ANALYSIS OF SYSTEM MODELS FOR PRODUCT PIPELINE PLANNING AND MEASUREMENT

by

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ABSTRACT

The product pipeline can be defined as the set of all operational activities connected with the delivery of a product to the end customer. A single objective measurement of product pipeline performance can be meaningless as most of the performance measures interact with each other. This thesis looks at two approaches to analyze the interactions within a system of pipeline performance measures.

The first approach, termed structural analysis, combines a set of cooperative routines and simulation tools used in the context of scenario analysis. The second approach is a decision support model that was developed at the Digital Equipment Corporation (DEC) to facilitate planning for the company's product pipelines. It computes the interactions among five significant measures of product pipeline performance.

Applying the structural analysis methodology to a system containing five aspects of pipeline performance showed that in particular the simulation part can provide a reasonable description of the impact of interactions occurring within the pipeline. The DEC model was modified to analyze a pipeline including both "make-to-order" and "make to stock items." This analysis shows that it can capture some of the major interactions between measures that are of interest for the Finance and Marketing functions. However, it also shows that two proposed extensions are likely to make the DEC model more useful for Finance and Operations.

The first extension provides a framework to assess the need for "slack" manufacturing capacity. In particular, a mathematical programming model is proposed to find an efficient level of investment in inventory and manufacturing capacity throughout the pipeline. The second extension outlines methods to improve the manner in which inventory levels are set and changed throughout pipeline. Finally, the DEC model measures are integrated into a general measurement model for the evaluation of pipeline contributions to overarching organizational financial and service objectives.

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Chapter 1 Introduction

1.1 THE PRODUCT PIPELINE AND SYSTEM INTERACTIONS

In most companies throughout the world, the function of logistics has changed considerably within the past 30 years. It has moved from a support function, primarily concerned with traffic and distribution, to a "boundary-spanning activity."[1] A good description of these changes is given by Masters and Pohlen.[2] In their view, the evolution of logistics can be divided into three distinct phases: functional management of physical distribution (1960s and 1970s); internal integration of logistics functions (1980s); and the external integration of logistics between firms (1990s).

The first two phases looked within the firm to improve the internal management and integration of material flows. The third phase, however, looks outside the company for opportunities obtained through the coordination of logistics activities with all other firms that are associated with the delivery of a common product to the market. In the third phase, the greatest possible efficiency and effectiveness[i] is sought in the complete flow and storage of raw materials, work-in-process, finished goods, and associated information from the initial source to final consumption. The fundamental observation that drives this approach is that, in one way or another, every company pays for the inefficiencies or ineffectiveness of its up-stream suppliers and/or its down-stream customers.

Subsequently, operational methods and systems geared to improve both the efficiency and the effectiveness of logistics have emerged. Concepts such as Manufacturing Resource Planning (MRP II), Distribution Resources Planning, Quick response, and "Just-in-Time" (JIT) have been widely adopted. More recently, these have been extended by innovative approaches such as the shifting of value-added operations to third parties, vendor managed inventory, and the creation of "stock-less flow-through logistics operations." The latter rely on flexible manufacturing, cross

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[i] "Efficiency" refers to the quotient of actual output over actual input. Efficiency is thus the ability to achieve the agreed upon service level with the lowest amount of resources.
"Effectiveness" is the quotient of actual output to expected output. Effectiveness is thus the ability of logistics to guarantee a predetermined service level.

dock distribution facilities, and continuous replenishment inventory management. The objective of most systems is a reduction in inventory levels, improved customer service levels, greater velocity of inventory movement through the manufacturing and distribution network and, as a result, greater profitability.

Without spending much time explaining the specific characteristics of these concepts, one attribute that they have in common is a "channel view." A channel view encompasses the supply of materials and information extending over all participating companies included in producing a specific commodity or product. The complete "channel," or "value stream"[3] is therefore viewed as the relevant framework for analysis and improvement. In recent literature,[4] this framework has been termed the "integrated product pipeline." In the manufacturing sector, the material flow within a pipeline starts at the supplier of raw materials and extends through the parts procurement and assembly stages to the final distribution of a finished good through retailers. Usually a company will have many pipelines, each of which needs to be managed as a whole. Copacino[5] refers to this structure as an "account-focused organization." As implied, pipeline control comprises the sum of activities that are designed to ensure that the flow of goods (raw materials, semi-finished and finished products) moves as efficiently and as effectively as possible. Moreover, in some definitions, the scope of the pipeline is extended into the subsequent recovery and disposal of the product to conform to customer and government requirements. Although the product pipeline framework appears incomplete without incorporating this part, also known as reverse logistics, few comprehensive analytical models have been developed to date in this field. For a review of existing literature and an overview of current approaches see Pohlen *et al.*,[6] Giuntini[7] and Turner.[8]

Companies have used the product pipeline perspective in order to better position their customer base, redesign products and subcontract entire logistics functions in order to attain an optimal "flow" of material and information.[9] Such changes require however an analytical framework that can determine whether the intended improvements in product pipeline performance were actually achieved. In this context, contributions of the function of logistics are no longer likely to be measured by means of some transfer pricing mechanism, but are rather completely reflected in the overall pipeline performance - that is, the market share and sales levels of products flowing through the pipeline.

Many measurement systems geared to track pipeline performance fail to recognize that individual measures of product pipeline performance interact with one another. While knowledge of the interaction among product pipeline measures will generally give one an advantage, two examples are provided in order to show specific situations where it can be particularly useful.

Benchmarking: Benchmarking studies have recently emerged as a form of evaluation in which performance measures are compared side-by-side with those of compatible companies. Quite naturally, different companies will put different emphasis on various aspects of their pipeline performance. Thus, when the measures are compared, it is unlikely for one company to lead in the performance of all measures. Failure to recognize that performance measures interact could lead to proposing wrong improvement policies. For example, a company might attempt to improve all areas in which it did poorly without considering the possibility that such attempts could significantly deteriorate the performance of areas which are currently strong. Lack of understanding of those factors that have a strong impact on the performance measures could also lead to ambitious improvement efforts within specific areas that in fact have no real bearing on the fundamental problems that the company may be experiencing.

