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Performance measurements and performance control in supply chain management

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Introduction

Developing and using an adequate set of performance indicators nowadays is a generally accepted part of the managerial tool set. Performance indicators have been developed for many different aspects of the performance of an organization. Traditional performance indicators are for example production efficiency, material use efficiency, capacity use efficiency, and adherence to a budget. Over the last decades this set of indicators has been extended by quality performance indicators and logistics performance indicators (see e.g. Kenny and Dunk [1989]). Much attention has also been paid to methodological issues related to developing a consistent set of performance indicators. Special attention has been given to questions like how to attain a simple and limited set of performance indicators which are valid for the performance required from the organization, and which can be related to internal or external causal variables, or to variables which are under control of the organization (see e.g. Globerson [1985] or Fortuin [1980]).

A very important aspect of developing performance indicators is how to make sure that the measured variables can be related to the responsibility area of one or more persons in the organization. Often the cause-effect relationships in production processes and production organizations are complex; they may contain non-linearities or time dynamics, and interactions which are multiplicative instead of additive. As a result, it is often necessary to distinguish between result performance variables and process performance indicators. These latter indicators are intermediate variables which contain information about the state of the production system and which can be related to both external variables, controllable variables and result variables. Decomposing the entire production system in a number of loosely coupled subsystems which each can be provided with a separate set of performance indicators and which can be considered as the responsibility area of a person or group of persons, is an important step in developing performance indicators for a complex system. Pritchard[1990] has developed a

comprehensive approach towards developing consistent and complete sets of performance measurement and improvement systems. His approach is comprehensive in that it covers all aspects of the organization's performance that are considered relevant from the point of view of the organization and its environment. Furthermore in the Pritchard-approach the performance indicators are developed in close cooperation with the members of the organization and reflect the dispersion of authority and responsibility in the organization. In our view this is a very important aspect of developing performance indicators since performance measurements only make sense if it measures variables which can be influenced by persons who can be held responsible for the value of the variables measured.

In this paper we concentrate on the logistics aspects of the performance of organizations (see e.g. Anderson, Aronson and Storhagen [1989]); logistics refers to the control of volume, speed and timeliness of production, supply and distribution processes. Moreover we study the development of logistics performance indicators in supply chains. A supply chain is a sequence of supply, production and distribution processes for a specific set of products which belong to certain product-market combination.

Supply chains can be complex and may use a number of different production, supply and distribution processes, each belonging to different organizations or even different firms. Managing the supply chain for a certain product range means controlling the product and material content of the entire chain such that, in the end, a certain logistics performance is attained in the market place. Therefore from the perspective of the supply chain manager the system he controls is characterized by the lead times, and volume and mix constraints of each of the elements in the chain. These elements consist of production units and stock points. The state of the system is defined by amounts of materials in the stockpoints and the products as work in process in each of the production units. From the perspective of the supply chain manager, given the performance he wants to obtain, given the constraints in the system, there is an ideal state of the system. Much theoretical knowledge is available nowadays regarding the optimal distribution of materials and products in supply chains (see e.g. Lagodimos and Anderson[1993], Schwarz [1982]).

The question addressed in this paper is: who is responsible for the distribution of materials and products in the chain. In other words, who controls the work in process in the production units and the inventories at stock points who together constitute the state of the supply chain. In general production unit managers are responsible for their work in process, for the lead time reliability and their volume and mix flexibility. Often production units are part of various supply chains, e.g. a production unit which produces mechanical components may supply to two or more different end product groups e.g. copying machines and motor cycles. Thus the question is who is responsible for the service levels obtained in the intermediate stock points, and how

this relates to the responsibility for the customer service level. This question is addressed in this paper. We do this by analyzing the performance of three different supply chain management concepts.

The rest of the paper is organized as follows. In section two we discuss the three supply chain management concepts. Focus is on the role of allocation of control responsibility between a comprehensive, higher level, supply chain control unit and individual, lower level, production control units. In section three we describe the reference model, based on a real-life case, which is used as the basis for comparison of the three control concepts. In section four we present the results of a numerical comparison of the three concepts. The numerical results are derived from a combination of mathematical analysis of multi-echelon models and discrete event simulation. Finally in section five we draw conclusions and give direction for further research.

2. Supply chain control concepts

In this section we introduce three different supply chain control concepts, which differ in the allocation of control responsibility among the supply chain control level and the production unit control level. The supply chain control level is responsible for the overall performance of the supply chain, in terms of work in process, stock levels and customer service level. The supply chain consists of a network of production units and stock points (cf. Bertrand et al [1990]). We consider warehouses as production units with the special feature that no decisions have to be taken with respect to transformation of material into products. Due to the hierarchical relation between supply chain control and production unit control it is possible to design different control structures that all achieve the same customer service performance, i.e. the same external performance. The objective is to design the control structure such that the external performance is achieved at maximal internal performance, i.e. minimal costs, minimal capital, etc. Below we give three concepts for the supply chain control structure.

