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The impact of Vendor Managed Inventory on transport operations

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Abstract

This paper investigates the impact of a Vendor Managed Inventory (VMI) strategy upon transportation operations in a supply chain. Specifically, the issue of batching to enable better use of transport vehicles is studied. A system dynamics methodology is used to develop difference equation models of three scenarios – traditional, internal consolidation and VMI. The holistic nature of inventory management within VMI enables batching to minimise transport demand without negatively impacting the overall dynamic performance of the supply chain. Using the concept of cost escapability, it is shown that transport cost savings are possible in both the short and long term.

Key words
Transport, vendor managed inventory, supply chain dynamics, batching.

Introduction

In supply chains, a trade off exists between the manufacturing and transportation functions. For the smooth flow of materials through a traditional supply chain, deliveries have to be made every ordering period on an "as required" basis. However, this is likely to result in less than full truckload consignments, which does not optimise the utilisation of the vehicle payload. Conversely, by running full vehicles, the demand for transport is minimised and transport costs are reduced. Batching exists in supply chains because each player makes a 'rational' decision to minimise visible costs. This can be achieved in one of two ways. A product can either be routed through a consolidation centre or batching introduced into the ordering rule to only permit full vehicle loads. However, implementing the latter within a traditional supply chain structure will result in the batching or Burbidge effect (Towill, 1997). This is one of the five fundamental causes of the well-known (and costly) bullwhip phenomenon (Lee et al., 1997a and b), the others being demand signal processing, non-zero lead-times (together being known as the Forrester effect), price promotions and gaming. In this paper we specifically focus on the effect that a vendor managed inventory (VMI) strategy will have on the impact of batching behaviour in the transport operations of a supply chain.

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One such way in which this transport efficiency/inventory holding trade off can be avoided is to take a holistic view of inventory levels throughout the supply chain, delegating the control of all inventory, including shipments between echelons to a single point. This is known as a VMI strategy (Waller et al., 1999). This differs from vertical integration, as the participating companies remain autonomous, with the distributor trusting the manufacturer to ensure customer service levels are maintained.

The aim of this paper is to study explicitly the transport function within generic supply chain models, covering three different scenarios (a traditional supply chain, a situation where batching occurs within the order rule and a VMI supply chain) and provides some quantification as to their costs and benefits. This study will be carried out using a systems dynamics modelling approach (Richardson and Pugh, 1981). From the simulation outputs, the effect of the strategies on manufacturing on-costs, inventory holding costs and transport costs will be quantified and discussed.

We proceed by describing in detail a traditional (with transport despatches every time period) and a VMI supply chain structure, including a discussion on the use of transportation within these structures. Causal loop models are constructed to show that VMI enables manufacturing to be unaffected by the batching necessary to achieve full truckloads. To prove this, difference equations are used to create a dynamic simulation model of a two-echelon supply chain that is then investigated. The implications of our findings for supply chain dynamics and transport operations are then discussed. The broader implications of the findings on transport costs are outlined, using the concept of cost escapability. From these, conclusions are drawn.

Traditional supply chains

In a traditional supply chain, each company operates individually, with interactions between them limited to just the feed-forward flow of physical products and the feedback flow of information, in the form of orders and cash. A simple schematic of a four echelon supply chain, comprising retailer, distributor, warehouse and factory is illustrated in Figure 1. This structure has developed as a result of both the need for a company to be in control of its assets whilst looking to optimise their utilisation, the cost associated with the transfer of information and the perceived lack of benefits of this level of information flow. Only recently, with the falling cost of telecommunications and the availability of accurate information, has it been economic for the sophisticated data transfer required by the VMI strategy to take place.

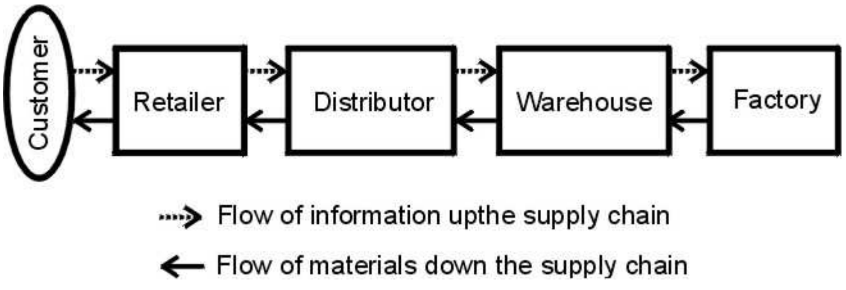

Figure 1. The traditional supply chain

As a consequence of the structure, the traditional supply chain suffers from long lead times, multiple decision points, unclear information and minimal synchronisation (Childerhouse and Towill, 2000). In generating orders, each echelon looks to manage their own situation, with orders based on incoming orders, inventory levels, goods shipped and received and, to some extent, orders placed but not yet received (Senge, 1990). Consequently, orders include not only actual incoming demand, but also components covering the echelon's own inventory, customer service levels and cost requirements (Disney, 2001).

The lack of visibility of end customer demand causes a number of problems. Firstly, the Forrester effect becomes evident, due to the structure of the ordering decision with its lead time for deliveries. The retailer as a result of forecasting customer demand introduces extra fluctuations into the pattern of demand. The distributor, whose forecast is based on the orders of the retailer, then increases these variations further. This effect continues up the supply chain, resulting in a significant distortion of the actual customer demand by the time the factory receives orders. Secondly, the batching of orders to achieve economies of scale from production or better utilisation of transport vehicles may occur. Therefore, orders placed upstream may become infrequent and inflated. This second effect is known as the Burbidge effect (Towill, 1997).