A lack of understanding of how pipeline performance measures interact can also lead to ambitious plans that are geared to improve pipeline performance in all areas simultaneously. A fitting example is the Digital Equipment Corporation who had developed a performance measurement system that covered both customer and shareholder objectives. Management attempted to improve the performance of all measures simultaneously by benchmarking every one with the top 20% in that category. Eventually management expected plants to have 100% product availability along with nearly no safety stock. From an operations viewpoint, this was hardly a feasible solution.

Third Party Logistics Bidding: An important reason for logistics managers to understand the degree of interaction among performance measures within the product pipeline is when a third party logistics provider is considered. Such providers engage in contract logistics services such as the management of transportation and warehousing for a client company. When bidding to take over the management of parts or all of a company's logistics operations, it might be simple for the logistics service provider to figure out its own costs along with the immediate transportation and warehousing costs that it is saving the client. However it might be much more difficult to determine the impact that it could have on the product pipeline of its client, if it were for example to increase the inventory service level for the supply of those parts that it intended to take over. It might also be important to understand the indirect impacts that its services could have on measures within the product pipeline of the client outside of the immediate realm of logistics.

1.2 SYSTEMS OF PERFORMANCE MEASURES

As the above examples show, decision makers need to consider the ways in which all relevant measures within a product pipeline interact. Like measures within scientific systems, pipeline measures can be correlated in varying degrees and can act in a reinforcing, counteractive, or as an explanation below shows, in an off-setting manner. In a literal sense, one can speak therefore of a "product pipeline measurement system" that needs to be maintained. In this context, pipeline measures represent empirically observable and measurable statistics based on transactions. The goal is to reflect the actual behavior of the product pipeline as accurately as possible.

When two measures correlate in a counteractive manner, one can speak of tradeoffs between them. These relationships have attracted the greatest attention because they are of great significance for decision makers searching for the optimal allocation of scarce resources. The general approach to looking at tradeoffs within a system is by applying tools such as utility curves. These look at the marginal increase in the amount of one measure that corresponds to a marginal decrease of the other. This approach to product pipelines was used by Rosenfield.[10] He observes the characteristics of "cost-service" trade-off curves by developing "efficient frontiers" for a given industry structure. Based on the structure of these "efficient frontiers," it is possible for firms to gain insight into the fundamental issues surrounding logistics services. In conclusion, Rosenfield sees a myriad of future research to be done in order to provide insight into the range of a firm's cost-service positioning within the marketplace.

Approaches to understanding the level and direction of interactions between measures can be classified as either empirical investigations of historical interactions, or assessments of the behavior that specific measures should demonstrate. As the analysis of historical interactions tends to be highly dependent on the specific industry, the latter category is by far more commonly used for decision support. Methods attempting to assess the expected behavior of measures can be of either qualitative or quantitative nature. Qualitative approaches are largely based on managerial concepts such as "scenario analysis," defined in chapter 2.

According to Bowersox,[11] quantitative approaches can be divided into three different categories: analytical models, simulations, and heuristics. Analytic models use mathematical methods to identify an "optimal" configuration of performance measures. They are based either on established relationships within logistics such as inventory equations or mathematical programming formulations. In contrast, models that utilize heuristics or simulation procedures, use numerical techniques to quantify specific problem solutions. Proponents of these modeling techniques seek a "better" as contrasted to an optimal configuration.

A comprehensive overview of simulation models for logistics systems is provided by Mossman *et al.*[12]. Perhaps the most prevalent work in the simulation of interactions between measures within the areas of production and distribution in the manufacturing environment has been accomplished by the three echelon Forrester system dynamics model.[13] Recent extensions of Towill et al.[14] have made this model highly applicable for product pipelines. A drawback of these approaches is the fact that they are very time consuming and focus primarily on the level of demand that propagates through the pipeline and on the resulting production rates and levels of pipeline inventory. While inventory and production rates might be important aspects of pipeline performance, the Forrester model and its extensions does not adequately capture other aspects of pipeline performance, such as changes in the level of pipeline supply reliability that would emerge due to unanticipated shifts in demand.

A high level of effectiveness is usually achieved by using the different model categories in combination. An example of an integrated solution methodology would be the use of analytical tools to identify solution alternatives followed by a comparative analysis under a range and variety of assumptions using heuristics or simulation.

Two approaches to improve the measurement of, and planning for a system of pipeline measures are outlined in chapters 2 and 3. The first approach, which can be termed a "structural analysis," applies methods of scenario analysis towards the structuring of qualitative information on system interactions in order to determine the specific nature of the system. This information can also be used as an input for a simulation that models the time dependent system impacts of changes in a system parameter. Joakin et al.[15] contend that approaches capable of modeling changes within large interdependent systems, which are similar in nature to the structural analysis, have shown to be particularly useful for high level analysis. The second approach, termed the "5-Box" model, is a spreadsheet model that was developed to gain an improved understanding of those dynamics that determine the levels of safety stock and supply reliability within a product pipeline. It has been used as a decision support tool for product pipeline management at the Digital Equipment Corporation since 1993. Although these approaches do not require sophisticated analytical modeling, a case study, described in section 3.3, shows that they demonstrate considerable effectiveness in illustrating fundamental interactions between some key measures within the product pipeline.

Chapter 4 proposes two general extensions to the 5-Box model. The first extension, in section 4.1, accounts for the issue of tradeoffs between inventory and production line investments in the situation of constrained manufacturing capacity. It outlines a framework to assess the need for additional capacity, and describes methods to determine an efficient combination of investments in production capacity and finished goods inventory. The second extension, in section 4.2, addresses the issue that the methods used the 5-Box model to set safety stock levels appear fairly arbitrary. It therefore reviews methods to determine local inventory levels, production and shipment sizes within the product pipeline that reflect the costs of operations, demand uncertainty, and fill rates throughout the pipeline. Based on this review, it proposes a heuristic to set efficient inventory levels for production inputs, work-in-process inventory, and finished goods within an integrated production-inventory storage stage in the conceptual pipeline used in the 5-Box model. Chapter 5 evaluates the models described in chapters 2 and 3 based on three system construction criteria: comprehensiveness, causal orientation, and accuracy. It then discusses two implementation issues of the models. These are the contexts within which they can provide effective decision support and the ability to extend these models into performance measurement systems. Finally, chapter 6 draws some general conclusions.