Decentralized operational control

The first concept is to make the production manager of the production unit that produces the items responsible for the availability of these items in the succeeding stock point and to set certain performance targets for each production unit manager. We call this decentralized operational control, (see Fig. 1).

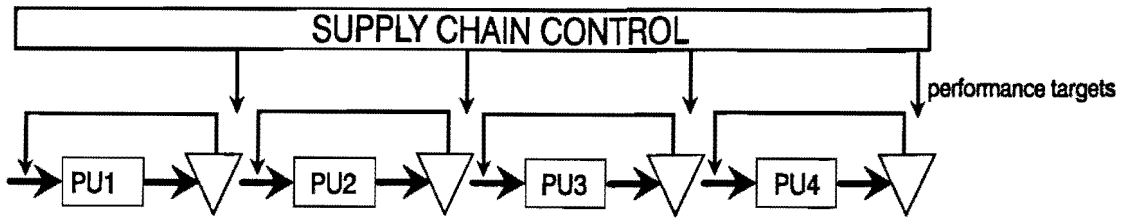


Fig. 1. Decentralized operational control of the supply chain.

In this case the supply chain manager is not involved in the operational control of the supply chain, he is only involved in setting the performance targets for each stock point. The chain is controlled by the production unit managers who each control the stock points after their unit by producing replenishment orders in their unit. This structure is similar to the classical supply chains studied by Forrester [1962] and also resembles the Kanban control structure (cf. Hall [1980]).

Centralized operational control

The second concept is to make the supply chain manager responsible for both the release of work orders to the production units, for the priority setting among the work orders in the production units and for the work in process inventory in the stock points. In this case the production unit manager of each unit is only responsible for the technical and organizational aspects of the production processes. This control structure we call the total centralized operational control, see Fig. 2.

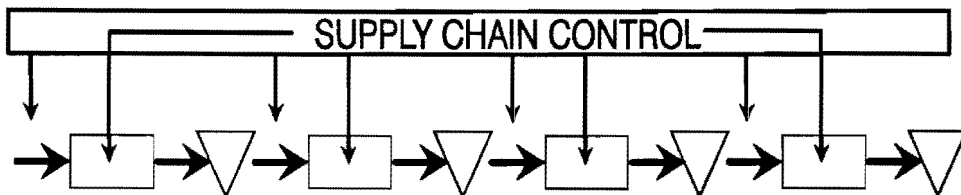


Fig. 2. Total centralized operational control.

This structure is to some extent similar to the structure originally proposed by Orlicky[1975] in his MRP I approach regarding materials management in supply chains, and very similar to the control structure which is implied by the OPT control system (cf. Fox[1984]). The supply chain control system in this case can be considered as an integration of subsequent MRP and DRP systems.

Decomposed operational control

The third concept is to make the supply chain manager responsible for stock points in between the production units and for customer service. The production unit manager of each unit is responsible for the volume and mix flexibility of its unit and for controlling the workload in accordance with agreed lead times. We call this decomposed operational control (see Fig. 3).

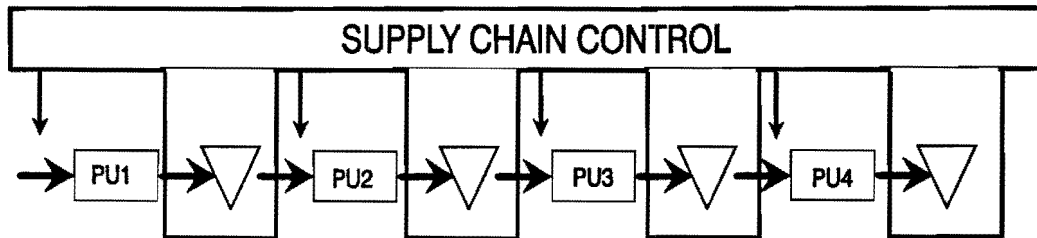


Fig. 3. Decomposed operational control.

This type of control structure is advocated by Meal [1984] and Bertrand et al. [1990] who both base their control structure on the notions that responsibility for performance variables should be allocated to the (parts of the) organization who have the best, most detailed and most timely information about the state of the system and have the power to control the variables.