Within the traditional supply chain, companies can adopt a variety of strategies to minimise their transport costs by consolidating loads to maximise vehicle fill. This can be done either internally or externally (McKinnon, 1989). With internal consolidation, constraints are placed on customers requiring them to either order or receive deliveries only in full truck loads. As mentioned above, this batching results in the Burbidge effect. External consolidation involves either the grouping of different suppliers loads together (McKinnon, 1989) or delivering to a group of customers using a single vehicle. In the former situation, consignments are made through a consolidation centre. Here, a number of small consignments are received from a variety of suppliers and grouped into a larger delivery for a specific customer. This strategy has become particularly prevalent in the grocery sector with the introduction of distribution centres between suppliers and the retail outlets. The use of multi-drop deliveries (also known as a milkround) is particularly useful where a number of customers are in close proximity to each other. In terms of quantifying the effect of consolidation, it appears that a reduction in transport mileage by 20 to 25% can be achieved (McKinnon, 1998). However, this is not directly proportional to cost savings, as the additional handling charges incurred through consolidation need to be considered.

VMI supply chains

An early conceptual framework for VMI was described by Magee (1958) when discussing who should have authority over the control of inventories. However, interest in the concept has only really developed during the 1990s. Companies have looked to improve their supply chains as a way of generating a competitive advantage, with VMI often advocated. This strategy has been particularly popular in the grocery sector but has also been implemented in sectors as diverse as steel (Lamb, 1997), books (Andel, 1996) and petrochemicals (Jones, 2001).

A simple diagram of a VMI supply chain can be found in Figure 2. With VMI, the supplier (which is often a manufacturer, but may be a distributor) controls the buyer's (in this case a retailer) inventory level, so as to ensure that predetermined customer service levels are maintained. In such a relationship, the supplier takes the replenishment decisions for the buyer, despatching a quantity of product that may be fixed (so as to maximise production or transport efficiency, for instance) or variable (Waller et al, 1999). Replenishment occurs when the stock level at the buyer reaches a specified level, based on both the average demand during the transportation lead-time and a safety stock to cover for demand variations (Kaipia et al, 2002). Consequently, there is no passing of orders between the two companies (Christopher, 1992). For VMI to be successful it is necessary for a large amount of information to be transferred between both parties, particularly data regarding end user sales and inventory levels at the buyer (Andel, 1996). With the advent of electronic commerce, it is only relatively recently that this strategy has become economically viable. At its simplest level, VMI has been introduced using just spreadsheets and e-mails (Holmström, 1998; Disney et al., 2001).

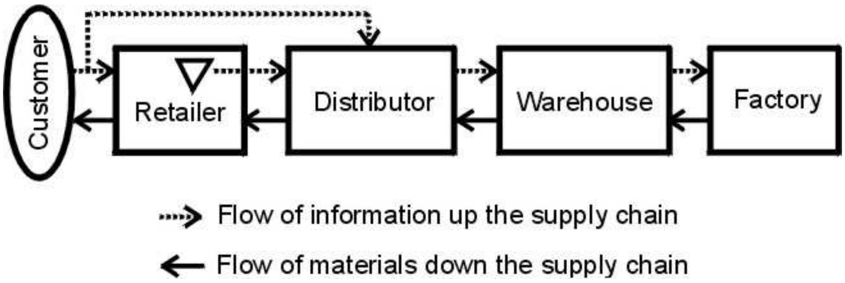

Figure 2. A VMI supply chain

VMI brings a number of benefits to all parties participating in the supply chain. Firstly, the impact of demand amplification is dampened as the manufacturer now receives a direct view of end consumer demand patterns and can use this in forecasting (Disney, 2001). This generates cost benefits through a reduction in buffer stocks at the buyer and supplier (Sabath, 1995) and a more efficient use of production facilities (Lamb, 1997), as output need not be ramped up and down according to perceived large swings in demand. Further, there are improvements in service levels as product availability is increased (Waller et al, 1999). Finally, VMI can, in the long run, increase the profitability of both the supplier and buyer in the supply chain (Dong and Xu, 2002). The buyer benefits from lower inventory costs and can offer a price reduction. This then increases sales volume, which benefits both parties in terms of increased profitability.

Studies of the transport function within the VMI supply chain have tended to be limited. They have not extended beyond an acknowledgement that, because the total inventory position is considered in any decision making, it is possible to batch transport despatches into full truck loads, and therefore reduce transport costs (for example, see Waller et al., 1999). By using system dynamics modelling, this paper will provide further insights into this important benefit.

Modelling the supply chains

In this paper, the basic model used will be taken from inventory and order based production control system (IOBPCS) family of models. The term IOBPCS was first used by Towill (1982) after studying a common scheduling system found by Coyle (1977) to represent UK industrial practice. In this model, the ordering rule is based upon forecast demand and the difference between a fixed target level of inventory and the actual level. Since then, a number of variants of this base model have been developed, and it is one of these that is used as the basis for the modelling in this paper – the automated pipeline inventory and order based production control system (APIOBPCS).

The difference between the APIOBPCS and IOBPCS models is that the ordering rule also takes into account work in progress (WIP), comparing actual levels with a target value (John et al., 1994). This generic model is actually a very general replenishment rule, as:

- it can be made to reflect lean and agile scheduling policies (Towill et al., 2001),
- order-up-to policies and many variants of it are special cases of APIOBPCS (Dejonckheere et al., 2002),
- Material Resource Planning (MRP) systems are another important special case of APIOBPCS (Disney, 2001),
- it is representative of much of UK industrial performance (Coyle, 1977), and
- it has been shown to represent human behaviour whilst playing the Beer Game (John et al., 1999).

In this paper, the VMI strategy is coupled with an APIOBPCS based supply chain. The VMI-APIOBPCS system has been studied in detail by Disney (2001), optimised by Disney and Towill (2002a) and undergone a stability investigation via z-transforms in Disney and Towill (2002b).