Chapter 2 STRUCTURAL ANALYSIS OF PRODUCT PIPELINE INTERACTIONS

INTRODUCTION

Chapter 1 pointed out product pipelines can be viewed as interdependent systems. In many situations, decision makers might have some intuitive understanding of general interactions between aspects of such pipeline systems, but are not able to synthesize this knowledge into a coherent picture. This chapter outlines a qualitative approach that analyzes the interactions between aspects of pipeline system performance, such that guidelines for changes to this system can be developed. This approach, termed structural analysis, applies in particular "scenario analysis" in order to identify important factors impacting system performance and to simulate the system changes that could occur if these factors were changed. Scenario analysis methods are generally used to assist decision makers in understanding and supervising complex, interdependent systems. While the particular method may vary, Götze[16] shows that all approaches of scenario analysis usually include the following three steps.

Step 1: Compilation of parameters relevant to the system.

Step 2: Identification of important factors impacting the system based on an understanding of the system interactions.

Step 3: Characterization of possible future situations, or scenarios, that could emerge given changes within the set of system parameters.

Section 2.1 outlines methods to facilitate a compilation of pipeline performance measures. Sections 2.2. and 2.3 show methods that are commonly employed in the second and third steps, respectively. These two steps are applied towards an analysis of interactions between the following five product pipeline measures: level of product pipeline "responsiveness," shipment reliability, average cycle time, accuracy of demand forecasts, and the level of safety stock maintained throughout the pipeline. Section 2.4 provides a definition of these measures and discusses the results of this example, while section 2.5 discusses the limitations and benefits of the methods outlined in this chapter.

2.1 COMPILATION OF SYSTEM ELEMENTS

This section describes methods that can be used to select a set of measures relevant for the description of product pipeline system performance. The focus of this chapter is on the identification of factors influencing the pipeline system and on the analysis of system interactions that are caused by changes in these factors. The methods for the compilation of relevant measures of pipeline performance are therefore outlined only in general terms. Section 2.1.1 provides guidelines to determine the relevance of performance measures while section 2.1.2 describes a hierarchical procedure to develop relevant performance measures.

2.1.1 Guidelines for the determination of the relevance of system measures

In recent years, consulting company studies[17] and multi-industry consortia[18] have proposed detailed lists of key pipeline performance measures. While these studies claim to have general applicability, it appears that the selection of measures to evaluate the performance of a specific product pipeline will ultimately depend on the organizational structure, on the business environment and on other external factors that the pipeline is embedded in. This is why the relevance of a general set of such measures is likely to vary significantly across industries and between individual product pipelines. Moreover, even if some measures within this set are important at one point in time, they might lose their relevance with changes in strategies, processes, markets and technologies. Thus, decision makers are likely to pay attention merely to those measures that are of relevance for the specific circumstances of the particular product pipeline at that point in time.

One method to check the relevance of the selected measures is by examining them with a general set of criteria. A good example of a set of criteria for product pipeline measures is given by the National Council of Physical Distribution Management.[19] These criteria are validity, coverage, comparability, completeness, usefulness, comparability, and cost effectiveness. A complete explanation of the criteria can be found in the Council's 1984 study. A review of further literature on criteria for the selection of measures for the product pipeline is given in Caplice and Sheffi.[20] While these criteria might assure that the selected measures are relevant for further analysis, they do not provide an explicit method to select these measures. This is why section 2.1.2 provides a short outline of methods to develop a set of performance measures.

2.1.2 Method to select relevant measures

A review of methods for the development of pipeline performance measures shows a widespread usage of procedures that dis-aggregate higher level measures in a hierarchical manner. A detailed description of one of these procedures, based on Sieper and Syska,[21] is shown in figure 2.1.

This method aligns all measures in a hierarchical manner along the lines of overall organizational objectives, functional objectives, and departmental objectives. Thus, bottom-line measures are derived from the sub-objectives of a department within a functional group of the overall organization, while higher level measures are established based on the objectives of the organization that manages the pipeline. These decision making levels, shown in figure 2.1, will be outlined in a more detailed manner in section 5.2. A simplified version of the procedure in figure 2.1 is described in Mentzer and Konrad.[22] Using this approach, Pfohl and Zöllner[23] construct a comprehensive product pipeline performance measurement system containing over 50 general measures. However, as mentioned earlier, it is not certain whether each of these measures will actually be relevant for the analysis of all possible pipeline structures.