Recently there has been strong tendency in industry to decentralize the responsibility for logistics control. In many supply chains, the centralized logistics control departments have been reduced in personal or power, and sometimes even eliminated. Driving forces for this tendency are the economical urge to design lean organizations (by elimination of overhead) and the psychological urge to increase empowerment (by decentralization of power). The question now is whether total decentralized control is always the best structure. In order to investigate this question, we compare the three proposed concepts and study the problem from the perspective of the supply chain manager and a production unit manager.

3. The reference model

To investigate in more detail the effect of performance targets for individual links in the supply chain on the overall supply chain cost we apply the analysis of a multi-echelon model to a case study. The case study is taken from one of the author's consultancy project, while he was employed by a European multinational consumer electronics company. In particular the case dealt with the analysis of the supply chain of high-end TV sets.

In this section we define the model in more detail, in the next section we discuss the results and

the consequences for the performance measures and targets to be used in individual links. We consider a 3-echelon model. The echelons are defined as follows. Echelon 1 is associated with common material stocked at a factory warehouse. Echelon 2 is associated with final products at a factory warehouse. Echelon 3 is associated with final products at J regional warehouses. The 3-echelon model is an extension of the hierarchical planning model described in De Kok [1990]. De Kok investigated a 2-echelon model, where echelon 1 was associated with a product family level and echelon 2 was associated with final products at local distribution centres. The product family level is equivalent to the common raw material, since all final products use the common raw material. It is assumed that all products contain the same number of common raw materials. The planning model in De Kok [1990] can be seen as a special case of the model discussed here, where no factory warehouse exists and no stocks of common raw materials are held.

Let us define the model in more detail. We assume that I final products are assembled from the common raw material and additional components, which have a negligible lead time compared with the common raw material lead time. Assembly of each product, including planning and shipment to the factory warehouse takes a positive lead time.

- D_{ij} := demand for product i in region j in an arbitrary period, $i=1, \dots, I, j=1, \dots, J$.
- L_0 := lead time of common raw material
- L_i := throughput time from release of order to assembly until receipt in the factory warehouse for product i
- L_{ij} := throughput time from release of order to the factory warehouse until receipt in local warehouse of region j

We assume that demand for product i at region j is stationary. Demands in different periods for product i in region j are mutually independent. Demands for different products are mutually independent. The lead times are assumed to be constant.

The supply chain is controlled in such a way that a prespecified fill rate is achieved at all local warehouses for each product. We define

- β_{ij} := the fraction of demand for product i satisfied from stock on hand in region j.
- β_{ij}^* := target fraction of demand for product i satisfied from stock on hand in region j..

We note here that there exist infinitely many solutions to the problem of controlling the supply chain such that $\beta_j = \beta_j^*$. We want to find solutions that yield this result at minimum cost. The cost structure is defined as follows.

- h_0 := holding cost of common material per final product per time unit
- h_i := holding cost of final product i at the factory warehouse per product per time unit
- h_{ij} := holding cost of final product i at the warehouse in region j per product per time unit.

We assume the holding cost to be the product of interest rate and price of the product. Note that if we assume that the interest rate is 1 then the total average holding cost equals the average amount of capital tied up in the supply chain. We do not take into account set-up or ordering costs due to the fact that we assume that each production unit (warehouse) uses a periodic review control policy with the same review period for all production units, typically one week. Furthermore we do not take into account costs of physical distribution, such as transport and handling. This is appropriate since the cost of physical distribution is partly fixed, such as cost of the warehouse and cost of the vehicle fleet, and partly only dependent on the average demand per time unit, which is assumed to be given.

In order to compute the holding cost we need to know the stock in the supply chain, consisting of pipeline stocks and physical stocks in warehouses. Assuming that the system is in its stationary situation, we define

- X_0 := physical stock of common material
- X_i := physical stock of final product i at the factory warehouse
- X_{ij} := physical stock of final product i at the warehouse in region j

Note that X_0 , X_i and X_{ij} are random variables. Now let C denote the total relevant cost used for comparison of alternative control structures. Then we have

$$C = h_0 E[X_0] + \sum_{i=1}^I h_i E[X_i] + \sum_{i=1}^I \sum_{j=1}^{J_i} h_{ij} E[X_{ij}]$$

We deliberately do not take into account pipeline costs, because these do not depend on the control structure chosen.

The problem we are faced with can thus be formulated as follows

min C(control parameters)

subject to

control structure

$$\beta_{ij} = \beta_{ij}^*$$

The reference model is used to compare the three alternative structures. However, before we can compare the three scenarios we have to define the control strategies in more detail, as applied to the reference model.

Decentralized operational control

In this case each production unit and distribution unit aims at achieving the performance targets set by the supply chain manager. Since the supply chain manager does not have any operational control the tendency is to set performance targets high in terms of availability of material, so that downstream processes are not affected by lack of material from upstream processes. In that way the availability of products to the market is ensured.

