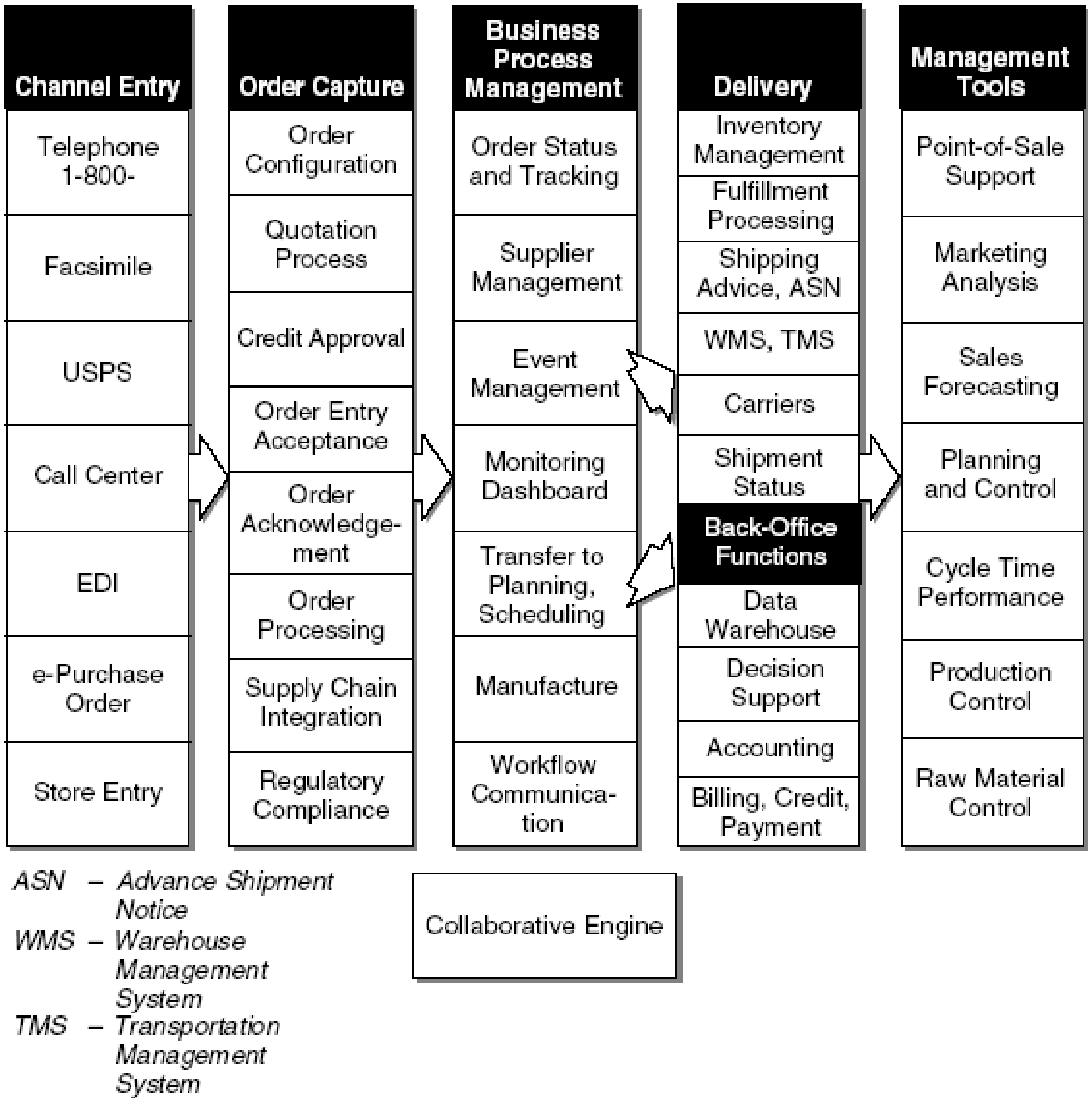
SUPPLY CHAIN , ORDER & INVENTORY MANAGEMENT

- The concept of customer order management (COM) as an important function of supply chain management remains elusive and is generally given second-priority attention. This is a mistake as attention to COM and the related issue of inventory management will have a high business payback.
- Included in the contemporary concept of supply chain order management are the process steps of error-free order entry, credit management, order processing, pricing, available-to-promise, tracking fulfillment, billing, invoicing, accounting, and accounts receivable processing.
- When the orientation of these steps is toward achieving greater customer satisfaction, as well as profit improvement, the idea of customer order management emerges.

- Can the firm, through its order management processing, respond quickly and accurately in a manner acceptable to its best customers?
- Are there any measurements that validate high performance with the system?
- Will the customer receive a good response, regardless of the channel through which the order was received — sales representative, telephone or fax contact, EDI, Web-based ordering, or store purchase?
- Is there credibility in the promises being made? Do false expectations get entered before processing begins?
- Are tools available to determine an accurate and reliable commitment is being made?
- How many errors and mistakes exist in the current system?
- How much time is spent cleansing these problems and reconciling them within the organization and with customers?
- Is the cost to accept and fill an order documented? If the costs are reduced through automation or e-commerce, will the savings be real or will the process simply be improved?
- Is there a profit in each and every order? Are there parameters to determine how to link pricing to customers and orders?

ELEMENTS OF ORDER MANAGEMENT CONTROL



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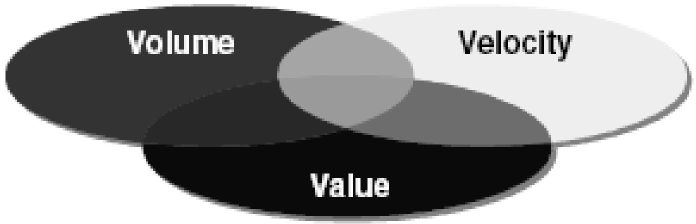


Volume pertains to the amount of physical inventory a company owns at any given time across the supply chain

Key Question: How much and what types of inventory do we own?

Key Measures: Total units, total pounds

Activities Affecting Volume: Improved forecasting techniques, supplier-provided consignment inventory

Value pertains to the unit cost and total dollar value of inventory

Key Question: What is the unit cost and total value of the different types of inventory we own?

