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# **THE DYNAMICS OF EMERGENCY TRANSHIPMENT SUPPLY CHAINS**

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## **ABSTRACT.**

Considers the dynamical effect of lateral emergency transshipments within a supply chain. Tests various different strategies for improving customer service via the MIT Beer Game. Four distinct strategies are considered.

1. "Electronic Point of Sales (EPOS)", where market place information is forwarded to all players throughout the supply chain
2. "Excel", where the stock levels in all echelons is controlled by the factory
3. "Emergency Transshipments", where an express transportation route bypassing an echelon in the supply chain is permitted
4. "Eliminate", where an echelon is removed from the supply chain.

The Beer Game strategies are also studied via a simulation exercise. Results show that the Excel strategy is flawed, whereas the EPOS strategy has a strong impact on inventory cost, Emergency Transshipments has a strong impact on customer service level and Eliminate results in less stock for an improved customer service level. Combinations of the three viable strategies are also tested. Concludes that the three strategies can be integrated to significantly improve supply chain performance.

## **KEY WORDS**

Lateral Transshipments, Systems Dynamics, Beer Game, Customer Service Levels, Inventory Levels.

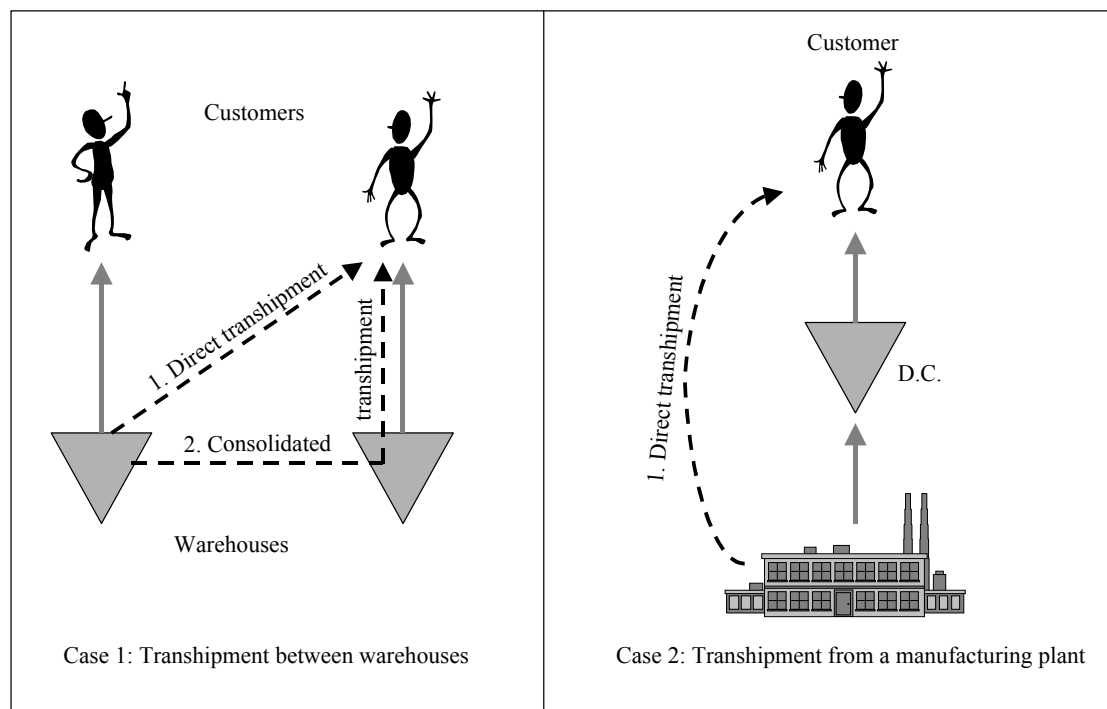
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## INTRODUCTION

There is an ever-increasing demand on businesses to continually improve on the “total value” they offer via their products and services to their customers. While in the past emphasis may have been placed on a particular performance metric “total value” stipulates the need to maximise quality and service while minimising total costs and total cycle times (Johansson et. al, 1993). In an ideal world the supply chain that delivers the final product or service to the end customer is strategically aligned to act as a seamless single entity (Towill, 1997). In reality many businesses resort to urgent tactical measures to satisfy an immediate customer.

One tactic utilised by businesses is the operation of an emergency transshipment channel. Under “normal” circumstance products are delivered to a customer by surface transport via a distribution centre, or “gateway”. Under the emergency transshipment channel scenario delivery of goods are direct and usually by air transport. The need for an emergency transshipment may arise due to rush orders from the customer that may not normally be met by the “gateway” stock or due to a short term measure to ensure customer service level in the light of capacity constraints. This scenario has been observed by the authors as part of an action research programme and is conceptualised as Figure 1.



*Figure 1: Different transshipment scenarios*

Furthermore, companies increasingly need to be responsive to customer's requirements. This can be achieved via agile manufacturing and can be extended to supply chains (Naylor et al., 1999). The theory behind agile manufacturing is that companies can react to their customer's requirements with very short lead-times. However in the reality, it also means using emergency transshipments to shorten these lead-times, often to compensate long manufacturing cycle times.

This paper aims to research the dynamic implications of emergency transshipments on the total supply chain. The paper describes some of the theoretical underpinnings of action research undertaken as part of a UK government sponsored programme. The research methodology described in the paper is;

- Review literature on emergency transshipments – the literature describes and analyses the operation of lateral emergency transshipments. While such transshipments occur between warehouses that are part of a formal distribution network this research examines a special case of the same scenario in which a manufacturing plant acts as a stocking point and delivers direct to the customer as indicated in Figure 1.
- Replicate a number of supply chain engineering strategies utilising the well-known "Beer Game" (Sterman, 1989). This is to compare and contrast the dynamic behaviour of emergency transshipment vis-à-vis continuous direct delivery, market information sharing and pipeline loading.
- Extend the lessons learnt from the "Beer Game" by computer modelling and simulating the various strategies tested. By doing so the aim is to eliminate possible "noise" that is frequently found in the "Beer Game" (game player errors) and to allow a more rigorous examination of the different strategies via a number of supply chain performance metrics. The supply chain simulation methodology adopted explicitly addresses the customer value requirements of inventory costs and order variance on-costs, lead-times and customer service levels (Naim & Towill, 1994).

## EMERGENCY TRANSHIPMENT - LITERATURE REVIEW

This research looks at the effect of emergency transshipments on supply chains dynamics. It is therefore important to look at the findings of other researchers on this particular subject.

The first important work on this theme is that of Maister (1976) with the verification of the "Square Root Law of Locations". The "Square Root Law" shows that "the total inventory in a system is proportional to the square root of the number of locations at which a product is stocked" (Maister, 1976). However, it must be emphasised that it is not a new finding as several other researchers made reference to this law (Starr and Miller, 1962, Brown, 1967 and Heskett et al., 1974), but none of them gave formal proof nor assumptions which could make the result explicit. Here the "Square Root Law" has to be understood in the case that stocks of a product are kept in several locations (decentralised system) but are then consolidated into one central inventory (centralised system). Then the ratio "decentralised cycle inventory to centralised cycle inventory" equals the square root of the number of locations.

In other words, with the use of the "Square Root Law" Maister shows the advantage of centralised inventory opposed to decentralised inventories in terms of cycle and safety stock levels, but especially with regards to safety stocks. However, it does not consider emergency transshipment between several warehouses, which is the case with Evers (1996 and 1997).

Evers (1996) has conducted research on the impact of the use of transshipment on safety stocks (opposed to cycle stocks). Zinn et al. (1989) developed the portfolio effect model and showed that the "Square Root Law" is a special case of the portfolio effect. As it has been shown previously, concentrating the inventory in one place can reduce the amount of safety stock in the system. However, it is frequently the case that some companies do not want to reduce their number of warehouses as order cycle time increases. Transshipment between facilities would allow such companies to keep their warehouses, and at the same time to reduce their safety stock requirements.

It is therefore important to give a definition of transshipment as used by Evers. He assumes that customer demands are satisfied by a defined stocking facility. Transshipment occurs when the customer demands are fulfilled using the stock of other stocking facilities. As shown in Figure 1 (case 1), the customer will either receive different shipments from different warehouses, or a consolidation will take place at his usual warehouse before being delivered. However, Evers (1996) emphasises the fact that the inventory savings resulting from the transshipment must be greater than the increase in transportation costs. It can then be concluded that the use of transshipments will lower the total logistics costs "with no effect on the level of customer service" (Evers, 1996). However, our experience has shown that the

resultant increase in transport costs is often significant and can outweigh inventory benefit (Disney et al., 1997).

The next question is, could this conclusion apply for transshipments used in emergency cases? Evers (1997) tries to prove that the portfolio model can apply to this new case of emergency transshipment with the expectation of having fewer stockouts and lower safety stock level (Tagaras, 1989). In this case, emergency transshipment only occurs when one facility can not satisfy the demand. Then a second facility is checked to see if there is enough stock, if not a third facility is checked and so on until the demand is satisfied. Evers (1997) makes three assumptions:

- \* Transshipment times are instantaneous.
- \* Customers do not mind the possibility of receiving multiple shipments.
- \* If the demand cannot be filled even after transshipments have occurred, a stockout results and it is considered that the demand is lost.

Finally, we can look at different case studies such as Yano's (1992) work who looked at the problem of optimising transport contracts in case of Just-In-Time deliveries. Yano concentrates on the use of emergency transshipments to complete an insufficient Just-In-Time delivery. Emergency transshipments happen when the cost of shortages exceeds the cost of these transshipments (Yano 1992). Here again, the same conclusion arises, with the use of emergency transshipments the amount of inventory decreases. This has, as a consequence, an impact on the cost of inventory for the supplier.