To emulate this situation we assume that each stock point is controlled according to an (R,S)-policy, i.e. periodic review, order-up-to-level policy, where the target service level at intermediate stockpoints equals 95%. We assume that due to decentralized operational control rescheduling actions and expediting of material supplies ensure effectively a 100% service level to downstream stages (cf. Inderfurth[1994]). In that way we can decompose the supply chain in independent subsequent stages, each of which ensures 100% delivery reliability, except for the most downstream stages, that ensure $\beta_{ij} = \beta_{ij}^*$.

Centralized operational control

In the case of centralized operational control both supply chain manager and production unit managers are not able to react effectively. The supply chain manager has the possibility to determine the priorities of the work orders in the production units, but will not have sufficient information about the constraints and restrictions of the shop floor to effectively use this power. The production unit managers are only supposed to realize the conditions (operators, equipments) in order for the shop to be able to execute orders according to the supply chain manager's instructions. The supply chain management system can be thought of a collection of MRP and DRP systems that are tightly coupled. Hence final customer demand is translated into work orders in each production unit based on backward scheduling logic using planned lead

times for production and distribution throughput times.

We model this situation by assuming that each production unit is controlled according to an (R,S)-policy, where S denotes the target echelon stock. Here the echelon stock is defined as the sum of stock on order, physical stock at the production unit plus all stock downstream of the production unit minus backorders at local warehouses downstream of the production unit (cf. Silver and Peterson [1985], Graves et al [1992]). We apply the echelon (R,S)-policies mechanistically, since we do not have information concerning priorities at the production unit level. An analysis of periodic review N-echelon models can be found in Verrijdt and De Kok [1995]. In this case we consider a 3-echelon model. Due to the fact that there is no operational control at production unit level, and the supply chain manager cannot control the production unit effectively, we must safeguard against the output uncertainty by a safety lead time. We assume a one week safety lead time for each production unit. It should be noted that this is likely to be a conservative estimate, since the centralized supply chain logic, based on tightly coupled MRP and DRP systems, implies backward scheduling logic for production units, which is likely to be very ineffective w.r.t. use of operational flexibility.

For tractability reasons we do not model the production units in detail. We resort to echelon stock control policies due to the computational intractability of the external performance of multi-echelon systems controlled according to DRP and MRP logic, except for special cases. We refer to Axsater and Rosling[1990], Lagodimos and Anderson[1993] and Lagodimos [1990] for a comparison of the echelon stock control policies and MRP.

Decomposed operational control

In the case of decomposed operational control we assume that the supply chain manager optimizes the supply chain based on a conceptual model, where each production unit is modelled as an infinite capacity with a planned constant lead time. The production unit manager uses his operational control and the volume and mix flexibility of the production unit (operators working overtime, reallocation of operators, work order priority setting) to achieve constant and predictable lead times. Due to operational control at production unit level we may assume that the planned lead times of production and distribution are realized. Hence no safety lead times are introduced. In this case the distribution of responsibilities is as follows: The production unit manager is made responsible for the due date performance of replenishment- or customer orders, not for the availability of stock downstream. The supply chain manager balances the stocks in the supply chain in order to minimize costs. Furthermore the supply chain manager is responsible for the orders generated by each production unit to its predecessor(s). Notice that in the previous cases no such clear cut distribution of responsibility is made.

Again we assume that the supply chain manager controls the supply chain according to (R,S) echelon control policies. In fact the only difference with the centralized control policy is the absence of safety lead times as indicated above. Hence we again apply the algorithms developed in Verrijdt and De Kok [1993,1995] and De Kok et al[1994] to come up with computational results.

4. Numerical comparison

The reference model contains so many different parameters that it is impossible to state general conclusions based on variation of all these parameters for the three supply chain management scenarios. Therefore we have decided to base our numerical comparison on real-world data for a particular case.