Key Measures: Total dollars, period-by-period unit value changes, ratio of sales to working capital

Activities Affecting Volume: Product simplification and standardization, leverage purchase agreements

Velocity pertains to how quickly raw material and WIP become finished goods that are accepted and paid for by the customer

Key Question: How fast do we move inventory toward the customer?

Key Measures: Inventory turns, material throughput rates, order-to-cash cycle time

Activities Affecting Velocity: Lean supply chain practices; make-to-order production

Working Capital Reduction	Increased Profitability	Increased Customer Satisfaction	Improved Asset Return

Performance Results

Principle	Key Learnings Position	Current	Next Steps	Priority
Employ Configuration Tools	• Use configuration tools that provide a seamless user interface • Select configuration tools designed to meet the specific challenges posed by your company's business processes • Employ standardized question sets to improve the order entry process • Combine order configuration and back-office applications to respond more quickly and effectively to customer requests • Identify point solutions that can be integrated into existing systems to minimize expenses			
Incorporate Quote Optimization and Point-of-Sale Support	• • Incorporate product visualization tools to enhance the selling process Employ electronic quote system that integrates the quote process with the order entry process Improve sales performance by increasing the sales team's ability to configure and price new or complex products Enable sales people to perform complex pricing calculations in the field			
Develop Alternative Order Entry Channels	• • Consider scanning technology for an easy, low-cost order entry alternative Provide alternative channels for order entryto reach a wider customer base Create global order entry stations to allow customers to place orders around the clock Deploy Internet-based order entry technologies that allow for configuration checks and supplier links			
Utilize the Order Entry System for Scheduling and Forecasting	• • Enter orders into a relational database to improve forecasting systems Integrate production planning and orderentry systems to provide accurate scheduling information Employ real-time, Internet-based order entry programs that allow configuration, constraint verification and production scheduling Align the order entry system with customer service and forecasting to ensure customers receive optimal service			

. ELEMENTS OF GOOD COM

- Contemporary thinking schools that this management begins with a classification of the inventory needed to support the orders, not just by category or value of the goods, including the risks and potential returns on the inventory. Inventory management is a process step basically oriented around decisions on when goods should be available, in what specification, and in what quantity.
- The return on holding goods in inventory becomes a function of the sales volume eventually derived and the profit margin received, allowing for the cost of carrying the inventory.
- The risk is a function of carrying too little or too much stock, which can result in back orders, emergency shipments, lost sales, and price discounts. Under best-case conditions, where the demand is well known, these costs are minimal. Under conditions of uncertainty, they can be the difference between profit and loss for small-margin businesses.

We consider a supply chain that consists of an arbitrary number of stages and stockpoints in which a product passes through multiple production sites before it is finally delivered to outside customers.

This supply chain is planned and controlled by a central decision authority that has access to all relevant status information (like inventory levels and work-in-process quantities) at all production sites and makes release decisions for the entire supply chain.

The release decisions result from a deterministic mathematical programming model that is solved in a rolling horizon setting (Stadtler and Kilger 2005), which has been implemented in an Advanced Planning and Scheduling system. For these kinds of planning models, safety stocks are input parameters that have to be determined externally.

Formulation of the planning problem by a mathematical programming model assumes a deterministic view of supply chain planning by considering all model parameters, as demand, lead times, production rates to be known with complete certainty.

This assumption of complete and deterministic information is desirable from a model complexity point of view, but given the dynamic and uncertain nature of most supply chains, this assumption is violating reality.

Demand uncertainty is an important factor to be considered in supply chain planning, and therefore, safety stocks are kept to cover part of the demand uncertainties

The core function of supply chain planning models is to coordinate material and resource release decisions in the supply chain such that predefined customer service levels are achieved with minimal costs.

Safety stocks are kept to deal with demand uncertainties and consequently to increase service levels. The service level is an increasing function of the safety stock level.

Therefore, more safety stocks are needed to increase the service level, which results in increased inventory holding costs. .