Tagaras (1992) is another researcher who looked at the effect of using emergency transshipment. His work deals with "the analysis of two-location periodic review inventory systems with non-negligible replenishment lead times" (Tagaras et al., 1992). This means looking at the use of inventory pooling arising from the use of emergency transshipment, this in order to respond to shortages at one location. He underlines that such pooling on a partial basis is used in the computer and automobile industries (Tagaras et al., 1992).

The results from Tagaras's (1992) research agree with others that "complete pooling dominates partial pooling" and that safety stocks are reduced at each location.

Finally, we can look at the work of Mercer and Tao (1996) who are looking at strategies to deliver a retailer's regional depot. This allows any lateral transshipment between the different warehouses. They concluded that when any lateral transshipments are allowed, short term

partial stock balancing with the low safety factor which provide protection against variation in demand performs best (Mercer and Tao, 1996).

From the literature review, it seems that emergency transshipments, whatever the case in which they are used, can be utilised to reduce the amount of the safety stock needed in the whole system. Such emergency transshipments would allow the supplier to cope more easily with variation in the demand. However, it will be important to verify if the expected benefits gained from the use of emergency transshipment would have a beneficial effect from a dynamic perspective.

Furthermore, it will be interesting to examine the results of a special case of emergency transshipment where the manufacturing plant is the stock holding point and use transshipment to deliver directly to the customer as given in Figure 1 (case 2). The aim is to determine whether or not the conclusions from the literature review can apply to such a case so as to evaluate the influence of emergency transshipments through the supply chain as opposed to across the supply chain.

### THE MIT "BEER GAME"

The MIT "Beer Game" (Sternan, 1989) represents a four-echelon supply chain including a retailer, a wholesaler, a distributor and a factory. A flow of information (orders) goes from the retailer to the factory and a flow of product returns. The game involves different delays: two weeks delay for the order to reach the next echelon and two weeks transport delay from the inventory of an echelon to the next as shown in Figure 2. Usually the players (representing one echelon) cannot speak to each other. A customer demand is inputted at the retailer level and after having satisfied the order, the retailer must decide the quantity needed to be ordered from the wholesaler. Each echelon has to pass an order to its supplier in order to fulfil the order of its immediate customer. The aim of the game is to minimise cumulative costs over the length of the game due to excess inventory and stock outs. One product in inventory costs £0.50 and one unit in stock-outs costs £1. It is considered that even if the supplier cannot satisfy the demand during one or several weeks, the products ordered are still required by the customer, thus a backlog is created. The goal of the game is to demonstrate to the players the existence of the demand amplification phenomenon which is not caused by any external disturbances but is due to the lead-times in the supply chain coupled with the players' feedback based decision making.

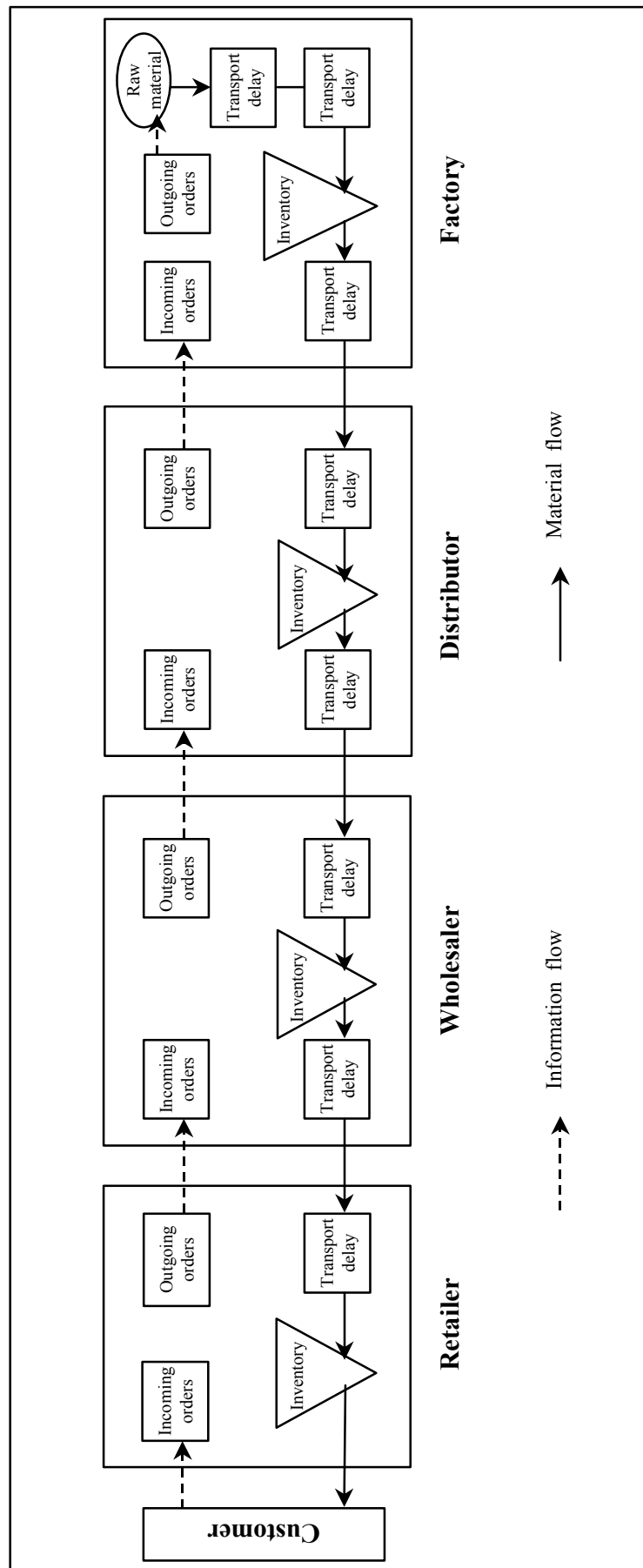


Figure 2: Schematic of the MIT "Beer Game"



### Playing the “Beer Game” under different strategies

While traditionally the “Beer Game” is utilised as a mechanism for allowing participants to experience the demand amplification phenomenon for themselves it may also be used to test different supply chain re-engineering scenarios (Mason-Jones, 1998). For the research described in this paper the forum for testing different strategies was the European University Network in Logistics (EUNiL) IV<sup>th</sup> European Post-Graduate Student Workshop in Cardiff in 1998. The workshop brought together students and staff from several universities (Dortmund - Germany, Eindhoven - Netherlands and Cardiff - United Kingdom) (Lalwani et al., 1998, Naim et al., 2000). Each University group had to elaborate a strategy to reduce the demand amplification phenomenon and keep a minimum inventory level that would still allow the player to satisfy their orders. Four strategies were proposed:

- **Epos (Electronic Point of Sale) strategy:** consists in feedforwarding the market demand to all the members in the supply chain. This is a strategy common in the grocery industry. Companies such as WalMart and Tesco have been promoting its use. Mason-Jones (1998) has also extensively studied it. Proctor and Gamble receive Point Of Sale data directly from the stores checks, via Wal-Mart’s dedicated satellite system, which despite its cost had a payback period of two years. They use this information to plan production and distribution to replenish Wal-Mart’s stocks. It is reported that Wal-Mart beats its main competitor by 50% on its inventory turns and its return on net assets, despite the fact that it pays its suppliers 33% faster (Stalk and Hout, 1990).
- **Excel strategy:** a pipeline loading strategy that allows the factory to have a view on the total stock in the supply chain. Only the factory makes decisions on what to order to ensure the pipeline from raw material to the end customer remains full. All other members simply order whatever demand they have received. This latter part of the strategy is often quoted as a good starting position whilst playing the Beer Game. Lee et al. (1997) suggest this is the optimum ordering decision for inventory costs if there is stationary demand, fixed lead-time, no fixed order cost and the purchase cost is stationary over time (Lambrecht and Dejonckheere, 1999).
- **Emergency strategy:** creates an emergency channel between the retailer and the distributor. This strategy was based on the experiences of one of the players and is an actual strategy used by a beer distributor in Bangkok, Thailand. This emergency channel was put in place as customers’ loyalties are not very high. This emergency channel is used when the retailer finds itself in backlog. Consequently the order is then passed

immediately to the distributor without any delay. The retailer then receives the goods within one week. The distributor also has increased buffer stock of 15 units instead of the usual 12. Often used in the automotive and manufacturing industries, it is often unplanned and used when demands are high for a significant period of time. A company will often resort to air-freight at very expensive rates in order to ensure availability which is often penalised in purchasing contracts.

- **Eliminate strategy:** removes the distributor from the supply chain so that there is continuous direct delivery from the warehouse to the retailer. Each echelon has a buffer stock of 14 units instead of the usual 12. This strategy may be enabled via the Internet that has allowed consumers to directly place orders to the manufacturer and is being used in the computer industry quite extensively, especially by Dell. In Dell's case, the company uses a web site where consumers specify their desired computer, payment confirmation triggers an order print-out in the factory, which then becomes the build list for the customer order.

