 3 starts smooth out when echelon 2 reverts from working at capacity and demands less from the next echel This interrupts the flow of orders to echelon 3 and the order rate takes an additional drop to what t been a level market - namely the level set by echelon 2 operating at capacity. This effect has be classified as "secondary dynamics" through the supply chain, where the additional kicks in the syst are self induced by the system and not through changes in the inputs to it (Evans 1992). Th secondary dynamics become more prominent the more responsive the supplier is. This effect be clearly shown on the order rate dynamics of echelon 3 in Figure 6. These increased dynamics material flows can incur significant costs in "real life" supply chains (Stalk & Hout 1990) and i therefore desirable to minimise these secondary dynamics.

It is interesting to note that echelon 3 should be confident in dealing with the increase in consur demand, with a capacity level at 30% over the steady state market increase, and should welcome