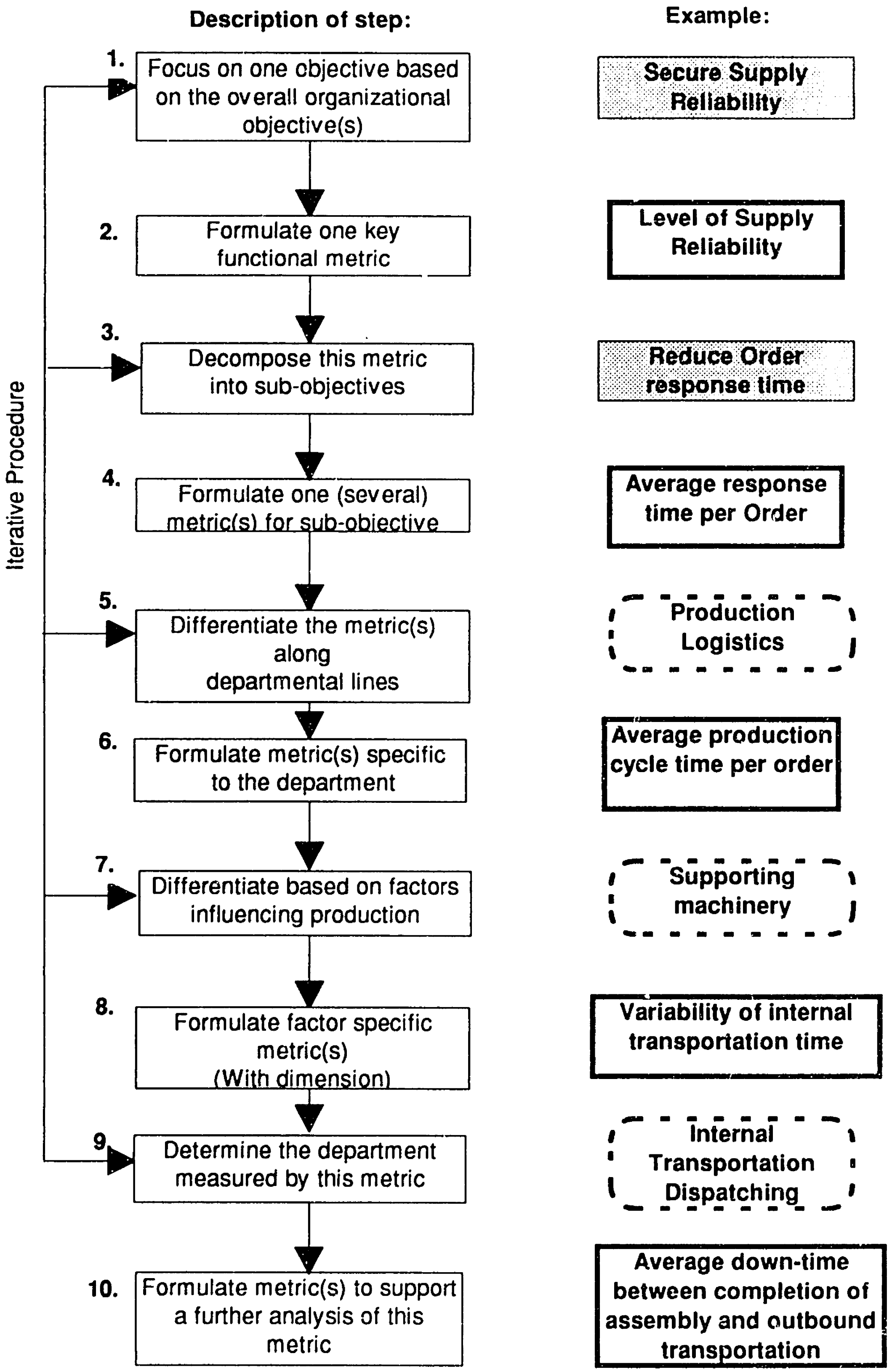


Figure 2.1: Iterative procedure to develop functional objectives and measures (From Sieper *et al.)*

While a hierarchical approach might be sufficient for the determination of a set of performance measures along with a set of performance objectives, it does not necessarily create a clear understanding of how these objectives can be accomplished. According to Caplice,[24] the resulting performance measurement system might not be *useful*, since it does not provide effective guidelines for policies geared to correct the deficiencies that were uncovered by the measures. The approach could thus be enhanced, if it were capable of identifying factors that would be likely to influence system performance such that specific objectives could be achieved. This is why section 2.2 lists methods to facilitate the search for such factors, provided that an adequate understanding exists of the interactions within this system. If these factors are translated into effective policies geared to change the system performance, a method outlined in section 2.3 can simulate the possible changes within the system that these policies could cause.

2.2 COMPILATION AND ANALYSIS OF SYSTEM INTERACTIONS

In the context of the analysis of sections 2.2 and 2.3, it is important to assume that, within an interdependent product pipeline system, some performance measures are likely to measure aspects of system performance that, if changed, can lead to changes in other pipeline performance measures. These measures can therefore be characterized as *influencing factors*. Moreover, it can be assumed that the degree of the changes that are created by those aspects that they measure will determine the degree, to which they act as an *influencing factor*. Given this ambiguity, it is useful to speak of a *system element* that is analyzed. A *system element* can be both a descriptor of system performance and a factor capable of influencing system performance.

The methods of sections 2.2 and 2.3 require the development of a set of time independent interactions within the group of elements that is intended to be analyzed. In general, the success of these methods depends on the ability to provide this input. If provided with this information, methods outlined in section 2.2 can determine the ability of each element to lead to system changes by means an analysis of its interactions with other system elements. A "structural analysis matrix," as proposed by Reibnitz,[25] is shown in section 2.2.1 to evaluate the elements based on the direct impacts that they have on other system elements, while the results obtained with the structural analysis matrix are visualized in section 2.2.2 in form of a system grid, defined below. In section 2.2.3, the nature of the system elements is evaluated based on the indirect linkages between system elements. This evaluation is done by means of the MICAMC method of Godet,[26] defined below. Section 2.2.4 summarizes the MICMAC results in form of a system grid in the same manner as section 2.2.2.

2.2.1 The Structural Analysis Matrix

Reibnitz[27] views the structural analysis matrix as a method to determine the specific nature of elements within an interdependent system based on the direct impacts that they have on other system elements. For the example that is applied throughout this chapter, the structural analysis matrix is constructed by entering five elements into the top row and first column of a 5x5 matrix, such as shown in figure 2.2. Next, the interactions occurring between these elements are captured inside of the matrix. The direction of impact within the structural analysis matrix points from the column elements to the row elements. This means that the value of the matrix element s_{mn} shows the magnitude of the impact of element m on element n. According to Vester,[28] two important aspects of any scale to evaluate this magnitude are the inclusion of a median value and the exclusion of zero. A common scale to evaluate the magnitude of impacts within the system - that is, the value of the elements within the structural analysis matrix - can extend from one to five, where:

1 = non existent or very weak impact
2 = weak impact
3 = medium impact
4 = strong impact
5 = very strong impact

These interactions can be determined by means of an "expert" survey, which implies to obtain some form of objective feedback that can rank the impacts. This information can be derived from group discussions or from interviews with experts. It should be noted that this set of interactions is nearly the only information that the structural analysis methods require from users.

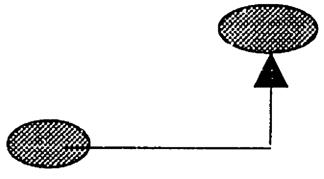
The structural analysis matrix is evaluated by computing the *active* and *passive* sum of each individual system element. The sum of each row represents the *active* sum of the element that has been assigned to this row, while the sum of each column represents the *passive* sum of the element assigned that has been to this column. A high *active* sum indicates that an element has a strong influence on other elements, while a high *passive* sum indicates that an element is likely to experience a large impact from other elements. According to Gomez,[29] the product and the quotient of the active and passive sums gives a first indication of the nature of an element within the system. The evaluation of the elements is discussed in greater detail in section 2.2.2.

The structural analysis matrix for the five elements of this example is shown in figure 2.2. The system elements are introduced in section 2.4.