The "Beer Game" was played with a random demand generated by a 12-sided die that was unknown to the players. The game was played for 25 simulated time periods (weeks). The result from the game is that the Eliminate strategy yields the lowest total inventory costs (that is, combined inventory and backlog). The ranked order of the remaining strategies is Emergency, then Excel and finally Epos. These results can be explained as follows:

- **Epos strategy:** Even though the research literature implies great benefits for information sharing (Mason-Jones et al., 1997), surprisingly this strategy achieved the worst result. It should be noted that although market information was shared with all echelons in the supply chain without any delays each player of this supply chain had their own ordering rule. The retailer for example tried to keep his inventory as low as possible and assumed that the wholesaler would keep enough inventories for a maximum order of 12 (Lalwani et al., 1998). The wholesaler smoothed the demand received before passing it to the distributor and the distributor averaged the previous customer demand. The factory attempted to produce the end customer demand each week. This result reinforces the finding that although sharing market information is potentially a good thing it will only yield benefits as part of an agreed overall supply chain decision making strategy (Mason-Jones, 1998)
- **Excel strategy:** This strategy was very simple to apply for the players, as each had an agreed strategy of only passing orders to their immediate supplier equal to the demand

placed on them by their immediate customer. This results in suppressing the demand amplification phenomenon. However, there is a considerable lead-time associated with the information flow reaching the factory and a backlog was created early on during the game at the retailer echelon.

- **Emergency strategy:** The emergency network allowed the retailer to cope with and satisfy quite rapid changes in customer demand. The wholesaler suffered from the use of this strategy as the distributor was giving priority to the retailer orders and so the wholesaler's orders were not fulfilled. The distributor also had to manage two supply chains that turned out to be a complicated task as a proper control mechanism had not been put in place. Finally, the factory was well buffered from the demand amplification effect by this strategy (Lalwani et al., 1998).
- **Eliminate strategy:** This game winning strategy supports the theory that when an echelon is removed demand amplification is radically reduced due to the elimination of delays and a decision making point in one fell swoop (Wikner et al., 1991). Eliminating an echelon can be seen as a special case of the Emergency strategy in which the retailer is continuously supplied by the wholesaler without the need for a "middle man". During the debriefing of the game with the players it also turned out that each echelon had well thought out, although independent, decision making rules. Each echelon developed rules with the aim of smoothing the demand profile as much as possible, especially the wholesaler who particularly absorbed the peaks and troughs of demand and supply. It seems that the player of the team that adopted this strategy has "done their homework" with regards to the understanding of system dynamics.

## SIMULATIONS

The results of the previous Section have supported as well as challenged some normally held perceptions of the dynamics of supply chains. The former with regard to the impact of removing an echelon from the supply chain (Wikner et al., 1991). The latter in terms of the positive expectations of feedforwarding demand down the supply chain (Mason-Jones, 1998). There is a need to ensure that the outcomes of the strategies adopted are not due to any "noise" that may influence the outcome of the "Beer Game" but strictly due to the strategies themselves. Thus, in order to evaluate the potential of each strategy adopted during the "Beer Game" the structures, rules and mechanisms proposed have been modelled and simulated through the use of difference equations applied on a spreadsheet.

## Causal loops

To simulate the “Beer Game” it is essential that the influence of the different components be understood. These components are the variables such as the customer demand, the average demand, the demanded transport rate, the inventory level, etc. In order to model these various relationships, an influence diagram may be utilised. Figure 3 shows an influence diagram using a pipeline feedback control system for a single echelon. This influence diagram has been shown to be representative of the decision rules adopted by players of the “Beer Game” (Sternan, 1989). Naim and Towill (1995) relate Sternan’s notation to the difference equation notation used in this paper and show that his model is representative of ordering rules adopted in industry (John et al., 1995, Berry et al., 1998). Four model parameters influencing different variables are utilised in the model.

- $T_a$  indicates the degree of smoothing applied to the demand.
- $T_i$  represents the proportion of inventory error feedback utilised in the ordering rule
- $T_w$  represents the proportion of inventory error feedback utilised in the ordering rule
- $T_p$  is the actual pipeline delay (between an order being placed and its receipt into stock) and  $T_p$  is the estimated pipeline delay

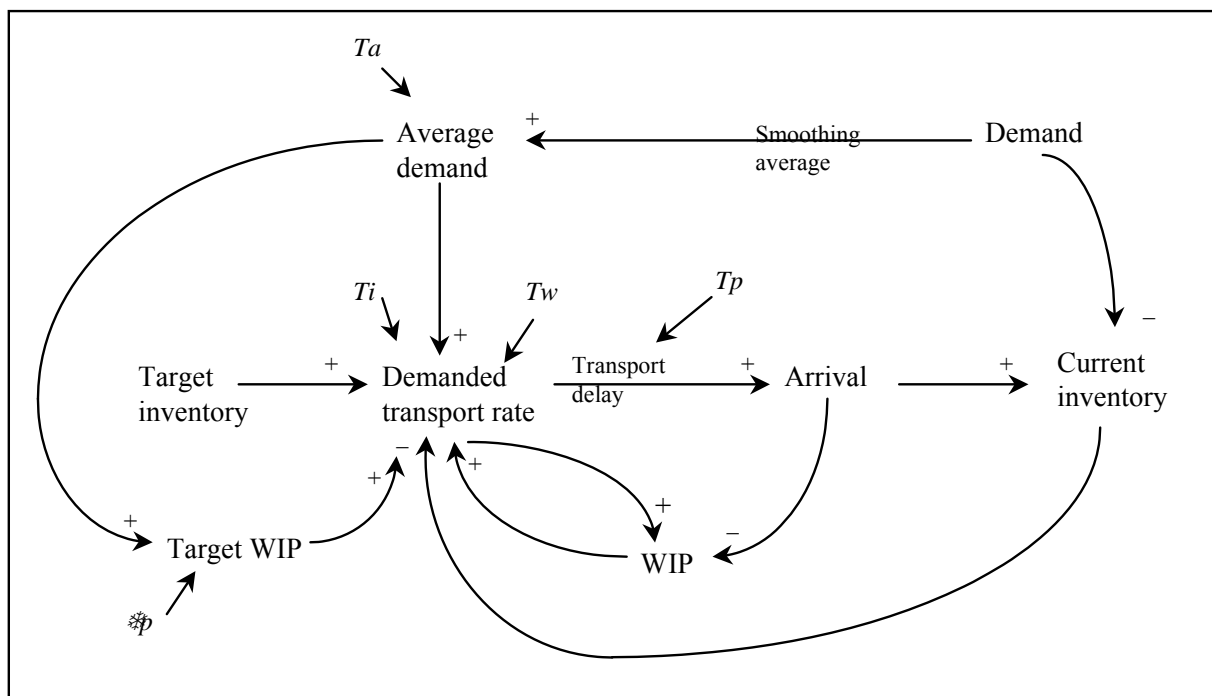


Figure 3: Causal loop model of pipeline feedback control system (single echelon)

To represent a four-echelon supply chain in the “Beer Game”, four identical influence diagrams would be used. They are connected via the demanded transport rate of one echelon (e.g. retailer) becoming the demand of the next echelon (e.g. distributor). Figure 3 models the “baseline” decision rules adopted in the standard playing of the “Beer Game” without any re-engineering strategies adopted.

Figure 4 shows the influences of each strategy applied to an echelon. The Eliminate strategy is not represented here as the retailer retains the “baseline” causal loop model but there are simply two subsequent echelons in the supply chain. The emergency channel of the Emergency strategy links the retailer to the distributor by bypassing the wholesaler. For the Excel strategy the causal loop model represents the factory, as it is the only echelon which makes an ordering decision. For the Epos strategy, each echelon receives the market demand and uses it to calculate the level of products to be transported.

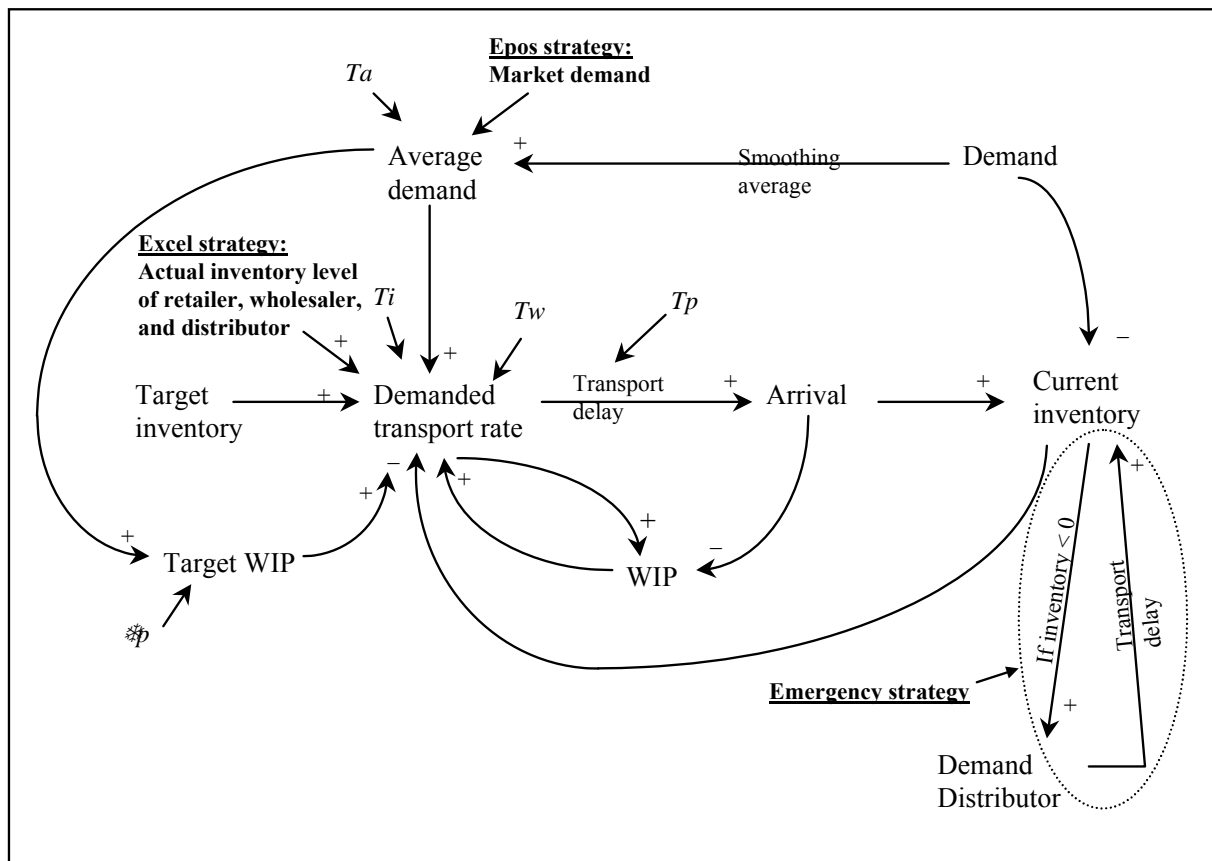


Figure 4: Influence of the chosen strategies on a causal loop model of a pipeline feedback control system (single echelon)