Having defined the models, it is necessary to conceptualise them (Vennix, 1996). The systems dynamics community often exploits causal loop diagrams to do this, as they concisely describe a system's structure. They are also used as a tool to identify fundamental dynamic properties of systems and can be used to develop block diagrams (from which a control theory analysis may be initiated) and difference equation models. Causal loop diagrams are based around linking variables using arrows. Causal loop diagrams may be interpreted as follows:

- Arrows denote an influence of the cause (the text at the tail of the arrow) on the effect (the text at the head of the arrow).
- A positive arrow denotes a positive influence, i.e. when the cause goes up (down) the effect goes up (down).
- A negative arrow denotes a negative influence, i.e. when the cause goes up (down) the effect goes down (up).
- Arrows where no sign is present represent parameters.

Figure 3 shows the causal loop diagram for a single APIOBPCS model. The traditional supply chain will actually be modelled using two APIOBPCS models with the distributor's orders forming the manufacturer's sales. The transport link is represented by the production delay at the distributor. Figure 4 shows the causal loop diagram for the VMI-APIOBPCS scenario. Both of these diagrams have resulted from the conceptualisation of published literature. Because the VMI scenario considers the total stock level, despatches between the distributor and manufacturer do not need to be shown. The two echelons are, however, spatially separated.

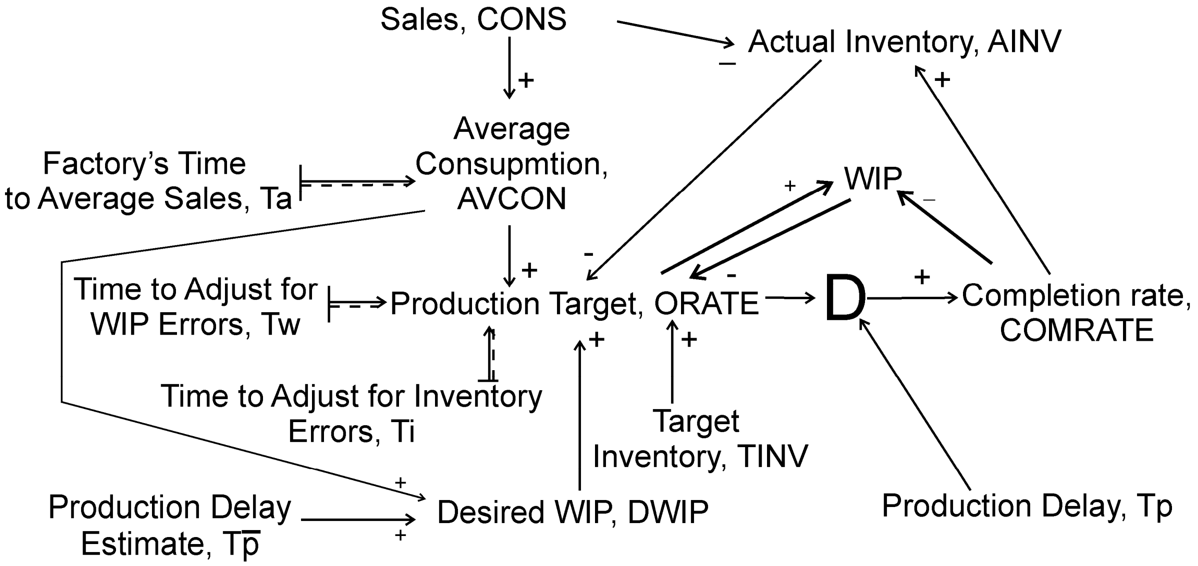

Fig. 3. Causal loop diagram of an APIOBPCS system (adapted from John et al., 1994).