Structural Analysis Matrix for Pipeline Elements

	A	B	C	D	E	AS	Rank	AS/PS	Rank
A	0	3	1	1	1	6	4	0.60	4
B	3	0	2	2	1	8	3	0.89	3
C	3	1	0	5	1	10	1	1.67	2
D	1	1	2	0	1	5	5	0.56	5
E	3	4	1	1	0	9	2	2.25	1
PS	10	9	6	9	4	38			
Rank	1	2	4	2	5				
PS*AS	60	72	60	45	36				
Rank	2	1	2	4	5				

A	Safety Stock
B	Supply Reliability
C	Cycle Time
D	Responsiveness
E	Forecast Accuracy



Direction of Impact

AS: Active Sum PS: Passive Sum

Figure 2.2: The Structural Analysis matrix

2.2.2 The System Grid based on direct system impacts

The results of section 2.2.1 can be analyzed graphically by means of a two dimensional coordinate system, a so-called system grid. The elements are entered into the system grid by plotting the values of an element's passive sum on the horizontal axis and the values of the active sum on the vertical axis. The averages of the *active* sums and of the *passive* sums are added to the graph as grid lines that divide it into four sub-fields. Reibniz[27] and Godet[30] describe the nature of elements that are located in the four resulting sub-fields in the following manner, starting from the top left field and continuing in clockwise order.

A system grid that evaluates the five elements of this example based on their direct impact on other elements is listed in chart 2.1.

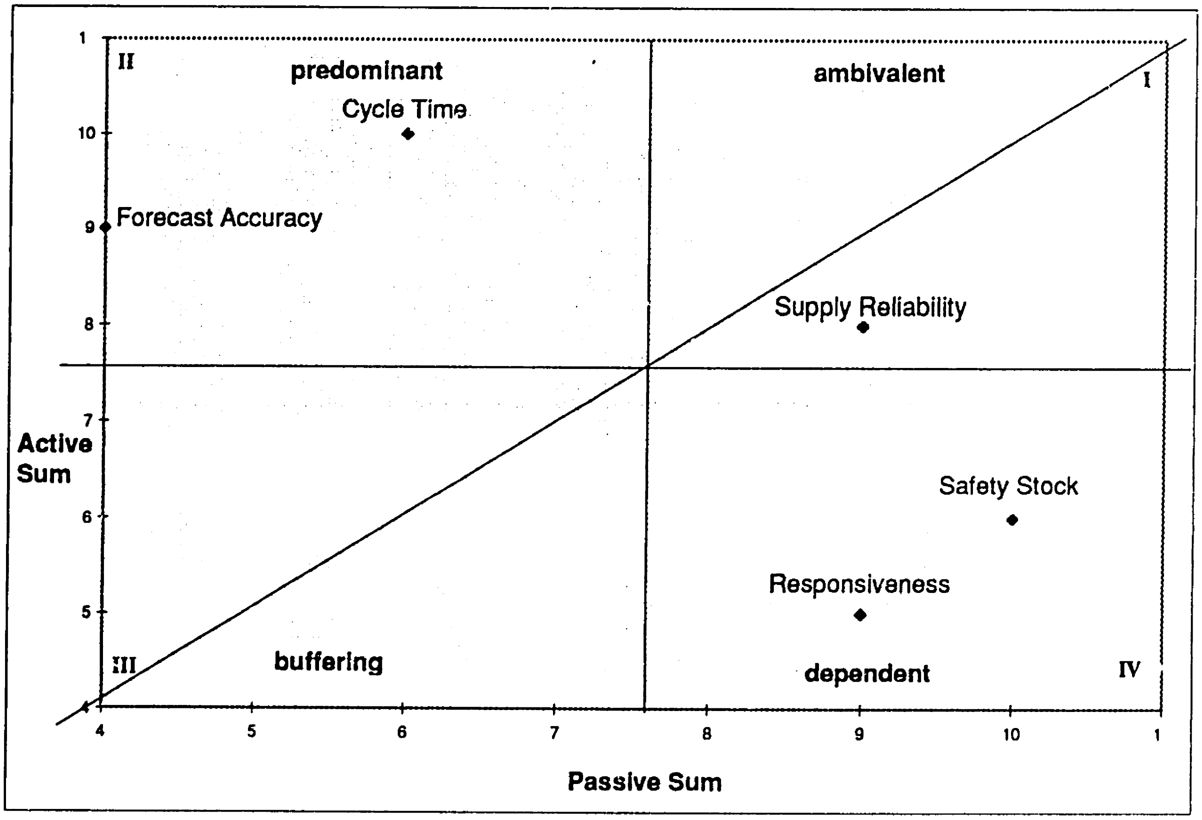


Chart 2.1: System Grid for direct impacts of pipeline elements

"Predominant element" field:

The top left field contains *predominant* elements that exert a strong influence on other elements, while experiencing only little influence from other elements. They are relatively stable and will, when changed, lead to lasting impacts on the entire system. These elements therefore represent the most effective and pervasive factors capable of making changes within the system.

"Ambivalent element" field:

The top right field contains *ambivalent* elements, meaning that they are heavily influenced by other elements while they are also capable of strongly influencing other elements. This is why they should be treated with great care when attempting to intervene in the pipeline system.

"Dependent element" field:

The bottom right field contains *dependent* elements that are highly influenced by most other factors in the system. They will usually be the first to react to any changes, and can thus serve as good indicators for the system behavior. However, changes in these elements are unlikely to impact the system.

"Buffering element" field:

Finally, the bottom left field contains buffering elements that experience only a marginal influence from other factors and usually remain unchanged, even after large scale changes within the system. They have however only little ability to influence the rest of the system and are generally unsuited for effective system interventions.

Angermayer-Naumann[31] points out that the diagonal through the origin of the system grid is the border between relatively *predominant* and relatively *dependent* elements. According to Gomez,[29] the relatively *predominant* elements have a quotient of *active* and *passive* sum that is greater than one and are therefore located above this line. In contrast, the elements with a quotient of *active* and *passive* sum that is less than one are relatively *dependent*, and will be located below this line.

The results of this step are discussed in section 2.4.

2.2.3 The MICMAC method

The study of the direct impacts in section 2.2.1 does not capture the importance of indirect linkages between system elements. For example, the two subsystems (sets of closely related elements) S_1 and S_2, that are shown in figure 2.3, might appear to be independent from each other - that is, if they were not linked by a series of connecting elements. An analysis of merely the direct impacts in figure 2.3 would conclude that *a* is influenced by subsystem S_1 and subsystem S_2 is influenced by *c*. This analysis neglects however element *b*, which serves as the relational link between the two subsystems S_1 and S_2.