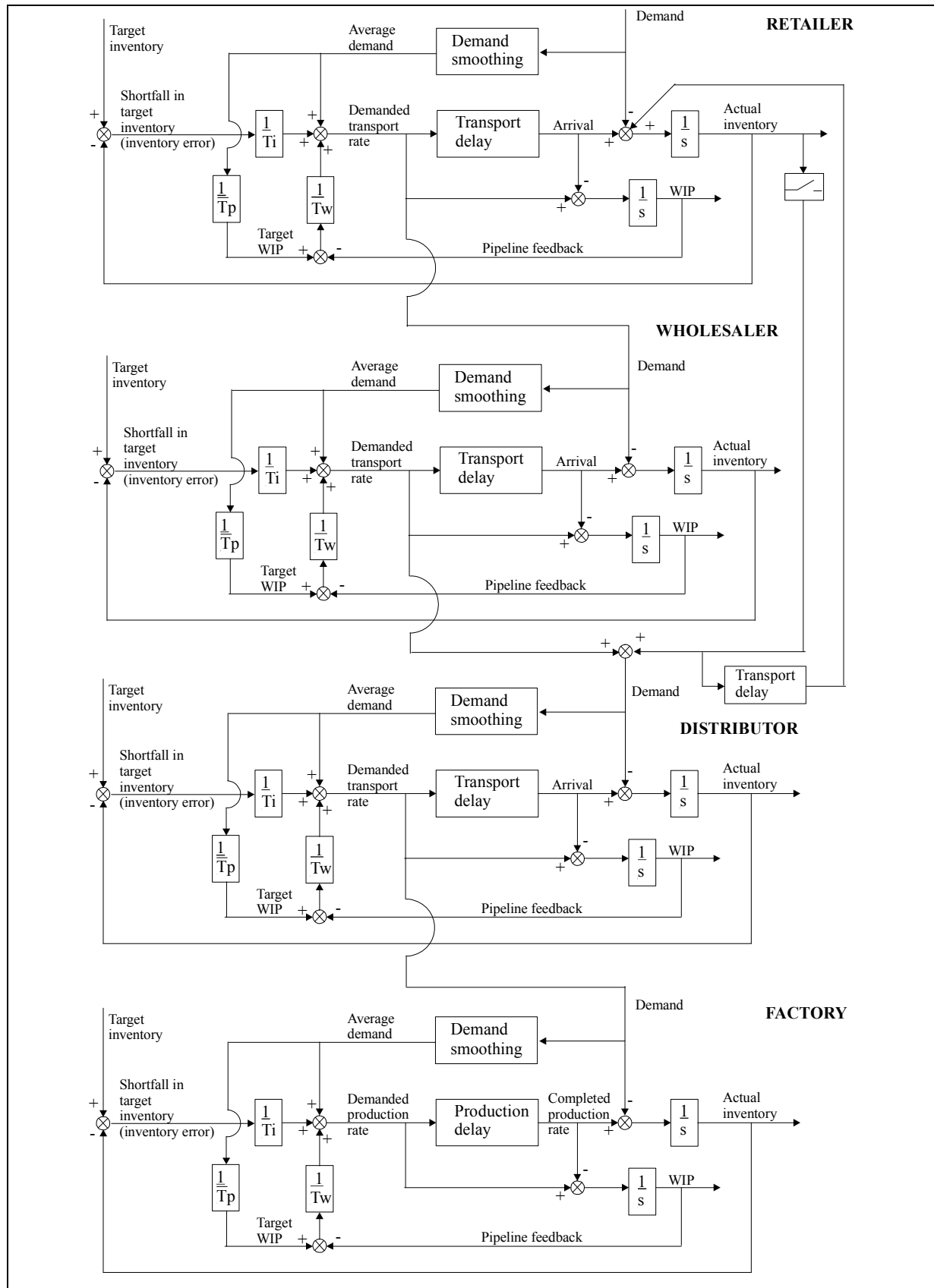


Figure 6: Block diagram of an Automatic Pipeline feedback compensated Inventory and Order Based Production Control System (APIOBPCS) for Emergency strategy.

## Block diagram

These different causal loop models can be represented through block diagrams using an Automatic Pipeline feedback compensated Inventory and Order Based Production Control System (APIOBPCS) model template. Figure 5 shows the representation of a “baseline” four-echelon supply chain and Figure 6 a four-echelon supply chain using the Emergency strategy as an example of implementing a strategy.

## Difference Equations

For our simulations, we make the assumption that the ordering policy for stock replenishment is based on the APIOBPCS principle. The simulation language EXSMO “which exploits the approximate equivalence between an exponential lag and the exponential smoothing function (where the data is sampled at time interval  $\Delta t$ )” (John et al. 1995) is used for the simulation equations. Based on Figure 5, the control law or ordering rule for each echelon is given in Appendix 1. Five models were coded using difference equations implemented in a standard off-the-shelf spreadsheet package. The models represent the baseline supply chain and the four re-engineering strategies. System dynamics specific software is available but the use of a simple spreadsheet shows that dynamic simulations do not need specialised tools to be realised (Berry and Towill, 1995, Evans et al., 1998).

## Parameters and initial values

The APIOBPCS model has been simulated and tested for dynamic performance via standard control techniques (John et al., 1995) and genetic algorithm optimisation (Disney et al, 1997). The parameters  $T_a$ ,  $T_i$ ,  $T_p$  and  $T_w$  were set according to the “best” design determined by John et al. (1995). Thus,  $T_w = 2T_p$ ,  $T_a = 2T_p$  and  $T_i = T_p$ . These ratios have been used and proven for a single echelon and Mason-Jones et al. (1997) have enlarged this result to a whole supply chain. The best ratios depend on the relationship between inventory and production on-costs and the available capacity flex (Disney, 1998). However these are generally held to be reasonable. The ratios to set the parameters can thus be used with confidence. For the simulation described in this paper  $T_p$  has been set at four weeks, hence  $T_i = 4$  weeks and  $T_w = T_a = 8$  weeks.



The initial values of all the variables have been chosen so as to mimic as much as possible the “Beer Game” played during the workshop. Each echelon has the same initial values and uses the same parameter values. The exception is the Excel strategy in which the parameter values  $T_i$  and  $T_w$  equal infinity and  $T_a$  equal zero for the first three echelons (see next Section). Therefore, the initial values for the demand, the demanded transport rate and the arrival rate are 4 units of beer. The inventories contain 12 beers in all cases except for the Eliminate strategy that has 14 units of beer in each echelon and for the distributor of the Emergency strategy that has 15 units of beer. The target inventory has been fixed as a constant (equivalent to the initial values) and the pipelines are filled up with 16 beers (equal to the pipeline lead-times multiplied by the initial demand).

### Decision rules

It is important here to define clearly the decision rules applied to each simulation. Five different strategies have been simulated: “baseline”, Epos, Excel, Emergency and Eliminate supply chains. For each one of them the decision rules were slightly different in order to apply the strategies. These changes have already been outlined in Figure 4 that shows the influence of each strategy on the baseline causal loop model. The decision rules employed are summarised in Table 1.

### Simulation Results

Each strategy has been simulated for;

- a step change in the demand from 4 to 8 barrels of beer per week at week 5
- an initial demand of 4 barrels of beer per week and then varying randomly between 1 and 12 from week 5

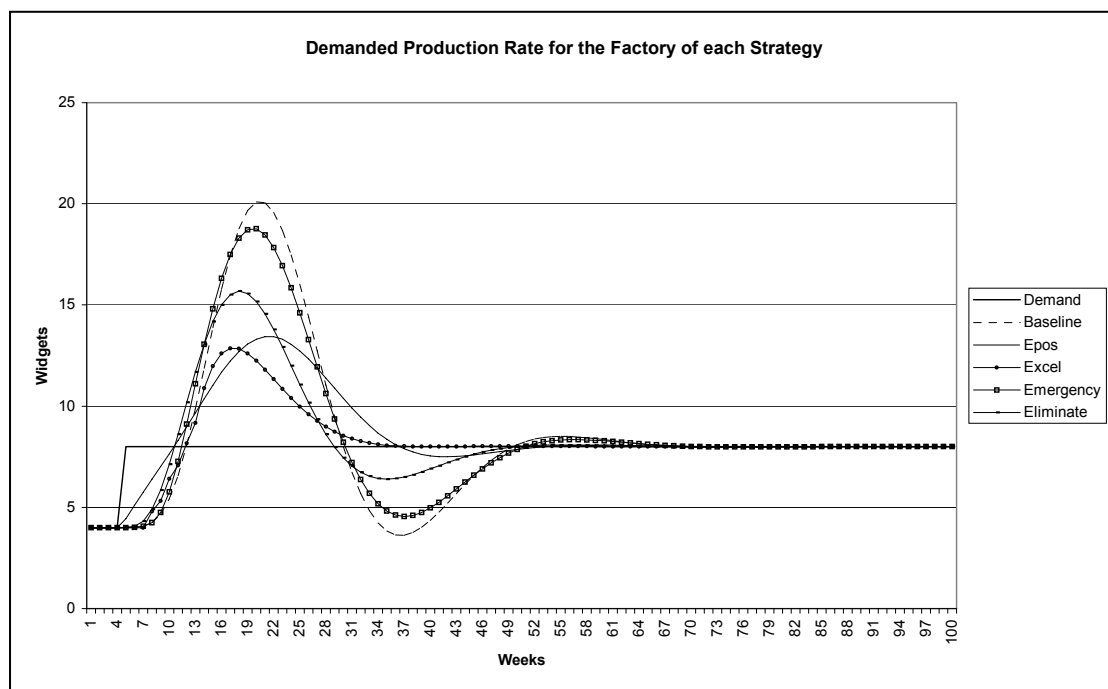
All the strategies have been simulated for 100 weeks. Before evaluating the results, the simulations had to be verified. This has been done by comparing the results of the simulations with known results obtain by John et al. (1995). The dynamics of arrival rate and actual inventory were utilised for this purpose. The verification showed that the simulation equations could be used with confidence. Another verification has been carried out using the exact transfer function solution elaborated by John et al. (1995).