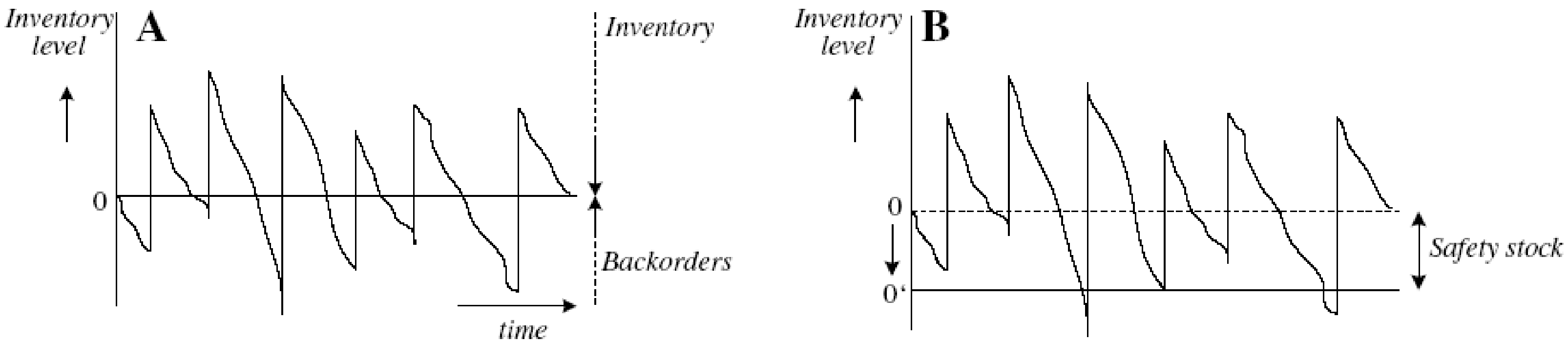
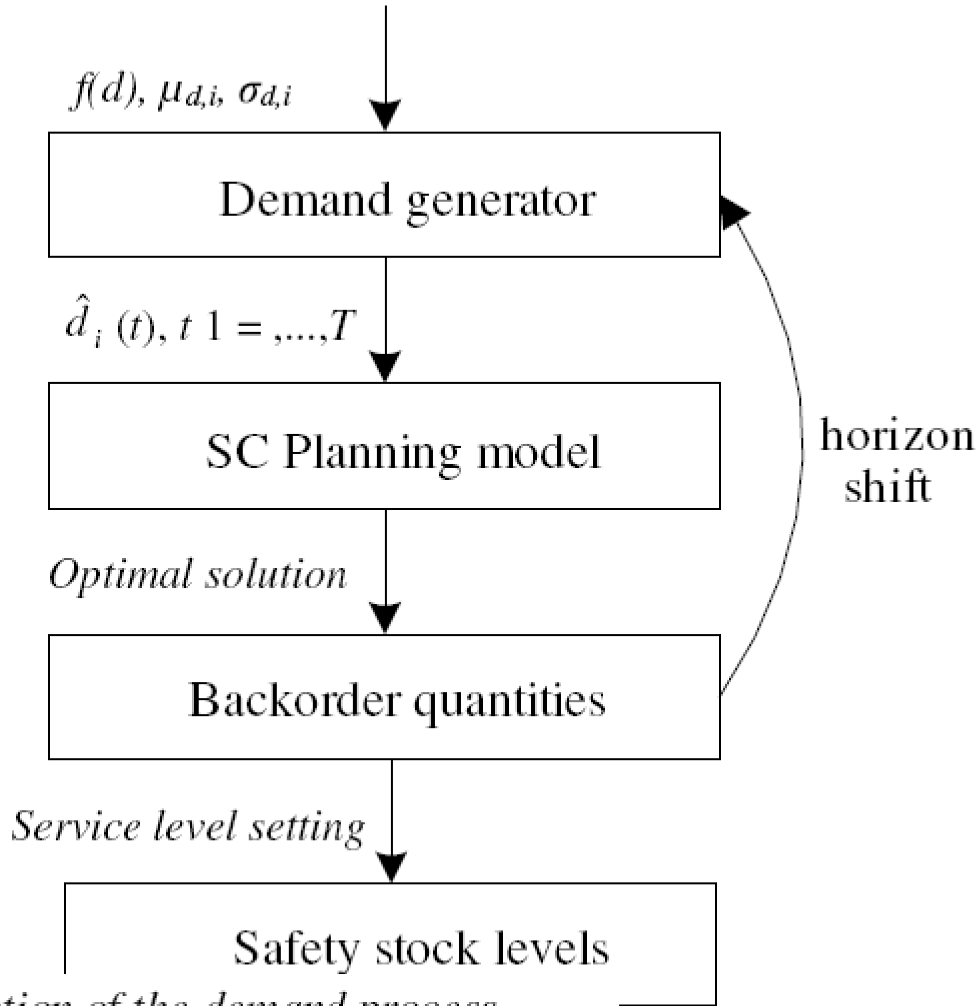


Fig. 1 The inventory development of a certain product; **a** shows the results of simulation runs and **b** shows how the horizontal axis is shifted to limit the number of backorders, i.e. to achieve a certain customer service level

THE APPROACH FOR MODELING



$f(d)$	*probability density function of the demand process*
$\mu_{d,i}$	*Expected (exogenous) demand of end-item i*
$\sigma_{d,i}$	*Standard deviation of forecast errors of end-iem i*
T	*Planning horizon*
$\hat{d}_i(t)$	*Forecast of demand of end-item i in period t(t=1,...,T)*

Suppose that we have historical sales data of n time periods, then $\mu_{d,i}$ can be calculated by

$$\mu_{d,i} = \frac{1}{n} \sum_{s=-n}^{-1} d_i(t+s) \qquad (1)$$

where $d_i(t)$ is the demand for item i in period t. Forecast errors can be determined by several measures (Silver et al. 1998). The Mean Absolute Deviation (MAD) is recommended for its computational simplicity. The MAD for item i as function of the forecast horizon h can be calculated by

$$\mathrm{MAD}_i(h) = \frac{1}{T} \sum_{s=-T}^{-1} \left(d_i(t+s) - \hat{d}_i(t+s-h, t+s) \right) \qquad (2)$$

where T is the length of the planning horizon, $d_i(t)$ the demand for item i in period t, and $\hat{d}_i(t-h,t)$ the forecast made in period $t-h$ for the demand in period t. It is reasonable to assume that the MAD is an increasing function of the forecast horizon h (Heath and Jackson 1994). The conversion of $\mathrm{MAD}_i(h)$ to $\sigma_i(h)$ is extensively discussed in Silver et al. (1998). Having determined the parameters of the demand distribution, the random generator can generate a series of forecasts of the demand $\hat{d}_i(t)$ for $t = 1, \ldots, T$. The generated forecasts are input for the supply chain planning model.

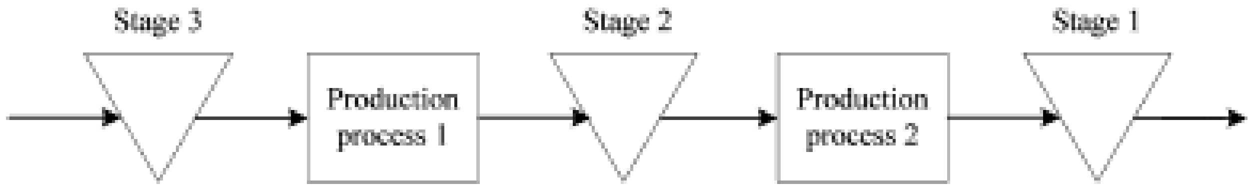


Fig. 3 A three-stage supply chain considered in the supply chain planning model

$$
\begin{aligned}
\text{Min TC} = &\sum\nolimits_{n_1} \sum_{t=1}^{T} c_1 \cdot \text{UD}_{n_1}(t) + \sum\nolimits_{n_1} \sum_{t=1}^{T} c_2 \cdot \text{OP}_{n_1} \cdot \text{BM}_{n_1}(t) \\
&+ \sum\nolimits_{n_1} \sum_{t=1}^{T} c_3 \cdot \text{EI}_{n_1}(t) + \sum\nolimits_{n_2} \sum_{t=1}^{T} c_4 \cdot \text{UD}_{n_2}(t) \\
&+ \sum\nolimits_{n_2} \sum_{t=1}^{T} c_5 \cdot \text{UDD}_{n_2}(t) + \sum\nolimits_{n_2} \sum_{t=1}^{T} c_6 \cdot \text{BC}_{n_2}(t) \\
&+ \sum\nolimits_{n_2} \sum_{t=1}^{T} c_7 \cdot \text{EI}_{n_2}(t) + \sum\nolimits_{n_3} \sum_{t=1}^{T} c_8 \cdot \text{UD}_{n_3}(t) \\
&+ \sum\nolimits_{n_3} \sum_{t=1}^{T} c_9 \cdot \text{UDD}_{n_3}(t) + \sum\nolimits_{n_3} \sum_{t=1}^{T} c_{10} \cdot \text{EI}_{n_3}(t) \qquad (3)
\end{aligned}
$$