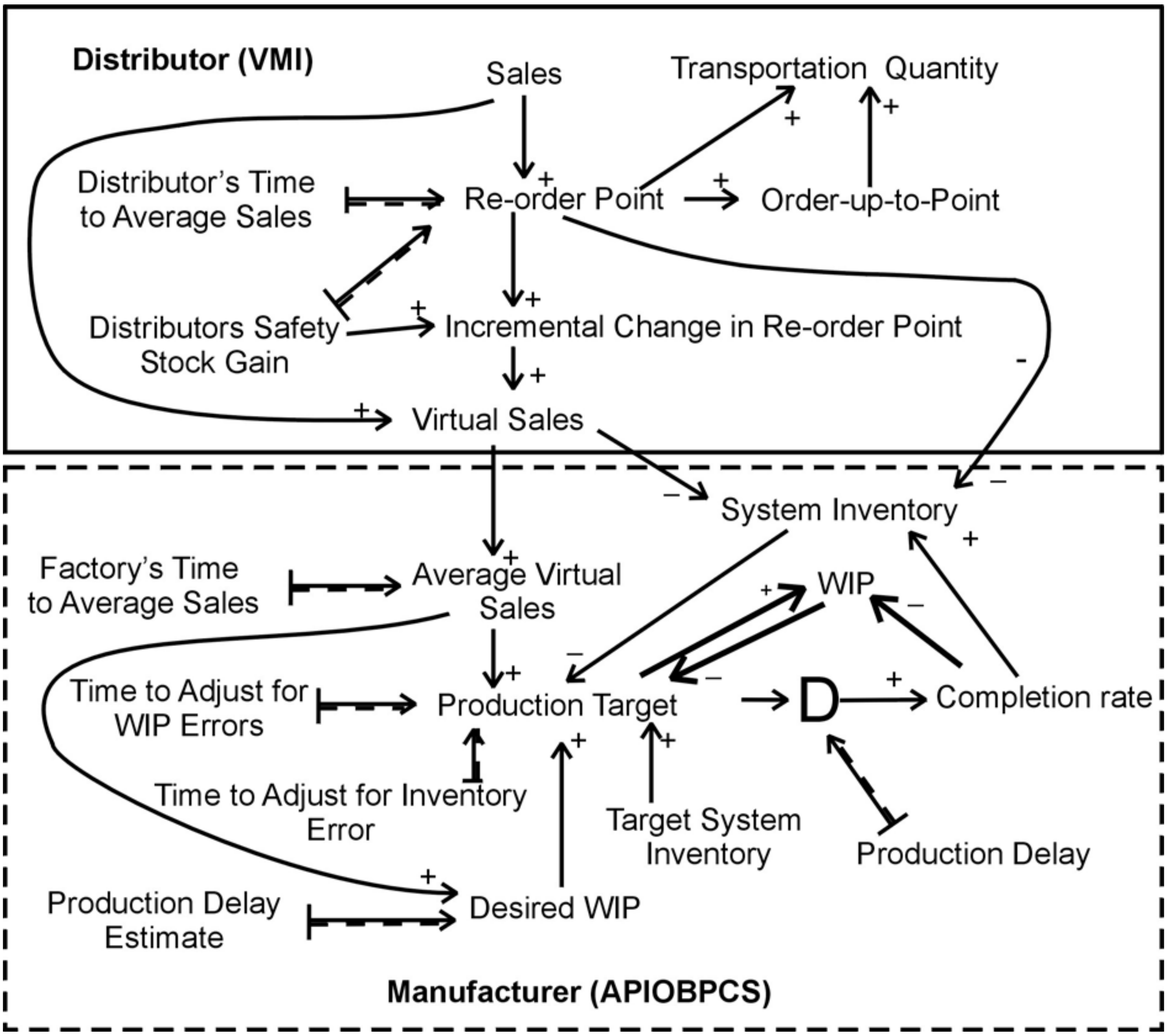

Figure 4. Causal loop diagram of VMI (Disney, 1999)

The first clue to the profound properties of VMI can be seen in the causal loop diagram shown in Figure 4. Careful inspection shows that the transport quantity system variable (in the top right corner of the diagram) has no influence, as it is not at the tail of an arrow. This is a significant insight because, as shown later, it implies that transport may be optimised without any adverse effect on the rest of the supply chain.

The next stage of a systems design methodology is to translate the causal loop diagram into a difference equation model. The equations for the traditional supply chain are shown in Appendix A, and VMI scenario in Appendix B. Values for the parameters to complete the models are in Appendix C. They may be readily incorporated into a spreadsheet model and used by readers to develop dynamic models of both supply chains for independent verification of the results presented below. Included in the model are equations for explicitly modelling the transport aspects of both supply chains and converting volumes into a figure for transport demand. Using these equations, a simple spreadsheet based Decision Support System has been developed by Disney et al., 2001 to control production and distribution targets in an actual industrial setting. Hence we may be absolutely certain that we are describing here a physically realisable and meaningful VMI supply chain model.

Three different scenarios have been modelled:

- Traditional supply chain – this will form the baseline scenario for the others to be compared against.
- Internal consolidation – the only difference between this model and the traditional supply chain is the inclusion of a batching constraint in the order rule of the distributor.
- VMI supply chain – this is the alternative situation proposed by this paper as offering a benefit for less than truckload consignments. A fixed transport quantity is used, as described by the equations in Appendix B.

The external integration scenario has not been considered for several reasons. Firstly, the scenario would require the modelling of a number of suppliers so that the full benefit of external consolidation could be realised. Secondly, a spatial dimension would also be required to determine whether the lowest cost route was direct or through a consolidation centre.

A number of assumptions have been made within the models. The lead times for deliveries has been set at 2 time units for the distributor and 4 time units for the manufacturer and a pure delay has been adopted. With a pure delay, all of the goods that were ordered at a particular point of time are delivered together once the lead time has elapsed. The economic transport quantity (ETQ) has initially been set equal to four, and assumed to be equal to one full vehicle. This will not reduced the generality of the results as it is merely used as a scaled unit factor. Finally, a step change has been used as a demand signal, increasing from 0 to 1 at time period 0. A unit step is the integral of the impulse response. The impulse response completely describes a linear system but it is easier to distinguish between similar responses when the integral is taken. It also contains information on how the system behaves to a stochastic demand, but we have not explored it here.

Impact on supply chain dynamics

Figure 5 shows the dynamic responses over time of the three scenarios to a step change in demand and has been produced from the spreadsheet models. The three graphs have been produced with the same axes to enable comparisons between them.

In the traditional scenario, by using transport despatches in every time period, it is possible to achieve a smooth manufacturer's order rate. This is because the dynamic responses of the other components involved in ordering decisions (inventory levels, goods in transit and incoming orders from the distributor) also respond in a smooth manner to the step change. However, demand amplification does occur within the supply chain, with the peak order rate from the manufacturer being 2.05 units against an incoming demand of 1 unit. The peak order rate provides an indication as to the extra costs incurred by the supply chain.

With internal consolidation, where batching is used in a traditional supply chain, the manufacturer's order rate becomes very erratic with a peak value of 4.20 units. Again, this indicates the presence of bullwhip, the effect of which is further exacerbated by the constant demand variation. This variation occurs because the manufacturer's forecast is based upon the batched orders received from the distributor. Furthermore, the inventory levels at the manufacturer suddenly experience sharp drops when despatches are made. However, there is some dampening of the bullwhip when compared against that created by the distributor due to the exponential smoothing of incoming orders.