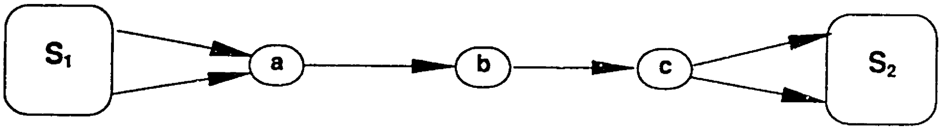


Figure 2.3: Indirect chains of influence

The MICMAC method, developed in 1974 by Godet and Cupperin,[26] provides a simple and intuitive approach to resolve this dilemma. MICMAC is a French acronym signifying the multiplication of cross impact matrices to obtain a classification of the indirect linkages between system elements. It investigates the indirect linkages, or chains of influence, that relate system elements with one another. The input that is required for the MICMAC method is a square Boolean matrix, identical in form to the input matrix for direct system impacts that was introduced in section 2.2.1. The MICMAC method requires a Boolean matrix as it measures the degree of indirect system linkages based on the total number of linkages connecting elements, not by means of the strength of individual interactions. This is why the input matrix for the MICMAC method observes merely the presence of system impacts, not the degree of these impacts. This input matrix can thus be obtained by modifying the input matrix for section 2.2.1 such that all impacts with values greater than 1 are set equal to the value 1, while those with values of 1 are set equal to the value 0. The MICMAC method proceeds by multiplying the initial matrix by itself repeatedly, up to the point, where a ranking of the values on the diagonal of the matrix no longer changes.

Godet,[26] justifies the computational procedure in the following manner. If A(*n*,*n*) is an initial (MICMAC) matrix for *n* elements, the following relations will exist:

All direct system impacts are of order 1 and can be written as $A = a_{ij}^1$, where $a_{ij}^1 = 1$ if there is an impact of element *i* on element *j*. In this case, a chain of influence of length 1 links *i* to *j*. Starting with the square of the initial matrix, it is possible to determine the indirect linkages. This means that an (indirect) impact of order 2 can be written as $A^2 = A * A = a_{ij}^2$, where:

$$a_{ij}^2 = \Sigma^n_{k=1}\, a_{ik}^1 * a_{kj}^1 \qquad [2.1]$$

for any intermediate element $k = (1,..,n)$. In particular, when $a_{ij}^2 = 1$, there exists an element *k* such that:

$$a_{ij}^2 = a_{ik}^1 * a_{kj}^1. \qquad [2.2]$$

In other words, element *i* has an impact on the element *k*, which in turn has an impact on the element *j*. (*i*—*k*—*j*). It is thus possible to speak of <u>one</u> chain of influence of length 2 linking *i* to *j*. Accordingly, when $a_{ij}^2 = 2$, there exist two elements, k_1 and k_2, such that:

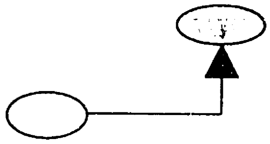
$$a_{ij}^2 = a_{ik_1}^1 * a_{k_1j}^1 + a_{ik_2}^1 * a_{k_2j}^1. \qquad [2.3]$$

In other words, there are two intermediate elements and <u>two</u> chains of influence of length 2 linking element *i* to *j*. Generally speaking, when $a_{ij}^2 = L$, there are *L* elements $k_1, k_2, \ldots k_L$, and *L* chains of influence of length 2 link *i* to *j*. After *n* multiplications, the chains of indirect influence have the length *n*, and $a_{ij}^n = L$ implies that there are *L* chains of influence of length *n* linking i to j.

Godet[26] contends that the values of *L* can be taken as a degree of the level of interaction between two elements, and that the MICMAC method can therefore produce a ranking of the indirect linkages between the system elements. Thus, in the same manner as outlined in section 2.2.2, the row and column sums of all elements can serve as an indicator of the relative level of *predominance* or *dependence* that each element has within the system. Elements with $i = j$ are located on the diagonal and denote the number of feedback loops that are present in the system. In general, $a_{ij}^1 = 0$, since a variable is assumed not to have an impact on itself. Throughout the matrix multiplications, the values of these elements are ranked and, as mentioned, the multiplications are continued until no further changes in the ranking of the feedback loop elements occurs. Godet[26] notes that this classification tends to stabilize rapidly and can be stopped after five to ten iterations.

The initial MICMAC matrix, used for the five elements of this example, is shown in figure 2.4. This matrix was multiplied ten times, and after seven iterations, the rank of the diagonal values stabilized. The value of the final matrix, V^{10}, was used as an input for the system grid, is also listed in figure 2.4.

MICMAC-Matrix for indirect relationships



Direction of impact

V^1=

	A	B	C	D	E	AS	Rk. a	Rk. b
A	0	1	0	0	0	1	4	1
B	1	0	1	1	0	3	1	1
C	1	0	0	1	0	2	2	1
D	0	0	1	0	0	1	4	1
E	1	1	0	0	0	2	2	1
PS	3	2	2	2	0	9		
Rk. c	1	2	2	2	5			

V^{10}=

	A	B	C	D	E	AS	Rk. a	Rk. b
A	16	11	11	10	0	48	4	1
B	22	16	21	11	0	70	2	1
C	21	11	16	11	0	59	3	1
D	11	10	11	6	0	38	5	4
E	27	17	21	15	0	80	1	5
PS	97	65	80	53	0	295		
Rk. c	1	3	2	4	5			

A	Safety Stock
B	Supply Reliability
C	Cycle Time
D	Responsiveness
E	Forecast Accuracy

AS: Active Sum PS: Passive Sum

Rk. a: Rank of Active Sum
Rk. b: Rank of values in Diagonal
Rk. c: Rank of Passive Sum

Figure 2.4: MICMAC matrices V^1 and V^{10}

2.2.4 The System Grid based on indirect linkages

The values of the active and passive sums of the final MICMAC matrix can be examined by a system grid for indirect linkages in the same manner outlined in section 2.2.2. The system grid for indirect linkages for this example is listed in chart 2.2. The results of this step will be discussed in section 2.4.2.