The first three terms of the objective function are related to the first stage in the supply chain. For this stage, we consider three cost factors that have to be minimized. The first terms are costs associated with unsatisfied demand (backorders) $c_1 \cdot \mathrm{UD}_{n_1}(t)$ where $\mathrm{UD}_{n_1}(t)$ is the backorder quantity for item n_1 in period t. The second term deals with costs for replenishing a quantity that deviates from the (minimum) replenishment quantity $c_2 \cdot \mathrm{OP}_{n_1} \cdot \mathrm{BM}_{n_1}(t)$. OP_{n_1} is the period order quantity for item n_1 and $\mathrm{BM}_{n_1}(t)$ the deviation from the minimum replenishment quantity for item n_1 in period t. Campaign sizes are determined based on a trade-off between ordering costs and inventory holding costs, whereas batch sizes are quantities that are determined by legislative authorities. Therefore, producing in fixed batch sizes is required, whereas deviating from the campaign size is undesired. The third term is the total inventory holding cost at this stage $c_3 \cdot \mathrm{EI}_{n_1}(t)$ where $\mathrm{EI}_{n_1}(t)$ is the inventory level of item n_1 at the end of period t.

For the second stage of the supply chain, four cost factors are considered. The first terms sum backorders that result from exogenous demand at this stage. So, $c_4 \cdot \mathrm{UD}_{n_2}(t)$ is unsatisfied demand (backorder) costs for item n_2 in time period t, whereas the second term $c_5 \cdot \mathrm{UDD}_{n_2}(t)$ considers unsatisfied demand (backorders) that result from endogenous (derived) demand from the first stage of the supply chain. Since the second stage in the supply chain considers the production of tablets in campaigns (a fixed multiple of batch sizes), the third term $c_6 \cdot \mathrm{BC}_{n_2}(t)$ considers costs associated with deviating from the fixed campaign size $\mathrm{BC}_{n_2}(t)$ for item n_2 in period t. The fourth term considers the total inventory holding costs for item n_2.

The third stage in the supply chain considers three cost factors: costs associated with unsatisfied demand (backorders) of exogenous demand $c_8 \cdot \mathrm{UD}_{n_3}(t)$, costs associated with unsatisfied demand (backorders) that result from endogenous demand (from the second stage of the supply chain) $c_9 \cdot \mathrm{UDD}_{n_3}(t)$, and total inventory holding costs $c_{10} \cdot EI_{n_3}(t)$ of item n_3. For confidentially reasons, we cannot show the values of the cost parameters, except that $c_1 > c_2 > \cdots > c_{10}$. The determination of these cost parameters was not part of this study, as they can be taken over from the objective function of the supply chain planning model.

The objective function (3) is minimized subject to several constraints, which are discussed below per stage in the supply chain. Equations (4) are materials balance equations with $\mathrm{EI}_{n_1}(t)$ is the inventory level of item n_1 at the end of period t, $TR_{n_1}(t)$ the replenishment quantity of item n_1 in period t, and $\mathrm{TD}_{n_1}(t)$ the (exogenous) demand for item n_1 in period t. The latter parameter contains data that are input to the planning model. Further, $\mathrm{EI}_{n_1}(0)$ is the initial inventory level.

$$\mathrm{EI}_{n_1}(t) = \mathrm{EI}_{n_1}(t-1) + \mathrm{TR}_{n_1}(t) - \mathrm{TD}_{n_1}(t), \quad n_1 = 1, \ldots, N_1, \;\; t = 1, \ldots, T \qquad (4)$$

Equation (5) determine the minimum replenishment quantity for item n_1 in period t, as the replenishments are based on periodic order quantity (OP). $ID_{n_1}(t)$ is the (forecast of) independent demand for item n_1 in period t.

$$\mathrm{MR}_{n_1}(t) = \sum_{i=1}^{\mathrm{OP}} ID_{n_1}(t+i), \quad n_1 = 1, \ldots, N_1, \ \ t = 1, \ldots, T \qquad (5)$$

Having determined the minimum replenishment quantity, Eq. (6) determine the real replenishment quantities $\mathrm{SM}_{n_1}(t)$ for item n_1 in period t. $\mathrm{BM}_{n_1}(t)$ is then the deviation from minimum replenishment quantity for item n_1 in period t that is considered in the objective function.

$$\mathrm{SM}_{n_1}(t) = \mathrm{MR}_{n_1}(t) - \mathrm{BM}_{n_1}(t), \quad n_1 = 1, \ldots, N_1, \ \ t = 1, \ldots, T \qquad (6)$$

The total replenishment quantity for item n_1 for the entire planning horizon (TR_{n_1} (t)) is determined by two parts: $\mathrm{SM}_{n_1}(t)$ which we have just discussed and $\mathrm{FP}_{n_1}(t)$ which are fixed replenishment quantities of item n_1 in period t determined in previous solving rounds. The binary parameter α regulates that within the lead time of the planning horizon no new decisions are taken.

$$\mathrm{TR}_{n_1}(t) = \alpha \cdot SM_{n_1}(t) + (1-\alpha) \cdot \mathrm{FP}_{n_1}(t), \quad n_1 = 1, \ldots, N_1,$$

$$t = 1, \ldots, T, \ \alpha = \begin{cases} 0 & if \ t \leqslant L \\ 1 & if \ L < t \leqslant T \end{cases} \tag{7}$$

Equation (8) determine which part of the exogenous demand $\mathrm{ID}_{n_1}(t)$ for item n_1 in period t is satisfied ($\mathrm{SD}_{n_1}(t)$). The unsatisfied demand quantity $\mathrm{UD}_{n_1}(t)$ for item n_1 in period t is punished in the objective function.

$$\mathrm{SD}_{n_1}(t) = \mathrm{ID}_{n_1}(t) - \mathrm{UD}_{n_1}(t), \quad n_1 = 1, \ldots, N_1, \; t = 1, \ldots, T \tag{8}$$