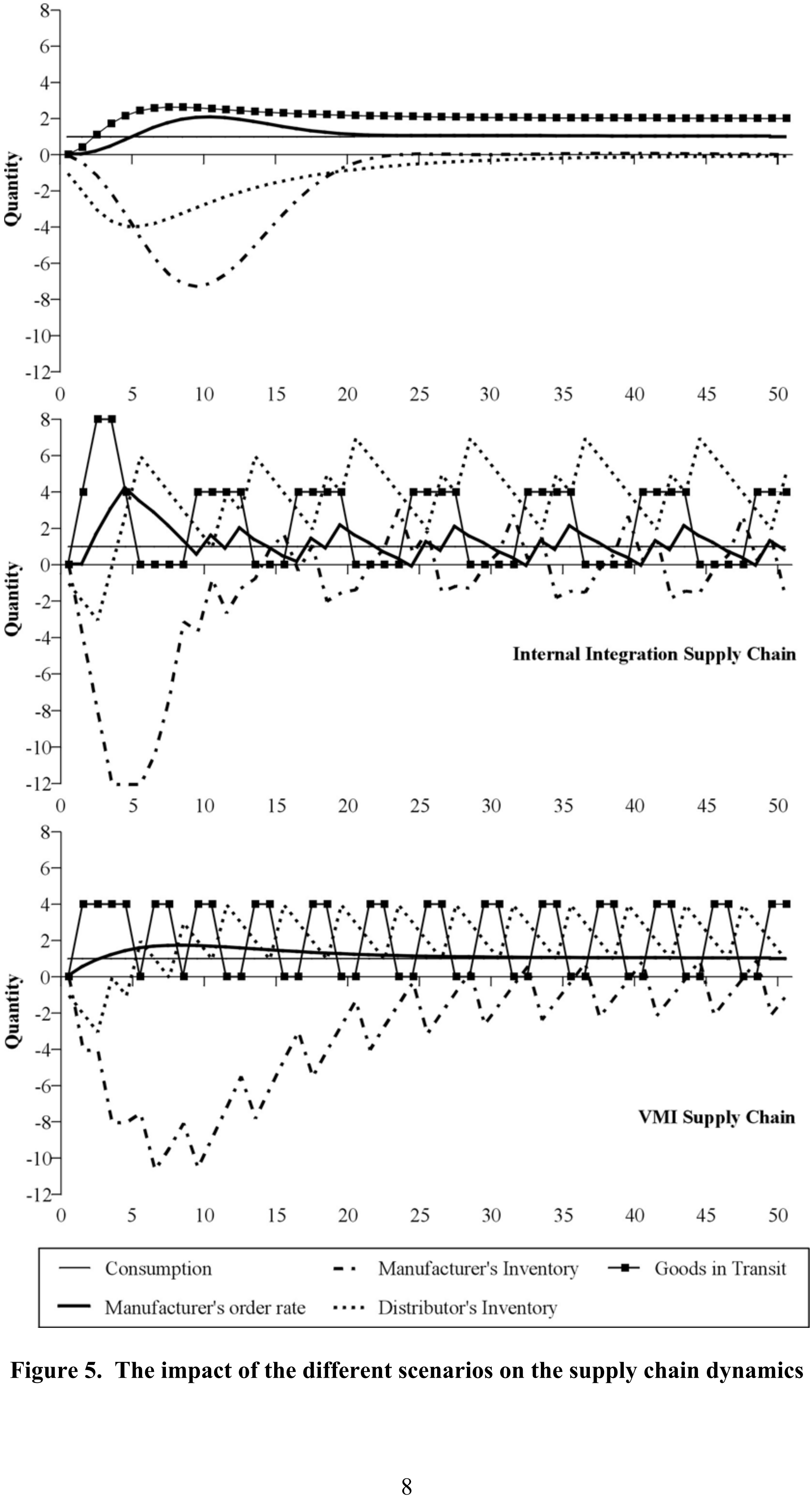

Figure 5. The impact of the different scenarios on the supply chain dynamics

In a VMI supply chain, batching may be exploited by the transportation system without introducing batching effects (like those just seen in the traditional supply chain) into the manufacturer's ordering decision. This is because the total supply chain inventory is summed in the production order rate decision and this neutralises the IF…THEN rule used to determine when a despatch is made between the two echelons. When a despatch is made, the decrease in the manufacturer's inventory level is compensated for by the increase in the volume of goods in transit. Upon delivery, there is a reduction in goods in transit with a corresponding increase in the distributor's inventory. These create a smooth inventory signal to use in the ordering decision. The VMI supply chain also reduces the level of demand amplification present within the supply chain. In the example in Figure 5, the peak order rate is 1.69 units (as opposed to 2.05 units in the traditional scenario).

Impact on the transport operations

The above discussion has focussed upon the system dynamics benefits of VMI over the traditional and internal consolidation scenarios. This section will now focus upon the transport benefits that can be achieved. Figure 6 shows the how the transport demand varies with time and has been plotted from the transport demand column of the spreadsheet model. As can be seen, the traditional scenario consistently requires two vehicles. This value represents the equivalent of one vehicle despatch per day with a 2 day lead time. By contrast, the transport demand in the internal consolidation and VMI scenarios is more variable but consistently less. This is to be expected as all despatches are made as full vehicle loads, whilst the traditional despatches whatever is available each time period. With a stable demand signal, such as that used in the models, it can be seen that both settle into regular patterns. The maximum level of transport demand is 1 vehicle whilst some time periods do not require any transport at all.