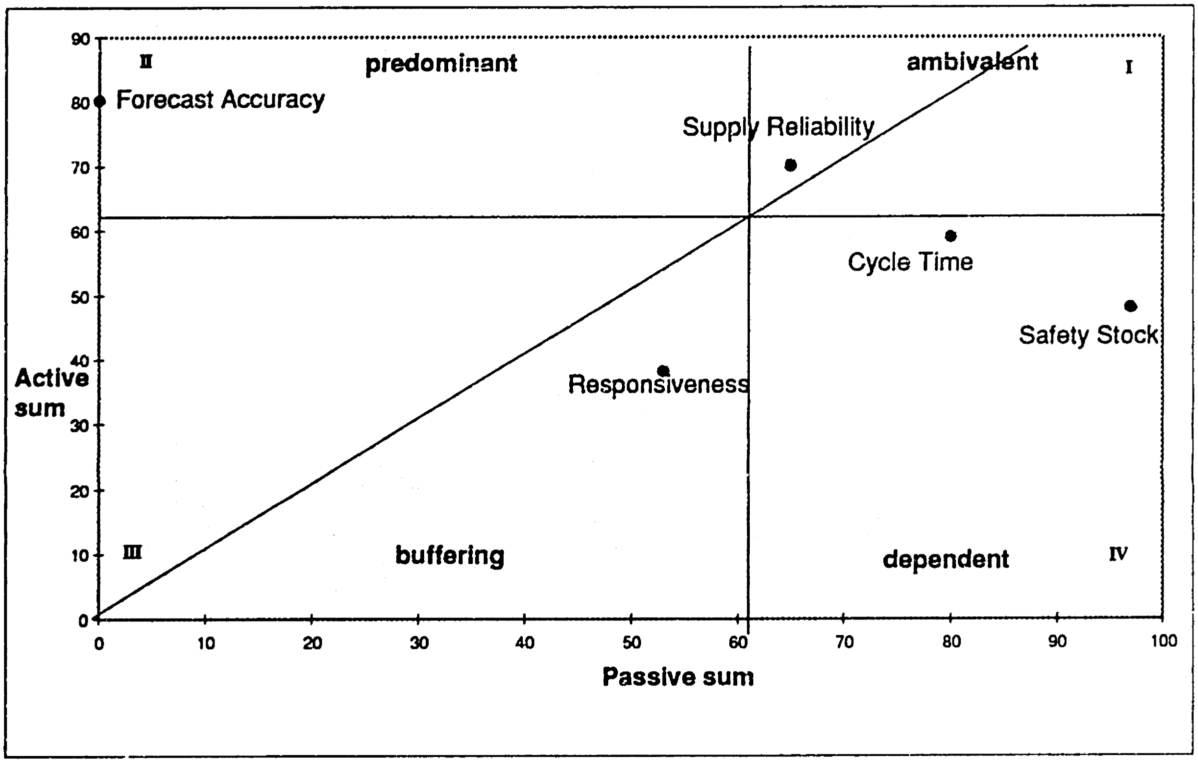


Chart 2.2: System Grid for indirect linkages between product pipeline elements

In conclusion, it can be noted that the analysis provided by the structural analysis matrix and the MICMAC matrix is limited to a description of the nature of the system elements that is based on a set of pre-specified interactions between the elements. These methods therefore can show the degree to which an element is likely to impact the system, but do not capture the manner in which a change of this element will impact the system over time. This issue is addressed with the Kane simulation, outlined in section 2.3.

2.3 TIME DEPENDENT INTERACTIONS OF SYSTEM ELEMENTS

Section 2.3 outlines the third part of the structural analysis. It describes a simulation model to determine the effects of time dependent, causal system interactions that result from the impact of a change in internal and external elements, given the set of interactions established in section 2.2.1. Götze[16] points out, that the Kane Simulation (KSIM) is one of the few dynamic simulation methods that is capable of modeling deterministic time independent interactions.

KSIM is a deterministic simulation model developed by Kane[32] and extended by Lipinski and Tydemann[33] that allows a dynamic simulation of system interactions. The model is based on equation 2.3, which portrays an S-shaped growth or decline of the variables being modeled. This equation provides the continuous, dynamic (time dependent) characteristics of KSIM. The elements to be modeled by KSIM, X_i, are first quantified such that the maximum and minimum permissible value of each element can be determined in order to normalize it on a scale of 0 to 1. Based on this scale, the initial values are entered, and the simulation marches forward, changing the values a step at a time using the differential equation:

$$\frac{dX_i}{dt} = \sum_{j=1}^{N}\left(\alpha_{ij} + \beta_{ij}\frac{dX_j}{dt}\right) X_i \ln X_i \qquad [2.4]$$

where:

X_i = The element that is described.

N = The total number of elements considered.

X_j = The impacting elements.

α_{ij} = The trend of X_j that is expected to occur with a change in X_i

β_{ij} = The impact of the rate of change of X_j on X_i

The solution to this logistic equation is:

$$X_i(t + \Delta t) = X_i(t)^{P_i(t)} \qquad [2.5]$$

where:

$X_i(t + \Delta t)$ = Value of element at the end of the time period

$X_i(t)$ = Value of X_i at the start of the time period

Δt = Time period

and:

$$P_i(t) = \frac{1 + \Delta t(\text{sum of inhibiting impacts on } X_i)}{1 + \Delta t(\text{sum of enhancing impacts on } X_i)}$$

which can be formulated as:

$$P_i(t) = \frac{1 + 0.5t \sum_{j=1}^{N} \left[\left| I_{ij}(t) \right| - I_{ij}(t) \right] X_j(t)}{1 + 0.5t \sum_{j=1}^{N} \left[\left| I_{ij}(t) \right| + I_{ij}(t) \right] X_j(t)} \qquad [2.6]$$

where:

$$I_{ij} = \alpha_{ij} + \frac{\beta_{ij}}{X_j(t)} \left[\frac{dX_j(t)}{dt} \right] \qquad [2.7]$$

The characteristics of the function generated by KSIM shows the standard features of an S-shaped curve. For example, when the sum of the inhibiting impacts is greater than that of the enhancing impacts, the power $P_i(t)$ in equation 2.4 will be larger than one. And, since $0 \leq X_i(t) \leq 1.0$, $X_i(t+\Delta t)$ will be smaller than $X_i(t)$. Further, all else being equal, the larger the element causing the impact, the greater the magnitude of that impact will be. Also, a given value of $P_i(t)$ will have less effect on the magnitude of X_i, if X_i is near either 0 or 1. This produces the S-shaped variation that can be expected of KSIM curves.