Equation (9) are equations for $\mathrm{TD}_{n_1}(t)$ which is determined by $\mathrm{SD}_{n_1}(t)$ that result from Eq. (8) plus $\mathrm{UD}_{n_1}(t-1)$ which is the unsatisfied demand in $t-1$, i.e. backorder quantity for item n_1 from period t.

$$\mathrm{TD}_{n_1}(t) = \mathrm{SD}_{n_1}(t) + \mathrm{UD}_{n_1}(t-1), \quad n_1 = 1, \ldots, N_1, \; t = 1, \ldots, T \tag{9}$$

Several constraints apply to stage 2 which will be discussed now. Like in stage 1, Eq. (10) are the balance equations for the materials flow. The symbols have the same meaning as in stage 1, except that indices show that the equations apply to this particular stage.

$$\mathrm{EI}_{n_2}(t) = \mathrm{EI}_{n_2}(t-1)+\mathrm{TR}_{n_2}(t)-\mathrm{TD}_{n_2}(t), \quad n_2=1,\ldots,N_2,\ \ t=1,\ldots,T \qquad (10)$$

Equation (11) determine the total replenishment quantity for item n_2 in period t where α is the same binary parameter that is used in Eq. (7). $PP_{n_2}(t)$ is the production quantity to be produced of item n_2 in t and $\mathrm{FP}_{n_2}(t)$ are firmed production quantities that are determined in previous solving rounds.

$$TR_{n_2}(t) = \alpha \cdot PP_{n_2}(t) + (1-\alpha) \cdot FP_{n_2}(t), \quad n_2 = 1, \ldots, N_2, \;\; t = 1, \ldots, T \tag{11}$$

Equation (12) require that the production quantity of item n_2 to be produced in period t must be an integer multiple of Q_{n_2}, the batch size of item n_2 multiplied by y_{n_2}, the yield factor of the production process that produces item n_2.

$$\mathrm{PP}_{n_2}(t) = Q_{n_2} \cdot y_{n_2} \cdot \mathrm{NB}_{n_2}(t), \quad n_2 = 1, ..., N_2, \;\; t = 1, \ldots, T, \tag{12}$$

with $NB_{n_2}(t) \in \mathrm{N}_0$.

Equation (13) determine the derived (endogenous) demand at stage 2. This is the multiplication of the (with lead time L shifted) replenishment quantities of items n_1 with the BOM factor.

$$\mathrm{DD}_{n_2}(t) = \mathrm{BOM}_{n_2,n_1} \cdot \sum_{n_1} \mathrm{SM}_{n_1}(t-L), \quad n_2 = 1, \ldots, N_2, \; t = 1, \ldots, T \qquad (13)$$

Equation (14) determine the costs associated with going below the campaign size $\mathrm{BC}_{n_2}(t)$, which is punished in the objective function. CS_{n_2} is the campaign size (a certain number of batches of n_2) of item n_2.

$$\mathrm{BC}_{n_2}(t) = \mathrm{CS}_{n_2} - \mathrm{NB}_{n_2}(t), \quad n_2 = 1, \ldots, N_2, \; t = 1, \ldots, T, \qquad (14)$$

with $\mathrm{BC}_{n_2}(t) \in \mathrm{N}_0$.

Unsatisfied demand from $t-1$ (resulting from either exogenous demand $\mathrm{UD}_{n_2}(t-1)$ or endogenous demand $\mathrm{UDD}_{n_2}(t-1)$ determine the backorder quantity $\mathrm{BO}_{n_2}(t)$ of item n_2 in period t.

$$\mathrm{BO}_{n_2}(t) = \mathrm{UDD}_{n_2}(t-1) + \mathrm{UD}_{n_2}(t-1), \quad n_2 = 1, \ldots, N_2, \;\; t = 1, \ldots, T \qquad (15)$$

Equation (16) show that the satisfied part of demand for item n_2 in period t $\mathrm{SD}_{n_2}(t)$ is equal to the exogenous demand $\mathrm{ID}_{n_2}(t)$ for item n_2 in period t minus unsatisfied demand quantity $\mathrm{UD}_{n_2}(t)$ for item n_2 in period t, which is punished in the objective function.

$$\mathrm{SD}_{n_2}(t) = \mathrm{ID}_{n_2}(t) - \mathrm{UD}_{n_2}(t), \quad n_2 = 1, \ldots, N_2, \;\; t = 1, \ldots, T \qquad (16)$$

Equation (17) are the application of the same idea (as Eq. 16) to the dependent (endogenous) demand for item n_2 in period t.

$$\mathrm{SDD}_{n_2}(t) = \mathrm{DD}_{n_2}(t) - \mathrm{UDD}_{n_2}(t), \quad n_2 = 1, \ldots, N_2, \ t = 1, \ldots, T \qquad (17)$$

The sum of $\mathrm{SD}_{n_2}(t)$, $\mathrm{SDD}_{n_2}(t)$, and the backorders for item n_2 in period t $\mathrm{BO}_{n_2}(t)$ are equal to $\mathrm{TD}_{n_2}(t)$, total demand for item n_2 in period t.

$$\mathrm{TD}_{n_2}(t) = \mathrm{SDD}_{n_2}(t) + \mathrm{SD}_{n_2}(t) + \mathrm{BO}_{n_2}(t), \quad n_2 = 1, \ldots, N_2, \ t = 1, \ldots, T \qquad (18)$$

Constraints (19) till (26) apply to the third stage of the supply chain. Equation (19) are the balance equations for this stage. $\mathrm{EI}_{n_3}(t)$ is the inventory level of item n_3 at the end of period t, $\mathrm{TR}_{n_3}(t)$ is the replenishment quantity of item n_3 in period t, and $\mathrm{TD}_{n_3}(t)$ is the total demand of item n_3 in period t.

$$\mathrm{EI}_{n_3}(t) = \mathrm{EI}_{n_3}(t-1)+\mathrm{TR}_{n_3}(t)-\mathrm{TD}_{n_3}(t), \quad n_3=1,\ldots,N_3, \;\; t=1,\ldots,T \qquad (19)$$