The case situation describes the production and distribution of TV-sets. We consider a family of 6 high-end TV-sets that have the same CRT. The CRT (Cathode Ray Tube) represents 40% of the material value of the TV-sets. The planned lead time of CRTs equals 4 weeks (including lead time for planning reasons). Assembly of TV-sets takes 1 week and distribution of the sets to 4 sales regions takes 1 week. We assume that the demand for a particular TV-set in each sales region has the same probability distribution. The target fill rates are identical for all sets at all sales regions. The detailed data are given in the table below.

$$I = 6, J = 4$$

$$L_0 = 4$$

$$L_i = 1, i=1, \dots, I$$

$$l_{ij} = 1, i=1, \dots, I, j=1, \dots, J$$

$$\beta_i^* \beta_j^*, i=1, \dots, I, j=1, \dots, J$$

$$E[D_{1j}] = 83, \sigma(D_{1j}) = 118, j=1, \dots, J$$

$$E[D_{2j}] = 125, \sigma(D_{2j}) = 93, j=1, \dots, J$$

$$E[D_{3j}] = 83, \sigma(D_{3j}) = 87, j=1, \dots, J$$

$$E[D_{4j}] = 83, \sigma(D_{4j}) = 54, j=1, \dots, J$$

$$E[D_{5j}] = 156, \sigma(D_{5j}) = 115, j=1, \dots, J$$

$$E[D_{6j}] = 156, \sigma(D_{6j}) = 143, j=1, \dots, J$$

Note the rather high variability of demand, in spite of the fast-moving character of TV-sets. This is partly caused by the fact that the TV-sets considered are high-end sets. Below we

subsequently discuss the results for decentralized-, centralized- and decomposed operational control.

All examples below have been analyzed by discrete event simulation. Each case has been simulated for 50.000 time units, which turned out to be sufficient to guarantee accurate point estimates. All control strategies have been determined using analytical models, since we wanted to base comparison on prespecified customer service levels. This is virtually impossible using discrete event simulation only due to prohibitive run times needed for solving the problem under multiple constraints. This fact supports the importance of mathematical analysis of supply chain models. We used the discrete event simulation for two reasons. Firstly, due to the complexity of the models under consideration exact analysis is impossible so that heuristics have been used. Secondly, the modelling itself ignores some aspects, such as imbalance and interactions between subsequent stockpoints in case of lack of upstream stocks. More details are given below.

Decentralized operational control

In case of decentralized operational control the analysis is straightforward. We compute the (R,S)-policies that satisfy the service level constraints imposed on each stockpoint. Intermediate stockpoints, i.e. CRT-stocks and factory stocks, have a target fill rate of 95%. The local warehouses have a target fill rate that varies as 90%, 95% and 99%. The computation of the (R,S)-policies is based on an algorithm described in De Kok [1990]. The results of the analysis are given below in table 4.1.

β	CRT		Factory			Local Warehouse			Total		
	weeks	value	β	weeks	value	β	weeks	value	β	weeks	value
0.90	1.4	1480	0.95	1.7	4784	0.90	2.6	7056	0.90	5.7	13323
0.95	1.4	1480	0.95	1.7	4784	0.90	3.3	9060	0.95	6.4	15325
0.99	1.4	1480	0.95	1.7	4784	0.90	4.9	13572	0.99	8.0	19836

Table 4.1 Performance of decentralized control structure

Decentralized operational control is considered to provide the reference situation, since this describes most adequately the way supply chains are managed nowadays across different organizations.

We applied the modelling assumption that 95% service level in the model ensures 100% service level in reality to downstream stockpoints. We checked this assumption with discrete event simulation. For the CRT stock we indeed find 95% fill rate, yet at the same time the gross lead time, i.e. planned lead time plus waiting time due to lack of stock, equals the planned lead time. Hence the waiting time of CRT orders from assembly is 0. This seems to be a paradox, yet the following reasoning applies here. Since at the upstream stages demand only occurs at review periods and planned lead times equal a multiple of the review period we have at each review period the following events. First of all demand is subtracted from the nett stock, i.e. physical stock minus backorders. Any backorders occurring at this moment are registered. Immediately thereafter a replenishment arrives which brings the nett stock to a positive value. This implies that all backorders are filled immediately after which they are "shipped" to the assembly stage. Hence there is effectively no waiting time of the backorders. This reasoning only holds when the probability that the nett stock is negative after replenishment is negligible, which is the case for high fill rates. The same reasoning applies to the factory warehouse situation for each TV set. However apparently now the fill rate drops to 90% towards the local warehouses. Still the waiting time of replenishment orders from the local warehouses is negligible, yielding the external fill rates as required. Clearly, one needs a more thorough understanding of the interrelationships between service levels in a decentralized control concept. This will be subject of further research. Major conclusion is that the modelling assumptions yield the target external performance.

Centralized control

As stated in section 3 we deal with the lack of flexibility caused by the centralized approach by assuming a safety lead time of 1 week for all intermediate stockpoints. We assume that the distribution process is reliable, so that we need not extend the distribution lead times. Hence we analyze a 3-echelon multi-echelon model with $L_i = 2$ for $i = 0, 1, \dots, 6$.