Strategies	Decision rules	Comments
<b>“Baseline” supply chain</b>	<p>(1) Average demand <math>(e+1)(t+1) = \text{average demand } (e+1)(t) + \alpha A</math>  <b>(demanded transport rate <math>(e)(t+1)</math> - average demand <math>(e+1)(t))</math></b></p> <p>(2) where <math>\alpha A = [1 / (1 + (T_a/\Delta t))]</math></p> <p>(3) Actual inventory <math>(e+1)(t+1) = \text{actual inventory } (e+1)(t) + \Delta t (\text{arrival rate } (e+1)(t+1) - \text{demanded transport rate } (e)(t+1))</math></p>	<p><math>(e)</math> represents the previous echelon and hence <math>(e+1)</math> represents the current echelon.</p> <p><math>\Delta t</math> is the simulation time increment.</p>
<b>Epos supply chain</b>	<p>(4) Average demand <math>(e+1)(t+1) = \text{average demand } (e+1)(t) + \alpha A</math>  <b>(demand <math>(t+1)</math> - average demand <math>(e+1)(t))</math></b></p>	Each echelon uses the end market demand to calculate their average demand
<b>Excel supply chain</b>	<p>(5) Inventory error <math>(t+1) = \text{target inventory} - \text{total actual supply chain inventory } (t+1)</math></p>	<p><math>T_i = \text{infinity}</math>,</p> <p><math>T_w = \text{infinity}</math> (the value 10,000 was used) and</p> <p><math>T_a = 0</math> for the first 3 echelons</p> <p>Target inventory = <math>12 \times 4 = 48</math> for the factory</p>
<b>Emergency supply chain</b>	<p>(6) Average demand (distributor)<math>(t+1) = \text{average demand (distributor)}(t) + \alpha A</math>  <b>(demanded transport rate (wholesaler)<math>(t+1)</math> + emergency order (retailer)<math>(t+1)</math> - average demand (distributor)<math>(t)</math></b></p> <p>(7) Actual inventory (retailer)<math>(t+1) = \text{actual inventory (retailer)}(t) + \text{arrival rate (retailer)}(t+1) - \text{demand (retailer)}(t+1) + \text{arrival emergency transshipment (distributor)}(t+1)</math></p> <p>(8) where arrival emergency transshipment (distributor)<math>(t+1) = \text{stockout (retailer)}(t)</math></p>	<p>The emergency channel “switches on” when the actual inventory of the retailer is below zero and “switches off” when the inventory level is equal to zero or more.</p> <p>(7) is used when the retailer receives the emergency transshipment.</p>
<b>Eliminate supply chain</b>	As for “Baseline” supply chain	Eliminate only has three echelons.

Table 1: Summary of the decision rules for each strategy

## Results using the MIT Beer Game evaluation criteria

Summary results from the factory, which suffers the most in dynamic terms, are displayed in graphical format in Figures 7 and 8. The Epos strategy appears to be the winning strategy for both a step change and random changes in demand. This result is based upon the inventory cost (£0.50 per unit of stock out and £1 per unit in stock), which is the only criteria used to rank the strategies when the “Beer Game” is played. Mason-Jones and Towill (1997) who explain that this strategy yields the least distortion in demand predict such a result.



*Figure 7: Demanded transport for the factory of each strategy.*

From Figure 7 and 8 we can see that the Excel strategy performs very well in terms of demanded production at the factory level. However, the Excel strategy is not overall a good one to adopt as the actual inventory level is building up at the factory facilities. This can be explained by the inadequacy of the pull policy used along the chain. The factory should be able to push the products down the supply chain.

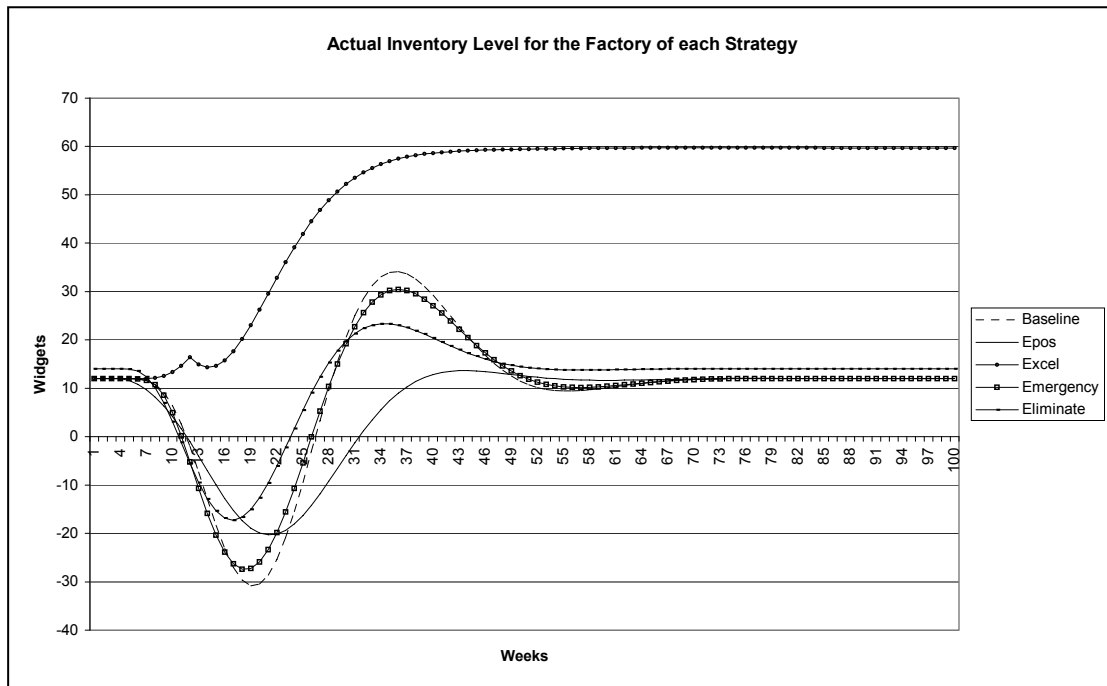


Figure 8: Actual inventory level for the factory of each strategy.

### Selection of other evaluation criteria

However, inventory cost is not the only criteria that may be taken into account. Thus five criteria, which assess the variables “demanded transport/production” and “actual inventory”, have been chosen: the requirement for safety stock, the inventory cost, the Integrated Time Absolute Error (ITAE) of demanded transport (for a step change in demand), the standard deviation of the demanded transport at the factory level (for a random change in demand) and the customer service level (CSL) for the retailer and total customer service levels. Each criterion has been assessed for each echelon of the different supply chain strategies (except the standard deviation). This gave a total result per criteria for the whole supply chain. Furthermore, as some supply chains studied included three echelons and some others four echelons, it was necessary to average those results per echelon. The underlying assumption with the assessment of results is that all criteria and all echelons in the supply chain are equally weighted.

The safety stock has been chosen as a criterion so that the results obtained will be comparable with the results from the literature review (e.g. Evers 1996 and 1997, Yano 1992 and Tagaras 1992). The amount of safety stock needed in each supply chain has been calculated from the minimum inventory level encountered during the simulation. The other criteria have been evaluated from the same simulation. This means that the inventory level has not been

maximised using the right amount of safety stock, but left at a level at which the players set it during the “Beer Game” (12, 14 or 15 barrels of beer depending on the strategy). This has been done in order to mimic as closely as possible the game played during the workshop.

The inventory cost criteria allows us to quantify the costs of holding an inventory or of suffering stock-out and has been calculated according to the “Beer Game” rules; i.e. £1 per unit on stock out per week and £0.5 per unit in stock per week.

The ITAE has been evaluated for the demanded transport and quantifies how well each system traces the input (in this case how the demanded transport curve traces the demand). The ITAE can be considered as regrouping four criteria that are usually studied when looking at dynamic performance: the peak and the trough of the oscillation and the time at which it occurs (Towill, 1981, Dorf, 1992). However, this criterion cannot be considered for a random change in demand as there is no reason for penalising more a peak or a trough in the demanded transport curves when it happens at a later time. Thus an alternative criterion, the standard deviation of demanded transport, is chosen for a random change in demand. The standard deviation, measuring how widely values are dispersed from the mean, shows how each system magnifies the input. Thus looking at the standard deviation of the demanded transport for the factory of each strategy is giving information on how each supply chain is magnifying or reducing the variations of the initial input, the customer demand.