The replenishment quantity $\mathrm{TR}_{n_3}(t)$ is partly determined in the previous solving rounds ($\mathrm{FP}_{n_3}(t)$, firm planned replenishment orders for item n_3 in period t) and new released orders $O_{n_3}(t)$ to be determined for item n_3 in period t. The orders are sent to (external) supplier(s).

$$\mathrm{TR}_{n_3}(t) = (1-\alpha)\cdot \mathrm{FP}_{n_3}(t) + \alpha \cdot O_{n_3}(t), \quad n_3 = 1,\ldots,N_3, \;\; t = 1,\ldots,T \qquad (20)$$

Furthermore, constraints (21) require that the ordered items are (a) integer multiple(s) of Q_{n_3}, batch sizes for item n_3.

$$O_{n_3}(t) = \mathrm{NB}_{n_3}(t) \cdot Q_{n_3}, \quad n_3 = 1, \ldots, N_3, \;\; t = 1, \ldots, T, \tag{21}$$

with $\mathrm{NB}_{n_3}(t) \in \mathrm{N}_0$.

The total demand for item n_3 is determined by adding the satisfied parts of the dependent (endogenous), independent (exogenous) demand plus the backorders for item n_3 in period t.

$$\mathrm{TD}_{n_3}(t) = \mathrm{SDD}_{n_3}(t) + \mathrm{SD}_{n_3}(t) + \mathrm{BO}_{n_3}(t), \quad n_3 = 1, \ldots, N_3, \;\; t = 1, \ldots, T \tag{22}$$

Equations (23) and (24) show how the satisfied parts of the dependent $\mathrm{SDD}_{n_3}(t)$ and independent demand $\mathrm{SD}_{n_3}(t)$ for item n_3 in period t are determined. $\mathrm{ID}_{n_3}(t)$ is the independent demand for item n_3 in period t and $\mathrm{DD}_{n_3}(t)$ is the dependent demand for item n_3 in period t.

$$\mathrm{SD}_{n_3}(t) = \mathrm{ID}_{n_3}(t) - \mathrm{UD}_{n_3}(t), \quad n_3 = 1, \ldots, N_3, \ \ t = 1, \ldots, T \tag{23}$$

$$\mathrm{SDD}_{n_3}(t) = \mathrm{DD}_{n_3}(t) - \mathrm{UDD}_{n_3}(t), \quad n_3 = 1, \ldots, N_3, \ \ t = 1, \ldots, T \tag{24}$$

The dependent demand $\mathrm{DD}_{n_3}(t)$ is determined by multiplying the BOM-factor with $\mathrm{TP}_{n_2}(t - L)$ with L is the lead time of second stage of the supply chain.

$$\mathrm{DD}_{n_3}(t) = \mathrm{BOM}_{n_3,n_2} \sum_{n_2} \mathrm{TP}_{n_2}(t - L), \quad n_3 = 1, \ldots, N_3, \ \ t = 1, \ldots, T \tag{25}$$

The backorder quantity for item n_3 in period t $\mathrm{BO}_{n_3}(t)$ is the summation of the unsatisfied dependent and independent demand for item n_3 in period $t-1$.

$$\mathrm{BO}_{n_3}(t) = \mathrm{UDD}_{n_3}(t-1) + \mathrm{UD}_{n_3}(t-1), \quad n_3 = 1, \ldots, N_3, \;\; t = 1, \ldots, T \qquad (26)$$

Finally, non-negativity constraints have to be considered.

$$\begin{aligned} &\mathrm{EI}_{n_1}(t), \mathrm{TD}_{n_1}(t), \mathrm{TR}_{n_1}(t), \mathrm{SM}_{n_1}(t), \mathrm{BM}_{n_1}(t), \mathrm{SD}_{n_1}(t), \mathrm{UD}_{n_1}(t), \mathrm{EI}_{n_2}(t), \\ &\mathrm{TD}_{n_2}(t), \mathrm{TR}_{n_2}(t), \mathrm{PP}_{n_2}(t), \mathrm{UD}_{n_2}(t), \mathrm{UDD}_{n_2}(t), \mathrm{SD}_{n_2}(t), \mathrm{SDD}_{n_2}(t), \mathrm{EI}_{n_3}(t), \\ &\mathrm{TD}_{n_2}(t), \mathrm{TR}_{n_2}(t), O_{n_2}(t), \mathrm{UD}_{n_2}(t), \mathrm{UDD}_{n_2}(t), \mathrm{SD}_{n_2}(t), \mathrm{SDD}_{n_2}(t) \geqslant 0 \qquad (27) \end{aligned}$$

The service level for the most downstream stage (stage 1) in the supply chain is determined by Eq. (28) where β_{n_1} is the fill rate for item n_1, i.e. the long-run fraction of independent demand $\mathrm{ID}_{n_1}(t)$ satisfied directly from shelf (without backordering).

$$\beta_{n_1} = \sum_t \left(1 - \frac{\mathrm{UD}_{n_1}(t)}{\mathrm{ID}_{n_1}(t)}\right), \quad n_1 = 1, \ldots, N_1 \tag{28}$$

For stages 2 and 3 of the supply chain, Eq. (29) determine the service level, as these stages face exogenous (independent) demand and endogenous (dependent) demand from the next (downstream) stage of the supply chain.

$$\beta_{n_j} = \sum_t \left(1 - \frac{\mathrm{UD}_{n_j}(t) + \mathrm{UDD}_{n_j}(t)}{\mathrm{ID}_{n_j}(t) + \mathrm{DD}_{n_j}(t)} \right), \quad j = \{2, 3\}, \;\; n_j = 1, \ldots, N_j \qquad (29)$$

Fig. 7 The supply chain of product B

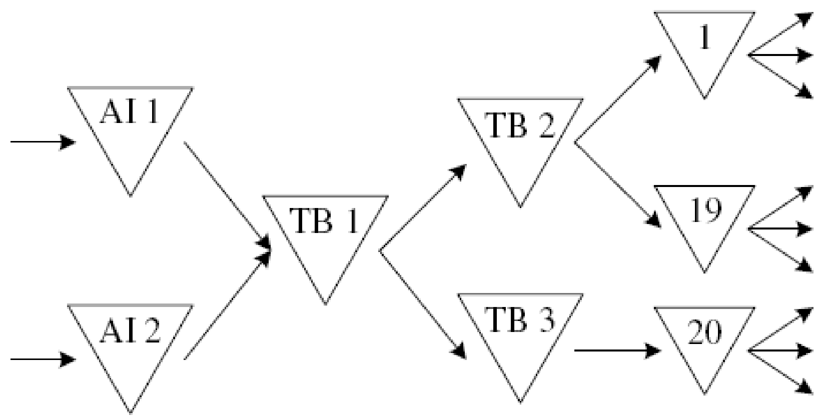


Table 2 Safety stock levels based on the proposed approach and the current safety stock levels

	Current situation	Model suggestion
National warehouses	162	136
Tablets stockpoint	71	46
Active ingredients	29	22

SUPPLIER MANAGED INVENTORY IN THE OEM SUPPLY CHAIN

Original equipment manufacturers (OEMs) often subcontract production of parts to specialized firms that, by working for various customers, can operate at a scale that allows for the economic operation of their technologies.