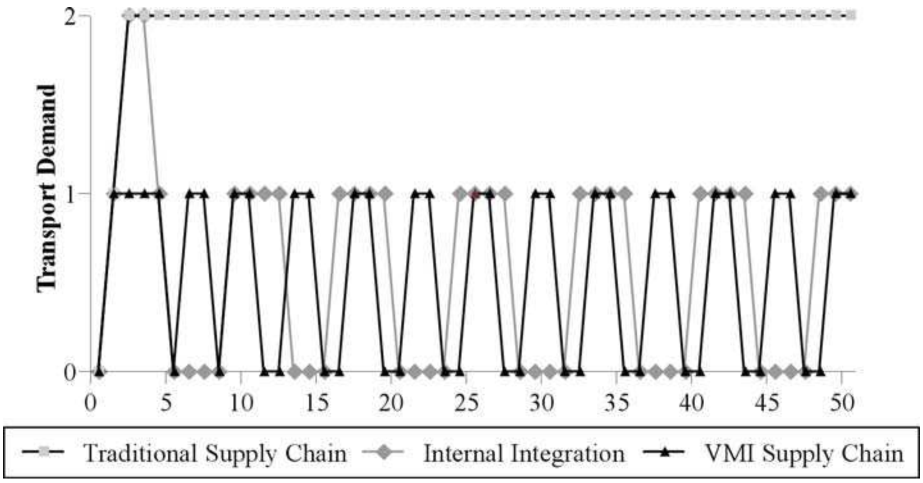

Figure 6. Transport demand for the three scenarios

Whilst the above analysis provides a clear insight into the impact on transport demand, the effect on transport costs is not so obvious. Transport costs comprise of two elements relating to the provision of assets for a service and the costs incurred in using them. Traditionally, these are regarded as fixed and variable costs. However, this paper will use the concept of escapability (Doganis, 1991). The escapability of a cost is determined by the time needed for it to be avoided. Some costs are immediately escapable, whilst some can only be avoided in the long term. Ultimately, all costs are escapable. Table 1 provides a summary of costs associated with road haulage, classifying them according to whether they are escapable in the short or long term. Similar costs would be incurred by other modes of transport although the time taken to escape them may differ. In this paper, those costs that cannot be avoided in the short term have been described as inescapable.

Escapable in the short term	Escapable in the long term
Fuel Day-to-day maintenance Subcontracted vehicle costs	Depreciation Property Rent Vehicle servicing Licences Insurance Interest Wages

Table 1. The escapability of costs for road haulage (adapted from Lowe, 1989)

The total daily transport cost is made up of both escapable and inescapable components, and can be summarised by the following equation:

$$C = f.n + v.l \qquad [1]$$

Where C is the total cost, f and v are the escapable and inescapable components respectively, n is the total number of vehicles in the fleet and l is the number of loaded vehicles. If the transport operation was provided in house, these costs would be clearly visible. If sourced from a third party, the rates are likely to be based either on a per tonne basis or as a fixed quantity per load. Either way, these will be set so as to cover the escapable and inescapable elements. Equation 1 applies both in the traditional and VMI scenarios, thus:

$$C_{TRAD} = f.n_{TRAD} + v.l_{TRAD} \qquad [2]$$

$$C_{VMI} = f.n_{VMI} + v.l_{VMI} \qquad [3]$$

If a company implements VMI within the supply chain then, in the short term, the fleet of vehicles would be the same size for both situations. This is because of vehicle divestment is unlikely to occur immediately. Therefore, the difference in transport costs, δ, can be calculated (it has been assumed that the escapable and inescapable costs are identical for both scenarios):

$$\begin{aligned}\delta &= C_{TRAD} - C_{VMI}\\ &= f.n_{TRAD} + v.l_{TRAD} - f.n_{VMI} - v.l_{VMI}\end{aligned}$$

Given that in the short term, $n_{TRAD} = n_{VMI}$,

$$\begin{aligned}\delta &= v.l_{TRAD} - v.l_{VMI}\\ &= v\,(l_{TRAD} - l_{VMI}) \qquad [4]\end{aligned}$$

As shown in Figure 6, fewer truckloads are required if despatches in VMI are batched. Therefore,

$$l_{TRAD} > l_{VMI} \qquad [5]$$

$$\delta > 0 \qquad [6]$$

This means that, regardless of the values for the escapable and inescapable costs, the overall total cost in a VMI supply chain is less than the traditional scenario in the short term.

In the longer term, when more costs become escapable, the opportunity may be taken to adjust the fleet size, so as to increase utilisation of the assets. Although the full capacity of the vehicles is used every time a despatch is made, the vehicles themselves may not be used every time period. This is likely to result in the VMI scenario using fewer vehicles than the traditional supply chain, with higher fleet utilisation. Once again, there are cost implications:

$$\begin{aligned}\delta &= C_{TRAD} - C_{VMI}\\ &= f.n_{TRAD} + v.l_{TRAD} - f.n_{VMI} - v.l_{VMI}\\ &= f\,(n_{TRAD} - n_{VMI}) + v\,(l_{TRAD} - l_{VMI})\end{aligned}$$

Given that equation 5 still holds true, and

$$\begin{aligned} & n_{TRAD} > n_{VMI} \\ \text{Then} \quad & (n_{TRAD} - n_{VMI}) > 0 \\ & (l_{TRAD} - l_{VMI}) > 0 \\ \text{Therefore,} \quad & \delta > 0 \qquad [7] \end{aligned}$$

This shows that the VMI scenario again produces the lowest cost solution with respect to transport costs, and includes differences in both escapable and inescapable costs. Further, fleet utilisation will increase as fewer vehicles are moving the same volume of goods. Depending upon the change in fleet size, it is possible to increase the total fleet utilisation above that in traditional situations. This provides further benefits for the transport company as expensive assets are spending less time standing idle.

The above discussion is based around the results produced when a step input represented the demand signal. To verify that the findings hold true for an alternative demand signal, the model was run again but with a random demand signal. Again, the transportation quantity has been set equal to four units, representing the capacity of one vehicle. The graph in Figure 7 shows the goods in transit and transport demand for the traditional and VMI scenarios over a 30 day period. It was decided not to model the internal integration scenario, as the transport output would be similar to that for the VMI supply chain. Given that total transport cost will be a function of the area under the graphs, it can be seen that a large amount of the costs incurred through a traditional supply chain can be escaped by implementing VMI.