The customer service level (CSL) has been assessed according to the number of weeks each echelon cannot supply the quantities required. The retailer CSL has been identified as being of importance as the final customer will only identify with this level of service. However the CSL of the whole supply chain or total CSL is still an interesting criterion as it shows how each particular supply chain performs as a whole in terms of stock out situations. Finally each criterion had the same weight for our assessment.

### **Assumptions**

To summarise, the assumptions for the simulation results are as follows:

- each echelon is using the same decision rule,
- each echelon has the same weight in the supply chain,
- all echelons are using the same parameters value,
- all the criteria are equally weighted,

- each criteria has been averaged for one echelon except for the standard deviation criterion which only looks at the factory,
- there are no capacity restrictions.

## Simulation results

The ranking of the strategies for each criterion is summarised in Tables 2 and 3.

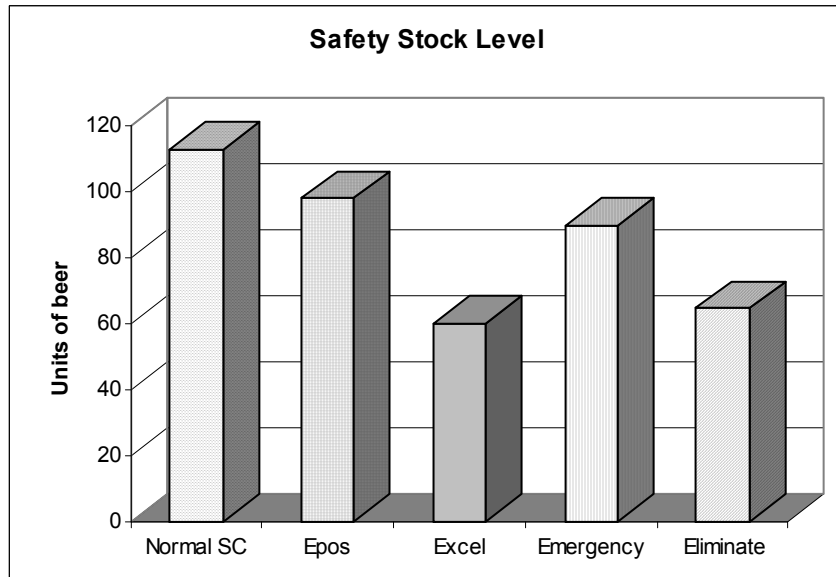
Strategy	Safety stock					Rank.	Inv. cost	Rank.	ITAE of $D^{ed}$ trans.	Rank.	Retailer CSL	Rank.	Total CSL	Rank.	Final Ranking
	Retailer	Whole.	Distrib.	Factory	Total										
Baseline SC	16.1	22.6	31.3	42.9	112.8	5	£ 682	4	10,527	4	10	3	13	3	4
Epos	16.1	22.1	27.6	32.3	98.1	4	£ 598	1	8,138	2	10	3	16	4	3
Excel	15.9	15.9	15.9	12.0	59.8	1	£ 894	5	115,802	5	85	5	62	5	5
Emergency	14.4	18.6	23.0	33.9	89.8	3	£ 676	2	9,506	3	6	1	12	2	2
Eliminate	14.1	20.6		29.9	64.6	2	£ 677	3	6,978	1	7	2	10	1	1

*Table 2: Results and ranking of the strategies for a step change in demand.*

Strategy	Safety stock					Rank.	Inv. cost	Rank.	Stddev $D^{ed}$ trans.	Rank.	Retailer CSL	Rank.	Total CSL	Rank.	Final Ranking
	Retailer	Whole.	Distrib.	Factory	Total										
Baseline SC	17.5	25.5	37.4	56.2	136.6	5	£ 863	4	7.059	5	14	3	24	5	5
Epos	17.5	21.8	21.8	20.4	81.5	3	£ 617	1	2.488	1	14	3	21	2	2
Excel	21.8	21.8	21.8	12.0	77.3	2	£ 691	2	3.338	2	32	5	23	4	3
Emergency	15.0	23.0	32.5	54.5	125.1	4	£ 876	5	7.058	4	8	2	21	2	4
Eliminate	15.5	23.5		35.4	74.5	1	£ 757	3	4.675	3	6	1	15	1	1

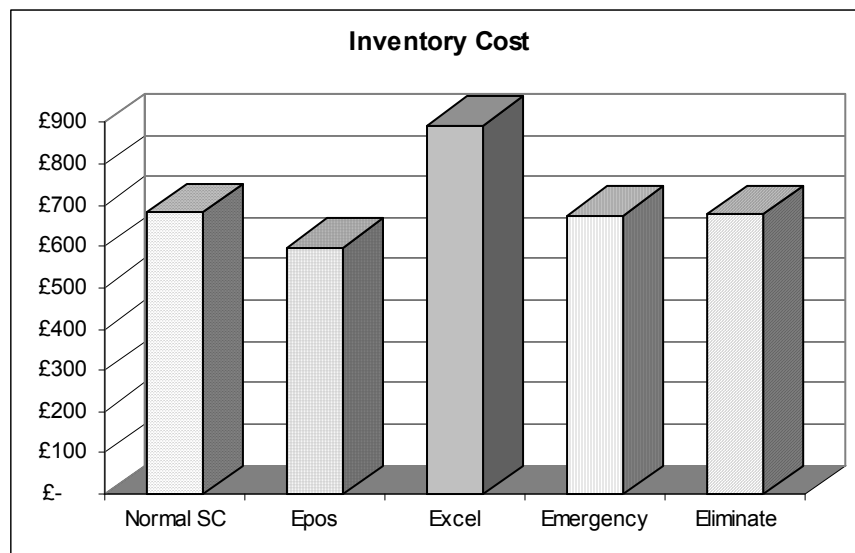
*Table 3: Results and ranking of the strategies for a random change in demand.*

As seen previously, the Excel strategy has a negative impact on the inventory cost and the retailer CSL for a step change in demand. In other words it makes things worse. This is due to the same reasons as stated above, namely the factory did not have the possibility to push the products down the supply chain. Figures 9 and 10 show the comparisons of the amount of safety stock and the inventory for each strategy for a step change demand.



*Figure 9: Amount of safety stock for each strategy (averaged for one echelon over 100 weeks) for a step change demand.*

As it can be seen from Tables 2 and 3, Eliminate is the winning strategy for both demand patterns. Epos is third for a step change and second for the random demand while Emergency is respectively second and fourth.



*Figure 10: Inventory cost for each strategy (averaged for one echelon over 100 weeks) for a step change demand.*

	Safety stock	Inventory cost	ITAE D <sup>ed</sup> transport	Retailer CSL	Total CSL
Baseline SC	-	-	-	●	●
Epos	-	●	●	●	-
Excel	●	-	-	-	-
Emergency	●	●	●	●	●
Eliminate	●	●	●	●	●

Legend:

- strong beneficial impact
- beneficial impact
- slight/modest beneficial impact
- No beneficial impact

*Table 4: Influence of different strategies on key criteria for a step change demand.*

The influence of each strategy on each criterion is summarised in Table 4. It is interesting to note from Table 4 that the Emergency strategy has only a slight beneficial impact on the total safety stock level for a step change in demand. The Excel and Eliminate strategies both have a stronger beneficial impact. However, it is important to interpret more closely the results summarised in Tables 2 and 3. If we consider the total safety stock, Emergency strategy finished third for a step change in demand and fourth for a random change in demand. This could be seen as contradictory with the findings from the literature review (e.g. Evers, 1996 and 1997, Yano, 1992 and Tagaras, 1992). It must however be stressed that these authors did not consider a four-echelon supply chain but a two-echelon supply chain.

Hence if we look at the safety stock for the retailer and the wholesaler, Emergency strategy is second and first for step change in demand and a random change in demand respectively. This means the Emergency strategy does reduce the amount of safety stock especially at the retailer level. Nevertheless, it has to be admitted that the factory suffers from an emergency system. The Emergency strategy is fourth for both demand patterns at the factory level.



The poor result obtained by the Emergency strategy for the inventory cost for a random change in demand can be explained by the fact that the inventory levels were not optimised with the necessary safety stock, but were left at the level at which the players set them (12 and 15 units for the distributor). Hence the Emergency strategy was often stocked out which is translated into a high inventory/backlog cost.

Furthermore, it is important to highlight that the Emergency strategy improves the retailer customer service level, especially for a step change demand. As it can be seen in Figure 11, the inventory level of the retailer recovers very quickly from a step increase in demand.