The problem that occurs now is the following. The supply chain manager wants to optimize the supply chain by choosing the right balance between CRT-stock, which is only 40% of the value of the final product, factory stocks and local warehouse stock. First we note that since factory stocks and local warehouse stocks have equal value, it is optimal to have no factory stocks (cf. Van Houtum and Zijm[1991]), provided that imbalanced local warehouse stocks do not occur. For a discussion of imbalance we refer to Zipkin[1984], Lagodimos[1992], Eppen and Schrage[1981] and De Kok [1990]. Hence for each TV we choose the order-up-to-levels at the local warehouses such that their sum equals the order-up-to-level of the factory warehouse. This is identical to the situation studied in De Kok[1990] and Eppen and Schrage[1981]. Then it

remains to choose the order-up-to-levels for the factory warehouse and CRT such that the appropriate amount of CRT stock remains, exploiting the commonality of the CRT and its low value compared to the TV sets.

We do not attempt to optimize the supply chain. Instead of that we compare situations where we choose the average CRT physical stock equal to 0, 0.2 and 0.8 weeks of demand. The results of the analysis are given in table 4.2 below. The results are derived by applying a generalization of the algorithm of Verrijdt and De Kok[1995] for solving N-echelon divergent systems without intermediate stocks.

However the assumption that no imbalance occurs when having zero factory warehouse stocks is not valid. Therefore we choose to withhold some stock for TV1 and TV3 at the factory warehouse. The alternatives with positive factory warehouse stocks are included in table 4.2.

β	CRT			Factory			Local Warehouse			Safety lead time		Total	
	weeks	value	β	weeks	value	β	weeks	value	β	weeks	value	weeks	value
0.90	0	0	0.17	0	0	0.13	2.7	7368	0.88	2	3842	10.7	11211
0.95	0	0	0.17	0	0	0.13	3.2	8904	0.93	2	3842	11.2	12743
0.99	0	0	0.17	0	0	0.13	4.4	12016	0.97	2	3842	12.2	15856
0.90	0.2	247	0.89	0	0	0.32	2.7	7488	0.89	2	3842	10.9	11578
0.95	0.2	247	0.89	0	0	0.32	3.4	9308	0.94	2	3842	11.6	13396
0.99	0.2	247	0.89	0	0	0.32	4.8	13172	0.98	2	3842	13.0	17262
0.90	0.8	918	0.99	0	0	0.33	2.7	7428	0.89	2	3842	11.5	12192
0.95	0.8	918	0.99	0	0	0.33	3.4	9240	0.94	2	3842	12.2	13999
0.99	0.8	918	0.99	0	0	0.33	4.8	13088	0.98	2	3842	13.6	17847
0.90	0.2	247	0.89	0.1	265	0.42	2.7	7464	0.89	2	3842	11.0	11758
0.95	0.2	247	0.89	0.1	265	0.42	3.4	9385	0.94	2	3842	11.7	13739
0.99	0.2	247	0.89	0.1	265	0.42	4.9	13556	0.99	2	3842	13.2	17910
0.90	0.8	918	0.99	0.1	330	0.44	2.7	7403	0.89	2	3842	16.6	12493
0.95	0.8	918	0.99	0.1	330	0.44	3.4	9314	0.94	2	3842	12.3	14404
0.99	0.8	918	0.99	0.1	330	0.44	4.9	13471	0.99	2	3842	13.8	18561

Table 4.2 Centralized control

Comparing the results in tables 4.1 and 4.2 we find that the centralized approach is superior. Yet we should note that the results in table 4.2 are dependent on the safety lead time of 1 week. This may be too optimistic in the case of complex supply chains. The choice of the safety lead time should be derived from measurements of due date reliability.

Decomposed control

The case of the decomposed control is identical to that of centralized control where the only difference is the omission of the safety lead times in the former situation. In table 4.3 we give the results of a number of what-if scenarios.

β	CRT		Factory			Local Warehouse			Total		
	weeks	value	β	weeks	value	β	weeks	value	β	weeks	value
0.90	0	0	0.2	0	0	0.18	2.6	7076	0.88	2.6	7079
0.95	0	0	0.2	0	0	0.18	3.1	8580	0.93	3.1	8580
0.99	0	0	0.2	0	0	0.18	4.2	11612	0.97	4.2	11611
0.90	0.4	448	0.97	0	0	0.49	2.6	7252	0.89	3.1	7701
0.95	0.4	448	0.97	0	0	0.49	3.3	9112	0.94	3.7	9558
0.99	0.4	448	0.97	0	0	0.49	4.8	13144	0.99	5.2	13593
0.90	0.7	815	1.00	0	0	0.50	2.6	7236	0.89	3.4	8057
0.95	0.7	815	1.00	0	0	0.50	3.3	9096	0.94	4.0	9913
0.99	0.7	815	1.00	0	0	0.50	4.8	13132	0.99	5.5	13950
0.90	0.4	448	0.97	0.1	193	0.57	2.6	7251	0.89	3.1	7893
0.95	0.4	448	0.97	0.1	193	0.57	3.3	9174	0.94	3.8	9815
0.99	0.4	448	0.97	0.1	193	0.57	4.9	13403	0.99	5.4	14044
0.90	0.7	815	1.00	0.1	209	0.58	2.6	7235	0.89	3.4	9260
0.95	0.7	815	1.00	0.1	209	0.58	3.3	9157	0.94	4.1	10175
0.99	0.7	815	1.00	0.1	209	0.58	4.9	13286	0.99	5.7	14411