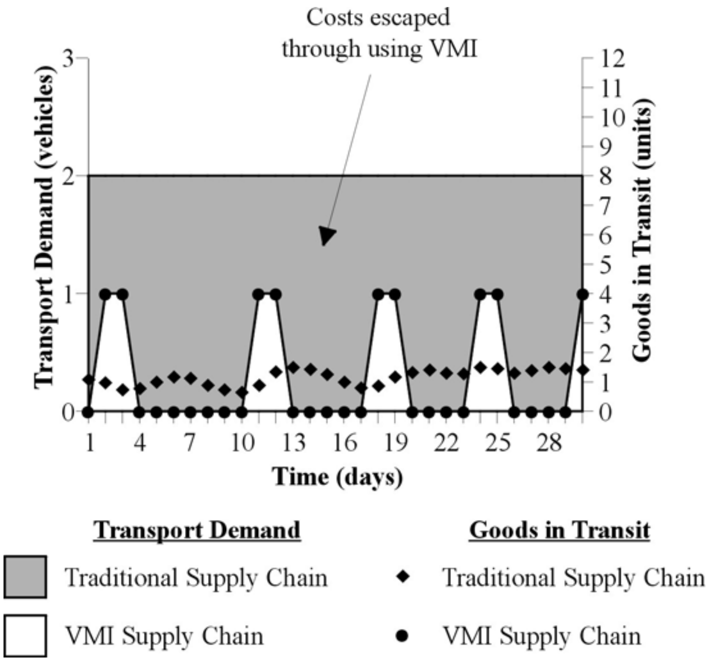

Figure 7. The transport costs escaped by using VMI

Limitations to the model

There are several limitations to the above modelling that the reader should be aware of. The models assume that the lead time is fixed between the manufacturer and distributor. In reality, there may be some variance, often due to external influences such as traffic congestion or vehicle failure.

Additionally, in some circumstances it may be possible to use alternative modes of transport for shipment, and this would have an effect not only on the lead time but also the economic transport quantity. The models also do not include any manufacturing or transport constraints, both of which will affect the dynamic response of the models. Finally, external consolidation may occur in the traditional supply chain, but this has not been modelled due to the need to model more than one supplier and create a spatial dimension.

Conclusion

By investigating a generic two level supply chain model, in traditional serially linked or VMI mode, we have highlighted some very interesting ‘emergent properties’ of VMI in relation to the transport operations and order batching activities. The purpose of using simulation is to provide a simplified environment into which a number of situations and ideas can be tested. Although the basis for the model here is generic, its components (both the manufacturing and VMI elements) have been found to be representative of current industrial practice. Therefore, the results that have been achieved here are repeatable (maybe to a lesser or greater extent) in most industrial settings.

Three different scenarios were modelled – a traditional supply chain, an internal consolidation scenario (with batching in the order rule) and the VMI supply chain. Whilst the traditional scenario creates a smooth dynamic response, there is a penalty with regards to transport demand as it is necessary to despatch products every time period, regardless of the volume available. Conversely the internal integration scenario reduces the level of transport demand by only despatching full vehicle loads, but this has a detrimental effect on the dynamic response of the system, adding extra manufacturing costs.

The VMI supply chain enables a smoother dynamic response than that associated with the traditional supply chain, enabling a reduction in manufacturing on-costs. However, it incorporates the batching of transport despatches that has a significant distortion effect on the dynamic response of the internal integration scenario. Therefore, it circumnavigates the trade off between improved dynamic properties (reducing manufacturing costs) and the minimisation of transport demand. Using the concept of escapability, the paper has shown that transport cost savings are achievable both in the short and long term when comparing the traditional and VMI supply chains. This saving is independent of the level of escapable and inescapable costs. It is these insights into the impact of VMI on transportation that provides the contribution of this paper to the literature.

Subsequent research will be directed towards the policy implications of our findings. For example, what types of supply chains are best suited to VMI? What are the learning requirements for distribution and production schedulers? This will involve the use of case studies, from which it should be possible to fully quantify the benefits that VMI can deliver.

Appendix A. Difference equations required for the two level APIOBPCS model

The definitions and values for the parameters Tp_1, $\overline{Tp_1}$, Tp_2, $\overline{Tp_2}$, Ta_1, Ti_1, Tw_1, Ta_2, Ti_2, Tw_2 and ETQ can be found in Appendix C.

Description	Difference Equation	Initial conditions~
Distributor's actual WIP	$WIP_t = WIP_{t-1} + ORATE_t - COMRATE_t$	0
Distributor's completion rate	$COMRATE_t = ORATE_{t-(Tp_1)},$	0 for Tp time units
Distributor's desired WIP	$DWIP_t = AVCON_t * T\overline{p_1}$	NA
Distributor's error in system inventory levels	$EINV_t = TINV_t - SINV_t$	NA
Distributor's error in WIP	$EWIP_t = DWIP_t - WIP_t$	NA
Distributor's forecasted consumption	$AVCON_t = AVCON_{t-1} + \frac{1}{1+Ta_1}(CONS_t - AVCON_{t-1})$	0
Distributor's inventory levels	$AINV_t = AINV_{t-1} + COMRATE_t - CONS_t$	0
Distributor's order rate	$ORATE_t = AVCON_{t-1} + \frac{EINV_{t-1}}{Ti_1} + \frac{EWIP_{t-1}}{Tw_1}$	0
Distributor's typical target inventory	$TINV_t = 0$	NA
Manufacturer's Actual WIP	$MWIP_t = MWIP_{t-1} + MORATE_t - MCOMRATE_t$	0
Manufacturer's Completion rate	$MCOMRATE_t = MORATE_{t-(Tp_2)},$	0 for Tp time units
Manufacturer's Desired WIP	$MDWIP_t = MAVCON_t * T\overline{p_2}$	NA
Manufacturer's error in inventory levels	$MEINV_t = MTINV_t - MAINV_t$	NA
Manufacturer's Error in WIP	$MEWIP_t = MDWIP_t - MWIP_t$	NA
Manufacturer's forecasted consumption	$MAVCON_t = MAVCON_{t-1} + \frac{1}{1+Ta_2}(ORATE_t - MAVCON_{t-1})$	0
Manufacturer's Inventory levels	$MAINV_t = MAINV_{t-1} + MCOMRATE_t - ORATE_t$	0
Manufacturer's Order rate	$MORATE_t = MAVCON_{t-1} + \frac{MEINV_{t-1}}{Ti_2} + \frac{MEWIP_{t-1}}{Tw_2}$	0
Manufacturer's typical target inventory	$MTINV_t = 0$	NA
Typical test input	$CONS_t = \left\{\begin{matrix} 0 \text{ if } t < 0 \\ 1 \text{ if } t >= 0 \end{matrix}\right\}$, for a step input	NA
Goods in Transit	$GIT_t = \sum_{i=t}^{i=t-Tp1+1} ORATE_i$	0
Number of Vehicles	$VEH_t = \frac{DES_t}{ETQ_t}$, rounded up to nearest integer	NA
Transport Demand	$TDEM_t = \sum_{i=t}^{i=t-Tp1+1} VEH_i$	0