Such parts manufacturing shops generally use a number of different technologies grouped into work centers to manufacture a wide range of parts, with varying routings in the shop and each part having low to medium demand. These shops are characterized in the literature as job shops.

In this paper we study whether it can be advantageous for a parts manufacturing shop to engage in a supplier managed inventory (SMI) relationship with its customers.

In such a relationship, it is the supplier who manages the inventory of customer-specific parts that it produces for the OEMs. For the supplier, a main advantage of engaging in the SMI relationship is the possibility to optimize production batch sizes, resulting in lower system-wide costs.

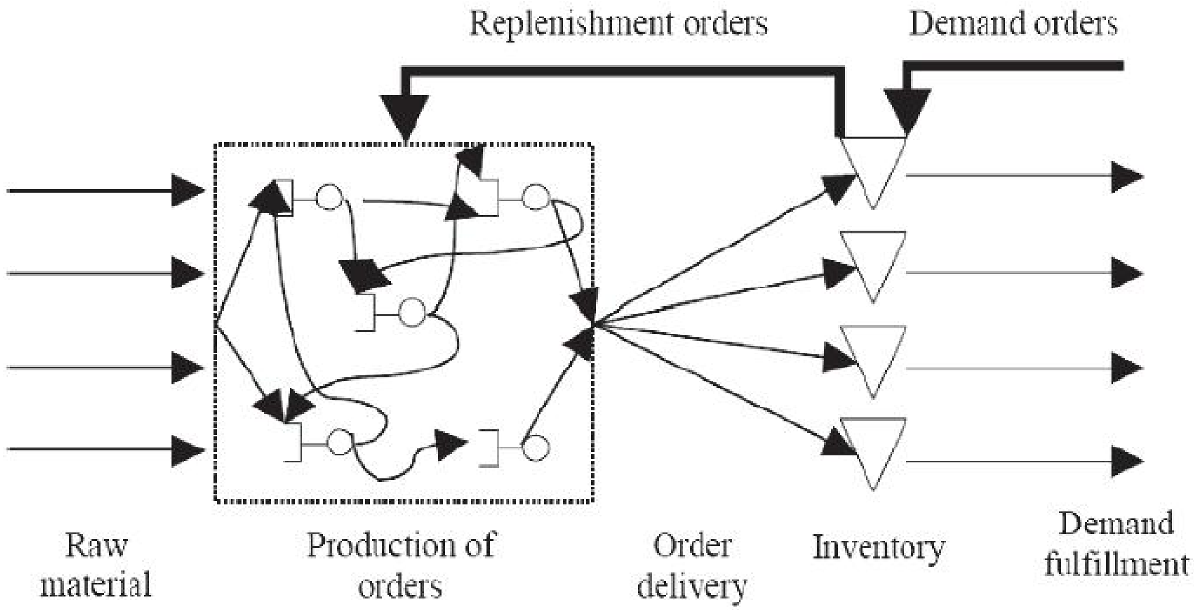


Fig. 1 Supplier–OEMs relationship modeled as a multi-product, multi-machine production–inventory system

Table 1 Characterization of supplier–OEM relationships

	Non-SMI	SMI-NC	SMI-S	SMI-C	SMI-F
Inventory control	O	S	S	S	S
Inventory storage	O	O	S	O	S
Inventory ownership	O	O	O	S	S

O original equipment manufacturer (OEM), *S* supplier

1. Non-SMI. The OEMs are responsible for ordering and storing their own parts.
2. SMI–Non consignment (SMI-NC). The supplier is responsible for the inventory management at the OEM's premises, but does not incur any inventory costs.
3. SMI–storage (SMI-S). The supplier is responsible for the management and storage of the OEM's parts.
4. SMI–consignment (SMI-C). The supplier is responsible for the inventory management at the OEM's premises. Moreover, he owns the products until they are taken from the stock.
5. SMI–full (SMI-F). The supplier is responsible for the management and the storage of the OEM's parts. Additionally, he owns the products until they are taken from the stock.

We consider five cost elements:

1. ordering costs (OC),
2. financial inventory holding costs (FIC),
3. physical inventory holding costs (PIC),
4. production setup costs (SC) and
5. Work in- process holding costs (WIPC).

Table 2 Allocation of costs over OEMs and supplier

Cost element	NON-SMI	SMI-NC	SMI-S	SMI-C	SMI-F
OC	O	S	S	S	S
FIC	O	O	O	S	S
PIC	O	O	S	O	S
SC	S	S	S	S	S
WIPC	S	S	S	S	S

O OEM, *S* supplier

$$OC_k(Q_k) = \frac{o_k}{Q_k E[A_k]}$$

$$\text{FIC}_k(\Phi) = h_k^f \left[\frac{Q_k}{2} + ss_k(\Phi) \right]$$

$$\text{PIC}_k(\Phi) = h_k^p \left[\frac{Q_k}{2} + ss_k(\Phi) \right]$$

$$\text{SC}_k(Q_k) = \frac{s_k}{Q_k E[A_k]}$$

$$\text{WIPC}_k(\Phi) = h_k^{wip} \frac{E[T_k(\Phi)]}{Q_k E[A_k]}$$

$$Q_k^{\text{NON-SMI}} = \sqrt{\frac{2(o_k + s_k)}{E[A_k]\left(h_k^f + h_k^p\right)}}$$