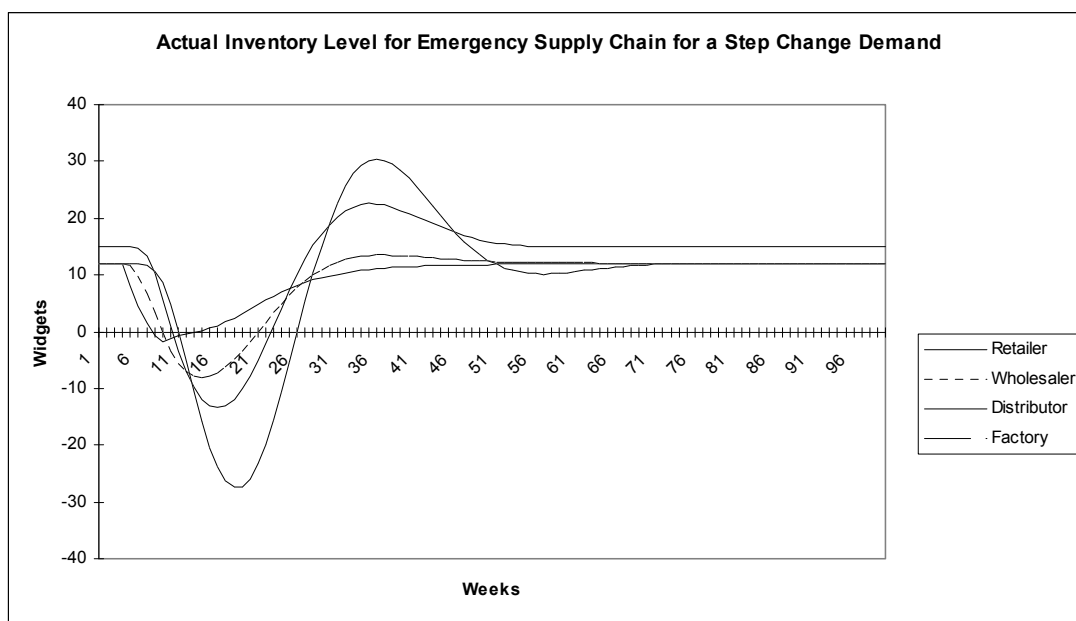


Figure 11: Actual Inventory Level for Emergency Supply Chain for a Step Change Demand

### Further simulations

After the analysis of the results obtained, further simulations can be undertaken. For example, it is of interest to see which combination of strategies gives the best results. Epos may be used as the benchmark as it reduces the inventory cost. This criterion is an important one as the research is to ultimately apply the knowledge gained as a decision support in a real supply chain re-engineering programme. Because the results show that Excel strategy is incomplete (the factory should have the capability to push the products to lower echelons) (Hong-Minh 1998), this strategy will not be taken into account.

Thus three new strategies have been created: Epos / Emergency, Epos / Eliminate and Epos / Emergency / Eliminate. The results are, not surprisingly, Epos & Emergency & Eliminate strategy is the best strategy combination.

The lessons that can be learned from all the above results are summarised in Table 5.

<b>Strategies</b>	<b>Lessons</b>
<b>Excel</b>	cannot be considered without any changes, as the strategy is incomplete and yields poor results.
<b>Epos</b>	influences strongly the inventory cost, the ITAE and the standard deviation of demanded transport.
<b>Emergency</b>	has a major impact on the retailer customer service level and reduces the amount of safety stock for the first two echelons.
<b>Eliminate</b>	reduces the amount of safety stock needed in the whole system and provides the best total customer service level.  Eliminate appears to be the best strategy, this can be explained by the fact that the complexity of the system is reduced and thus its dynamic is improved.
The combination of the three best strategies gives the best overall result.	

*Table 5: Overall simulation results and lessons to be learnt*

## CONCLUSION

It can be seen that the dynamic simulation results agree with the main findings of the literature review: emergency transshipments reduce the amount of safety stock in the system when only two echelons are taken into consideration; the emergency transshipment being used in terms of accelerating the product deliveries and bypassing an echelon. In this case, the distributor acts as a stock holding point and delivers directly to the retailer whenever needed.

Furthermore, this study clearly shows the influence of several strategies on selected criteria, although with the underlying assumption that each echelon of the supply chain uses the same decision rules and with the same parameters. It has been shown that the Epos strategy (where each echelon of the supply chain knows the final customer demand) reduces the inventory cost, the ITAE and the standard deviation of demanded transport in the supply chain, while

the Eliminate strategy reduces the amount of safety stock needed in the whole system and the ITEA of demanded transport. The Excel strategy cannot be considered as a possible solution to improve the dynamic of a supply chain without undertaking changes in the decision rules used.

Finally the Emergency strategy improves the customer service level for both the retailer level and the total CSL of the whole supply chain, this being true for a step change in demand and a random change in demand. It is however important to stress that emergency transshipments are strictly for use during an “emergency” and should not be used as a day-to-day strategy. The Emergency strategy can nevertheless be vital for such where missing parts can results in expensive penalties.

Further work could be carried out using the optimum safety stock level as the starting stock level in order to comprehend how well each strategy performs when set up in an optimum way. In particular, the economics of the effects of different inventory holding, order backlog and production adaptation costs could be studied and optimum decision parameters could be sought against those cost profiles.

Further Laplace or z-transform analysis could also yield insights into the supply chains. The effect of transportation costs within each strategy is also a further limitation as they are not explicitly included in the study.

## **NOMENCLATURE**

<b>APIOBPCS</b>	Automatic Pipeline feedback compensated Inventory and Order-Based Production Control System.
<b>CSL</b>	Customer Service Level.
<b>D.C.</b>	Distribution Centre
<b>EPOS</b>	Electronic Point Of Sale.
<b>EUNIL</b>	European University Network in Logistics.
<b>EXSMO</b>	Exponential Smoothing.
<b>IOBPCS</b>	Inventory and Order-Based Production Control System.
<b>ITAE</b>	Integrated Time Absolute Error.
<b>MIT</b>	Massachusetts Institute of Technology.

<b>Ta</b>	Time to average consumption
<b>Ti</b>	Time to adjust inventory
<b>Tw</b>	Time to adjust WIP
<b>Tp</b>	Actual pipeline lead-time
<b>WIP</b>	Work In Progress

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## APPENDIX 1: EXSMO SIMULATION EQUATIONS FOR APIOBPCS

$$\begin{array}{l} \text{Orders} \\ \text{placed} \end{array} = \begin{array}{l} \text{Average} \\ \text{demand} \end{array} + \begin{array}{l} \text{a fraction of any} \\ \text{inventory errors} \end{array} + \begin{array}{l} \text{a fraction of} \\ \text{any WIP error} \end{array} \quad (1.1)$$

The EXSMO simulation equations for WIP-compensated decision support system are as follows:

### Average demand rate equation

$$\text{Average demand (t+1)} = \text{average demand (t)} + \alpha A (\text{demand (t+1)} - \text{average demand (t)}) \quad (1.2)$$

$$\text{where } \alpha = [1 / (1 + (\tau/\Delta t))], \quad (1.3)$$

Here A depends on time to average demand  $T_a$ , thus here  $\tau = T_a$ , and  $\Delta t = 1$  as the time unit used in the simulations is one week.

### **Demanded transport/production rate equation**

$$\begin{array}{l} \text{Demanded} \\ \text{production} \\ \text{rate (t+1)} \end{array} = \begin{array}{l} \text{inventory} \\ \text{average demand (t+1)} \\ \text{Ti} \end{array} + \frac{\text{error (t)}}{\text{Ti}} + \frac{\text{WIP error (t)}}{\text{Tw}} \quad (1.4)$$

### **Arrival rate equation**

$$\text{Arrival rate (t+1)} = \text{arrival rate (t)} + \alpha P [\text{demanded production rate (t+1)} - \text{arrival rate (t)}] \quad (1.5)$$

$$\text{where } \alpha P = [1 / (1 + (Tp/\Delta t))]. \quad (1.6)$$

### **Actual inventory level equation**

$$\text{Actual inventory (t+1)} = \text{actual inventory (t)} + \text{arrival rate (t+1)} - \text{demand (t+1)} \quad (1.7)$$

### **Work in progress level equation**

$$\text{WIP (t+1)} = \text{WIP (t)} + \text{demanded production rate (t+1)} - \text{arrival rate (t+1)} \quad (1.8)$$

### **Inventory error equation**

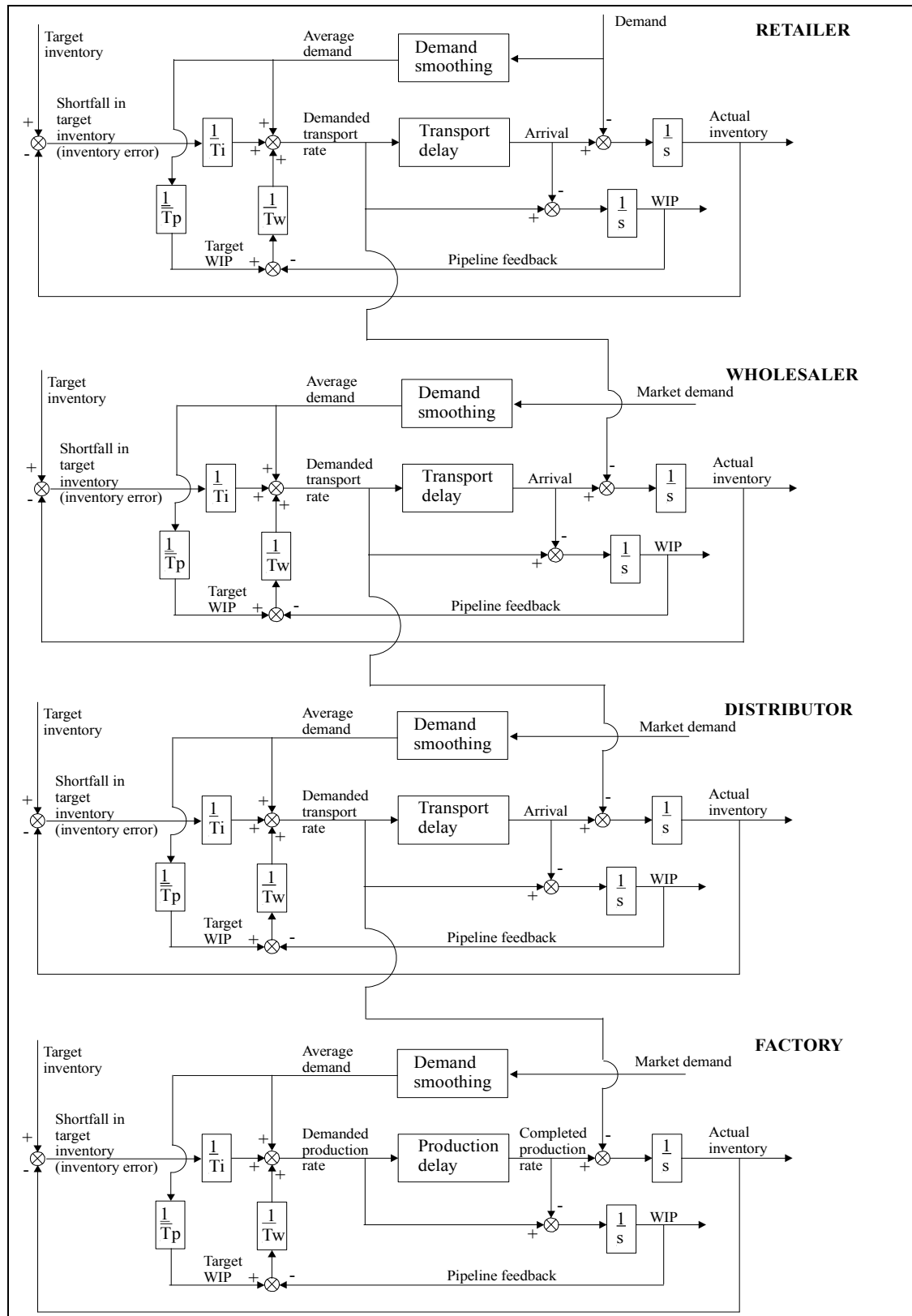
$$\text{Inventory error (t+1)} = \text{target inventory} - \text{actual inventory (t+1)} \quad (1.9)$$