Table 4.3 Decomposed control

The results of decomposed control are clearly better than the other two cases. Note that the numerical results indicate that, despite the low value of CRT stock compared with the value of TV stock, the scenarios with low CRT stocks give the best overall performance. This is in line with the results in De Kok et al[1994]. Apparently withholding upstream stocks implies the creation of dead stock. We checked this result found for centralized and decomposed operational control also for the case of decentralized control. The results of simulation experiments are given in table 4.4 below. The control parameters have been determined iteratively taking into account the backorder waiting times derived from the discrete event simulation experiments.

β	CRT		Factory			Local Warehouse			Total		
	weeks	value	β	weeks	value	β	weeks	value	β	weeks	value
0.90	0.4	452	0.4	0.2	557	0	3.1	8621	0.90	3.7	9630
0.95	0.4	452	0.4	0.2	557	0	4.1	11267	0.95	4.7	12276
0.99	0.4	452	0.4	0.2	557	0	5.8	15977	0.99	6.4	16982
0.90	0.7	782	0.7	0.2	556	0	3.2	8691	0.90	4.1	10029
0.95	0.7	782	0.7	0.2	556	0	4.1	11340	0.96	5.0	12678
0.99	0.7	782	0.7	0.2	556	0	5.9	16061	0.99	6.8	17399

Table 4.4 Performance of decentralized control structure with low intermediate stocks

Hence the conclusion that intermediate stocks should be low holds for all three control concepts.

This implies that in upstream stages striving for high availability is counterproductive. This poses a problem since it will be hard to motivate people by setting an availability target of 50%, say. To circumvent this problem we propose that the replenishment orders are generated by the supply chain management level according to some logic. The resulting orders may be adjusted for short term constraints with respect to material availability and capacity. The replenishment orders are released to the production units as work orders to be delivered after the planned lead time agreed upon between production units and supply chain management. Hence we measure internal performance by due date reliability instead of stock availability. In this way we can motivate people to achieve 100% performance without creating huge stocks. This control structure is only possible if we use the decomposed operational control approach. Only this structure makes it possible to make a clear distinction between supply chain stock responsibility and work order due date reliability.

5. Conclusions and further research

In this paper we have studied the question of performance measurement and performance control in supply chains consisting of production units and stock points, in relation to the organization structure. We have started with a short discussion of performance measurement and evaluation, and have concluded that performance evaluation in supply chains should be geared to the distribution of responsibility and power in the chain. To study the effect of different distributions of responsibility we have introduced three typical types of distribution of responsibility: decentralized control, centralized control, and decomposed control.

Both centralized and decentralized control try to control the performance by controlling the stock levels in the stock points in the chain. With decentralized control, each production unit manager controls his stock point in accordance with a target set at the supply chain level; with centralized control the supply chain manager tries to control the delivery performance by simultaneously controlling the stocks and work in process in the system. With decomposed control, the supply chain manager controls the stock points in the chain by placing orders at the production units, whereas each production unit manager is responsible for the delivery performance of the accepted orders. From an organizational point of view the decomposed control is to be preferred because it is consistent with the general distribution of power and responsibility in business chains or networks.

To compare the possible performances of the three control structures we have modelled each of them using realistic assumptions about the quantitative effects of the control structures. We have derived quantitative results for each structure. In the results we determine for each structure the total cost inventory in the supply chain, needed to achieve a certain delivery performance. Given that our assumptions are realistic the results show that decomposed control is superior to both centralized and decentralized control.

The most important result obtained is that in spite of low costs of upstream materials optimal allocation of material along the supply chain results in relatively low upstream stocks. This implies that upstream availability, i.e. fill rate, is low. If we would use fill rate as performance measure at upstream stages, then the low targets set would demotivate people. Therefore we conclude that order sizes and release moments should be decided on by supply chain management, who is responsible for external delivery reliability. The production unit managers are responsible for meeting due date reliability targets. This is in line with the decomposed control structure.