SMI-NC

$$\sum_{k=1}^{K} \left[\frac{o_k + s_k}{Q_k E[A_k]} + h_k^{\text{wip}} \frac{E[T_k(\Phi)]}{E[A_k]} + \left[\left(h_k^{\text{f}} + h_k^{\text{p}}\right)\left(\frac{Q_k}{2} + ss(\Phi)\right) - \text{FIC}_k^{\text{NSMI}} - \text{PIC}_k^{\text{NSMI}} \right]^+ \right]$$

SMI-S

$$\sum_{k=1}^{K}\left[\frac{o_k + s_k}{Q_k E[A_k]} + h_k^{\text{wip}}\frac{E[T_k(\Phi)]}{E[A_k]} + h_k^{\text{p}}\left(\frac{Q_k}{2} + ss(\Phi)\right) + \left[h_k^{\text{f}}\left(\frac{Q_k}{2} + ss(\Phi)\right) - \text{FIC}_k^{\text{NSMI}}\right]^{+}\right]$$

SMI-C

$$\sum_{k=1}^{K}\left[\frac{o_k+s_k}{Q_k E[A_k]}+h_k^{\mathrm{wip}}\frac{E[T_k(\Phi)]}{E[A_k]}+h_k^{\mathrm{f}}\left(\frac{Q_k}{2}+ss(\Phi)\right)+\left[h_k^{\mathrm{p}}\left(\frac{Q_k}{2}+ss(\Phi)\right)-\mathrm{PIC}_k^{\mathrm{NSMI}}\right]^{+}\right]$$

SMI-F

$$\sum_{k=1}^{K}\left[\frac{o_k+s_k}{Q_k E[A_k]}+h_k^{\mathrm{wip}}\frac{E[T_k(\Phi)]}{E[A_k]}+\left(h_k^{\mathrm{f}}+h_k^{\mathrm{p}}\right)\left(\frac{Q_k}{2}+ss(\Phi)\right)\right]$$

5.1 Supply chain's optimal cost

In the case of SMI-F the supplier carries all the relevant costs. Therefore, the supplier can optimize all the costs simultaneously (system-wide optimization), while in the other relationships only a subset of the costs are optimized (partial optimization). As a consequence, the total supply chain costs of the SMI-F relationship are lower than or equal to those of the other relationships and the cost of SMI-F is the supply chain's optimal cost:

$$\mathrm{TRC}_{\mathrm{SC}}^{\mathrm{SMI-F}} = \mathrm{TRC}_{\mathrm{SC}}^{*}$$

This observation is useful in situations where the achievement of the lowest system-wide costs is more important than the division of costs over the different parties. This may occur, for example, when the OEMs and supplier are subdivisions of the same company. In this case, it is more important to obtain the lowest cost for the whole company, than to locally optimize the costs of the subdivisions.

Suppose that initially the supplier and OEMs have a NON-SMI relationship. Further suppose that the supplier now wants to change the relationship into a SMI type relationship. The impact of this change is twofold.

1. Firstly, cost components are transferred from the OEMs to the supplier. This cost transfer is called here the *transfer effect*.
2. Together with the costs, however, also the power for controlling the inventory is transferred from the OEMs to the supplier. This allows the supplier to determine the batch sizes, which may results in cost reductions that we refer to as the *coordination effect*.

The OEM's transfer effect $\mathrm{TE}_{\mathrm{O}}^{x}$ can be computed for the different relationships x:

$$\mathrm{TE}_{\mathrm{O}}^{\mathrm{SMI\text{ - }NC}} = -\sum_{k=1}^{K} \mathrm{OC}_k^{\mathrm{NSMI}}$$

$$\mathrm{TE}_{\mathrm{O}}^{\mathrm{SMI\text{ - }S}} = -\sum_{k=1}^{K} \left(\mathrm{OC}_k^{\mathrm{NSMI}} + \mathrm{PIC}_k^{\mathrm{NSMI}}\right)$$

$$\mathrm{TE}_{\mathrm{O}}^{\mathrm{SMI\text{ - }C}} = -\sum_{k=1}^{K} \left(\mathrm{OC}_k^{\mathrm{NSMI}} + \mathrm{FIC}_k^{\mathrm{NSMI}}\right)$$

$$\mathrm{TE}_{\mathrm{O}}^{\mathrm{SMI\text{ - }F}} = -\sum_{k=1}^{K} \left(\mathrm{OC}_k^{\mathrm{NSMI}} + \mathrm{FIC}_k^{\mathrm{NSMI}} + \mathrm{PIC}_k^{\mathrm{NSMI}}\right)$$

From the point of view of the OEMs and the total supply chain, a transition from NON-SMI to SMI always results in lower costs.
Therefore, the only uncertainty is the cost impact of a change on the supplier's costs.

$$\mathrm{TRC}_{\mathrm{SC}}^{x} = \mathrm{TRC}_{\mathrm{SC}}^{\mathrm{NSMI}} + \mathrm{TE}_{\mathrm{SC}}^{x} + \mathrm{CE}_{\mathrm{SC}}^{x} \leq \mathrm{TRC}_{\mathrm{SC}}^{\mathrm{NSMI}}$$

Numerical analysis of a set of problem instances revealed that substantial system wide cost saving can be achieved under all SMI variants, in particular if the shop operates under high-capacity utilization and/or the OEMs require high service levels.

We have shown that these savings are due to the strongly reduced order throughput times that are possible if batch sizes can be coordinated. As a result, inventory costs always decrease under SMI, making SMI attractive for the OEMs.

However, for all problem instances studied, the supplier costs increased under SMI, because SMI implies the transfer of one or more cost components from the OEM to the supplier. The OEMs always are better off under SMI. This suggests that a supplier should not offer SMI to the OEMs unless there is some compensation for his net increase in costs. We have shown that, since system-wide costs always decrease under SMI, there exists under each SMI relationship a range of product price increases that at least compensate the supplier for his increased costs and still make it financially attractive for the OEMs to engage in the SMI relationship.

In this paper, we assumed that inventory holding costs are identical for supplier and OEMs.

In real life supply chains, this is often not the case. Cost differences may be caused by differences in the cost of capital (interest rate, required return on investments, etc.) or differences in the costs of labor and space (labor contracts, location of warehouses, etc.).

In future research, it may be worthwhile to investigate how these cost differences have an impact on the choice for a certain supply chain relationship type.