### **Work in progress error equation**

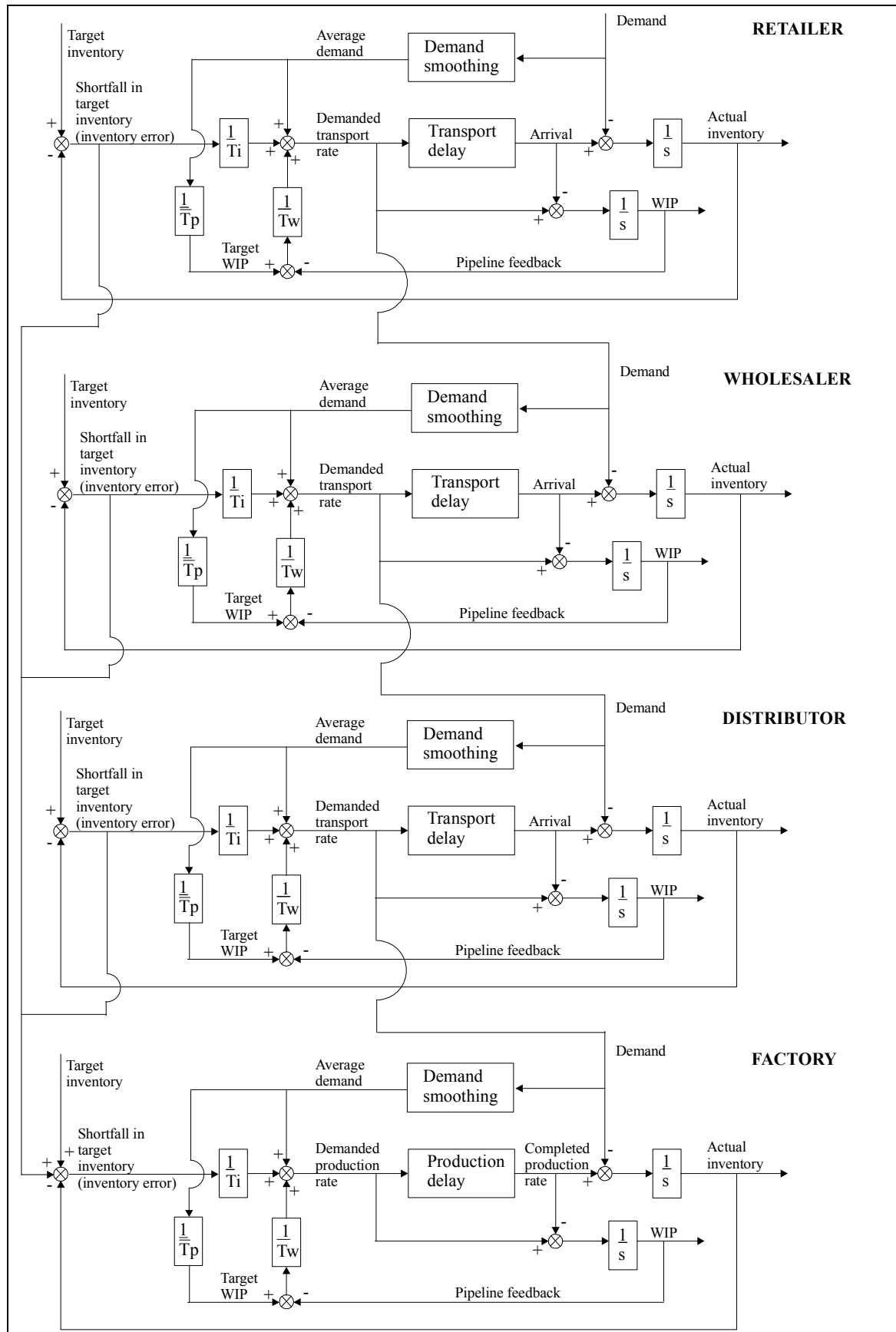
$$\text{WIP error (t+1)} = Tp * \text{average demand (t+1)} \quad (1.10)$$



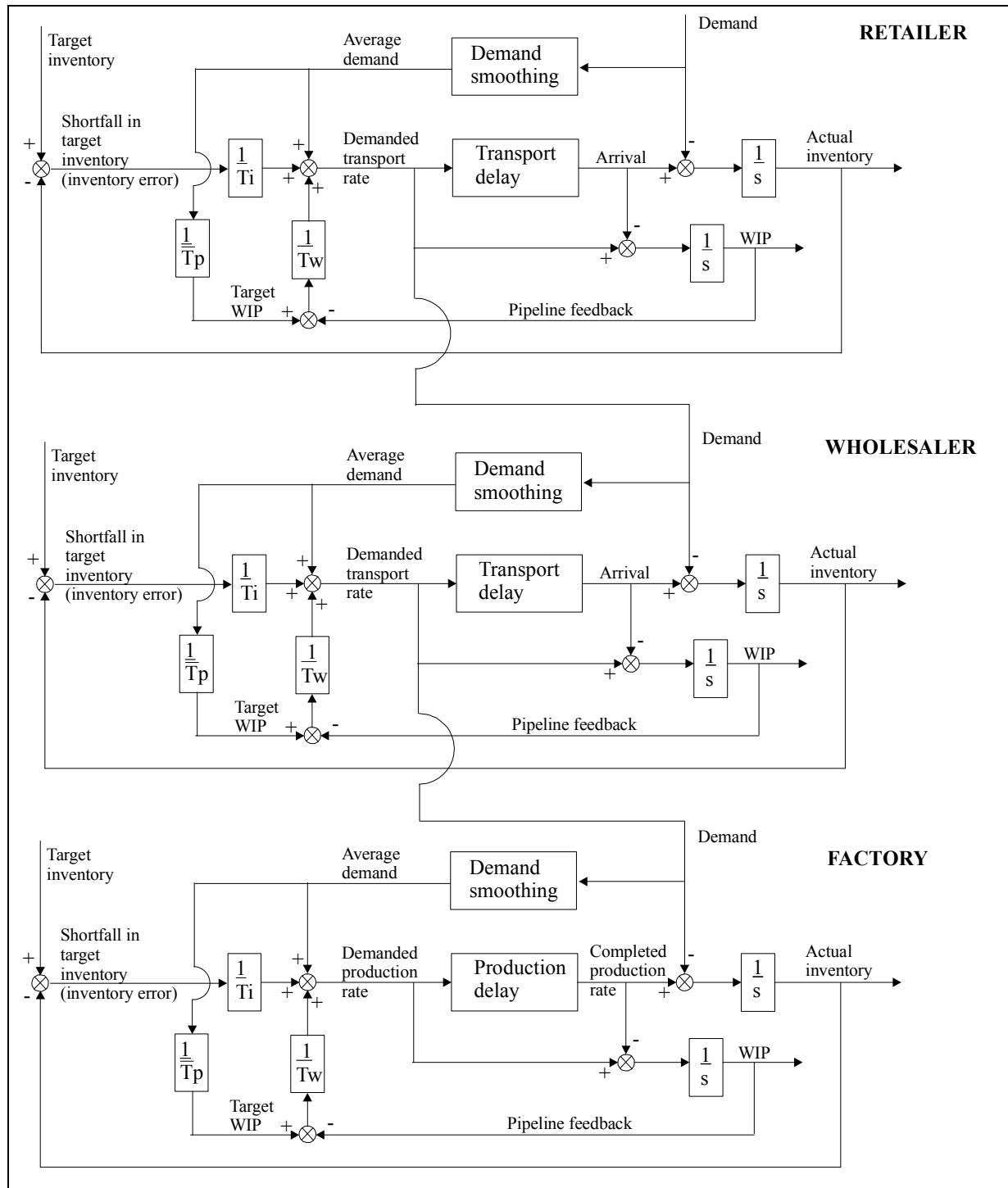
## APPENDIX 2: BLOCK DIAGRAMS FOR EPOS, EXCEL AND ELIMINATE STRATEGIES



*Block diagram of an Automatic Pipeline feedback compensated Inventory and Order Based Production Control System (APIOBPCS) for Epos strategy.*



*Block diagram of an Automatic Pipeline feedback compensated Inventory and Order Based Production Control System (APIOBPCS) for Excel strategy.*



*Block diagram of an Automatic Pipeline feedback compensated Inventory and Order Based Production Control System (APIOBPCS) for Eliminate strategy.*