Further research is required in developing supply chain models and supply chain management policies that reflect the real-world operational flexibility and interactions. In this regard we found a heuristic decomposition model for decentralized control to adequately estimate supply chain performance as found by discrete event simulation. Furthermore more evidence is needed of the feasibility of supply chain management across different organizations. The multi-echelon control strategies seem to provide a means for coordination. The effect of lot sizing on our conclusions is not yet clear. Nor is the impact of dynamic demand (i.e. trends and seasonality) taken into account.

6. References

1. Andersson, P., Aronson H. and Storkhagen, NN.S., 1989, Measuring Logistics Performance, Engineering Costs and Production Economics 17 , pp. 253-262.
2. Axsater, S., Rosling, R.A., 1990, Installation versus echelon stock policies for multi-level inventory control, Presented at IFORS XII Triennial Conference, 25-29 June, Athens.
3. Bertrand, J.W.M., Wortmann, J.C. and Wijngaard, J., 1990, Production Control: A structural and design oriented approach, Elsevier, Amsterdam.
4. De Kok, A.G., 1990, Hierarchical production planning for consumer goods, European Journal of Operational Research, 45, 55-69.
5. De Kok, A.G., Lagodimos, A.G. and Seidel, H.P., 1994, Stock Allocation in a Two-echelon Distribution System, Pre-Print Proceedings of Eight International Working Seminar on Production Economics, 193-210.
6. Eppen, G., Schrage, L., 1981, Centralised ordering policies in a multi-warehouse system with lead times and random demands, in Schwarz [4], pp.51-68.
7. Fortuin, L.G., 1988, Performance Indicators - Why, where and how, European Journal of Operational Research, 34, 1988, pp. 1-9.
8. Fox, R.E., 1984, OPT(imizing) Just In Time - Leapfrogging the Japanese, Proceedings APICS Conference, Las Vegas.
9. Globerson, S., 1985, Issues in developing a performance criteria system for an organization, Int. J. Prod. Res. 23 , no. 4, pp. 639-646.
10. Graves, S.C., Rinnooy Kan, A.H.G. and Zipkin, P.H., 1993, Logistics of Production and Inventory, Handbooks in Operations Research and Management Science, North-Holland, Amsterdam.
11. Hall, R.W., 1983, Zero Inventories, Dow Jones-Irwin, Homewood.]
12. Inderfurth, K., 1994, Safety stocks in multistage divergent inventory systems: A survey, IJPE 45, 321-329.
13. Kenny, G.K. and Dunk, A.S., 1989, The Utility of Performance Measures: Production Managers Perceptions, IEEE Transactions on Engineering Management, 36, no. 1, pp. 47-50.
14. Lagodimos, A.G., 1990, Protective inventories in manufacturing systems, Ph.D. Thesis, University of Cambridge.
15. Lagodimos, A.G., 1992, Multi-echelon service models for inventory systems under different rationing policies, International Journal of Production Research, 30, 939-958.
16. Lagodimos, A.G., Anderson, E.J., 1993, Optimal positioning of safety stocks in MRP, International Journal of Production Research, 31, 1797-1813.

17. Meal, H.C., 1978, Putting Production Decisions where they Belong, Harvard Business Review, 84, 102-111.
18. Orlicky, J.A., 1975, Material Requirements Planning, McGraw-Hill.
19. Pritchard, R.D., 1990, Measuring and improving organizational productivity: a practical guide, New York, Praeger.
20. Schwarz, L.B. (editor), 1981, Multi-level Production/Inventory Control Systems: Theory and Practice, North-Holland, Amsterdam.
21. Schwarz, L.B., 1981, Physical distribution: the analysis of inventory and location, I.E.E. Transactions, 13, 138-150.
22. Silver, E.A., Peterson, 1985, *Decision Systems for inventory Management and Production Planning*, 2nd Edition, Dow Jones-Irwin, Homewood.
23. Van Houtum, G.J., Zijm, W.H.M., 1991, Computational procedure for stochastic multi-echelon production systems, International Journal of Production Economics, 23, 223-238.
24. Verrijdt, J.H.C.M., De Kok, A.G., 1993, Distribution planning for a divergent two-echelon network without intermediate stocks under service restrictions, accepted for publication in European Journal of Operational Research.
25. Verrijdt, J.H.C.M., De Kok, A.G., 1995, Distribution planning for a divergent N-echelon network without intermediate stocks under service restrictions, International Journal of Production Economics, 38, 225-243.
26. Zipkin, P., 1984, On the imbalance of inventories in multi-echelon systems, Mathematics of Operations Research, 9, 402-423.