Table A1. Difference equations required for modelling a two level APIOBPCS supply chain

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~ when modelling the response to a unit step input

Appendix B. Difference equations required for the proposed integrated VMI system

The definitions and values for the parameters Tp_1, Tp_2, $\overline{Tp_2}$, Ta_1, G, Ta_2, Ti_2, Tw_2 and ETQ can be found in Appendix C.

Description	Difference Equation	Initial settings[~]
Forecasted Re-order point at the distributor	$R_t = R_{t-1} + \frac{1}{1+Tq}((G * CONS_t) - R_{t-1})$	0
Order-up-to point at the distributor	$O_t = R_t + TQ_t$	NA
Distributor's inventory level	$AINV_t = AINV_{t-1} - CONS_t + DES_{t-Tp_1}$	0
Goods In Transit between echelons	$GIT_t = \sum_{i=t}^{i=t-Tp_1+1} DES_i$	0
Despatches	$DES_t = \begin{Bmatrix} TQ_{t-1} \text{ if } DINV_{t-1} + GIT_{t-1} < R_{t-1} \\ 0 \text{ if } DINV_{t-1} + GIT_{t-1} >= R_{t-1} \end{Bmatrix}$	0
Transport quantity	$TQ_t = CONS_t \text{or } ETQ_t$	4
System inventory levels	$SINV_t = MINV_t + GIT_t + AINV_t - R_t$	NA
Manufacturer’s inventory levels	$MINV_t = MINV_{t-1} + COMRATE_t - DES_t$	0
Virtual consumption	$VCON_t = CONS_t + dSS_t$	NA
Net changes in the distributor's re-order point	$dSS_t = R_t - R_{t-1}$	0
Forecasted consumption for the manufacturer	$MAVCON_t = MAVCON_{t-1} + \frac{1}{1+Ta_2}(VCON_t - MAVCON_{t-1})$	0
Manufacturer’s desired WIP	$MDWIP_t = MAVCON_t * \overline{Tp_1}$	NA
Manufacturer’s actual WIP	$MWIP_t = MWIP_{t-1} + MORATE_t - MCOMRATE_t$	0
Manufacturer’s error in WIP	$MEWIP_t = MDWIP_t - MWIP_t$	NA
Manufacturer’s order rate	$MORATE_t = MAVCON_{t-1} + \frac{MEINV_{t-1}}{Ti_2} + \frac{MEWIP_{t-1}}{Tw_2}$	0
Manufacturer’s completion rate	$MCOMRATE_t = MORATE_{t-Tp_2}$	0 for Tp time units
Error in system inventory levels	$EINV_t = TINV_t - SINV_t$	NA
Typical test input	$CONS_t = \begin{Bmatrix} 0 \text{ if } t < 0 \\ 1 \text{ if } t >= 0 \end{Bmatrix}$, for a step input	NA
Typical target inventory	$TINV_t = 0$	NA
Number of Vehicles	$VEH_t = \frac{DES_t}{ETQ_t}$, rounded up to nearest integer	NA
Transport Demand	$TDEM_t = \sum_{i=t}^{i=t-Tp_1+1} VEH_i$	0

Table B1. Difference equations required for modeling VMI as an integrated system in a spreadsheet

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[~] when modelling the response to a unit step input

Appendix C. Parameter values for the supply chain models

These are the parameter values that have been used in the above models. The pipeline parameters are the same for both supply chains and are directly proportional to the lead times for the distributor and manufacturer. The dynamic parameters have been selected as they have been demonstrated to deliver the optimum performance for each system (John et al., 1994; Disney, 2001).

		APIOBPCS	**VMI-APIOBPCS**
Pipeline Parameters	Distributor's lead time, Tp_1	2	2
	Distributor's perceived lead time, $\overline{Tp_1}$	2	NA
	Manufacturer's lead time, Tp_2	4	4
	Manufacturer's perceived lead time, $\overline{Tp_2}$	4	4
Dynamic Parameters	Distributor's time to average sales, Ta_1	8	6
	Distributor's time to adjust inventory, Ti_1	4	NA
	Distributor's time to adjust WIP, Tw_1	8	NA
	Distributors safety stock gain, G	NA	1
	Manufacturer's time to average sales, Ta_2	8	6
	Manufacturer's time to average inventory, Ti_2	4	7
	Manufacturer's time to average WIP, Tw_2	8	42
Transport Parameter	Economic Transport Quantity, ETQ	4	4

Table C1. Parameters for the APIOBPCS and VMI-APIOBPCS models

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