It should be noted that the input matrices for KSIM differ from the impact matrices of section 2.2 in the sense that they indicate whether an impact has an enhancing or an inhibiting effect on an element. Porter *et al.*[34] set the range of the α and β matrix elements at (-3) to (+3), with (+3) indicating a strong enhancing impact, and (-3) indicating a strong inhibiting impact. Moreover, the effects of external impacts can be captured in form of additional elements that are added into the α and β matrices. This is done by entering the impacts as additional row values, but not column variables. Thus, an external impact will influence the elements in the model, however will not experience any influence stemming from these elements. Once the α and β matrices have been determined, a computer program can be used to solve the equations and show the interactions over time.

The value of β_{ij}, the impact of the rate of change of each element (dX_i/dt) on another element X_j, can be obtained from the input matrix for section 2.2.1. The values of this matrix are changed to the (+3) to(-3) scale of the β_{ij} values, shown in figure 2.5, in the following manner: Values of 1 are set equal to 0 in the β-matrix, values of 2 are set equal to 1, values of 3 and 4 are set equal to 2, and values of 5 are set equal to 3. In this example, the direction of impact of the β-matrix values is based on further assumptions, outlined in section 2.4.2. While this procedure appears somewhat inaccurate, a sensitivity analysis shows that the simulation results are fairly insensitive to the absolute values of β_{ij}. The values of α_{ij}, reflecting the trend of X_j that is expected to occur with changes in the value of X_i, are based on the conclusions that can be made from the analysis of section 2.2, which is captured in figure 2.6 in section 2.4.2. Finally, the initial values of the simulation are based on the particular situation that is intended to be modeled. The resulting system behavior is captured in charts that plot the values of the variables over several time periods. The KSIM charts for this example are shown in appendix 2.1.

Impact of row variables on column variables:

	1	*2*	*3*	*4*	*5*
1. Safety Stock	0	2	0	0	0
2. Reliablity	-2	0	-1	1	0
3. Cycle Time	2	-1	0	-3	0
4. Responsiveness	0	0	-1	0	0
5. Forecast Accuracy	-2	2	0	0	0

Figure 2.5: Beta-Matrix for the Kane simulation

It should be noted that the applicability of KSIM is limited by the fact that it assumes that all system elements along with their interactions can be defined accurately, that realistic bounds can be placed on the variables, that a growth curve adequately represents the change patterns being studied, that the pairwise relationships portrayed by the matrices adequately represent true causal interactions, and finally that it, much like the rest of the structural analysis, assumes a deterministic world. Given these issues, a more in-depth discussion of the general applicability of KSIM is provided in section 2.5

2.4 APPLYING THE STRUCTURAL ANALYSIS METHOD

Section 2.4 describes the elements and the assumptions that were used to illustrate the structural analysis matrix evaluation and the MICMAC method of sections 2.2 and 2.3, and it discusses the results obtained from this analysis.

2.4.1 Description of system elements and initial assumptions

This section defines the pipeline elements which, as noted in section 2.2, represent both performance measures and influencing factors. As mentioned in section 2.2, an element can influence the system if the aspect of the system that it tracks can cause system changes. The objective associated with each element and the measure that tracks its performance, are outlined in this section such as shown in the procedure of section 2.1. The description of the elements however does not follow a hierarchical order.

Element 1: Supply Reliability The objective associated with this element is the ability to deliver products to a customer within the product pipeline precisely at the time that was committed to the customer at order entry. This element is usually measured by determining the percentage of orders that are delivered on-time.

Element 2: Responsiveness The objective associated with this element is the ability to deliver a set of products in the minimum necessary time between customer order and final shipment. This element is measured by determining the amount of items offered to customers that are lower than the average order response time quoted by competitors.

Element 3: Safety stock The objective associated with this element is the minimization of working capital that is tied up in the storage of products throughout the product pipeline, either in form of raw material, work-in-process inventory, or finished goods. However, a policy to pursue this objective may be at odds with the need to avoid a disruption of the material flow through the pipeline. This element is usually measured by determining the days of supply that could be covered by the inventory at hand, if it had to meet demand without being replenished.

Element 4: Cycle Time The objective associated with this element is the minimization of the time that products remain in the pipeline. This element is usually measured by the elapsed time between the point that materials enter the product pipeline system as raw materials or semi-finished goods, and the point at which they leave it as finished products.

Element 5: Forecast Accuracy The objective associated with this element is to provide a prediction of demand patterns for specific periods in the future that is as accurate as possible. It is usually measured by taking the dollar amount of the discrepancy between the actual demand and the forecasted demand over the forecasting period, and dividing this discrepancy by the total amount of forecasted demand.

2.4.2 Identifying and analyzing system interactions

Using the definitions of section 2.4.1, one can assume six possible interactions within a "make to order" pipeline system containing the five pipeline elements:

- The pipeline *supply reliability* interacts with the pipeline *safety stock*. In the absence of innovative channel arrangements such as JIT, the level of safety stock maintained throughout the pipeline will have some impact on the ability to ship products to customers on-time. The degree of impact of *safety stock* on *supply reliability* is thus assumed to have a medium level of 3. Likewise, the level of safety stock that is maintained at a production site in order to guarantee a steady supply stream for production will be based on the reliability of incoming shipments from suppliers. This is why the degree of impact of *supply reliability* that is present throughout the pipeline on *safety stock* is also assumed to have a medium level of 3.

- The pipeline *supply reliability* interacts to some extent with the *cycle time*. Having material flow rapidly through the pipeline system is dependent on the ability of each point within the product pipeline to make production inputs available when they are ordered. While the availability of material is usually assured by the maintenance of safety stock, this might not be the only determinant of a steady stream of products. Thus, other components of supply reliability, such as the order completion cycle time, might impact the speed of material flow, too. As these aspects might only have minor significance for the ability to make goods available, the impact of *supply reliability* on *cycle time* is assumed to be weak, however present, and thus set at a level of 2. At the same time, a fast flow through the pipeline can be assumed to assure small lead times and might thus lead to improvements in *supply reliability*. This is why the degree of impact of *cycle time* on *supply reliability* is also assumed to be weak, however present, and also set at a level of 2.

- The pipeline *supply reliability* impacts the *responsiveness* of the product pipeline to some extent. The ability to provide a short order fulfillment time will be influenced by the capability to deliver products on-time. The degree of impact of *supply reliability* on *responsiveness* was however assumed to be weak and thus set at a level of 2.

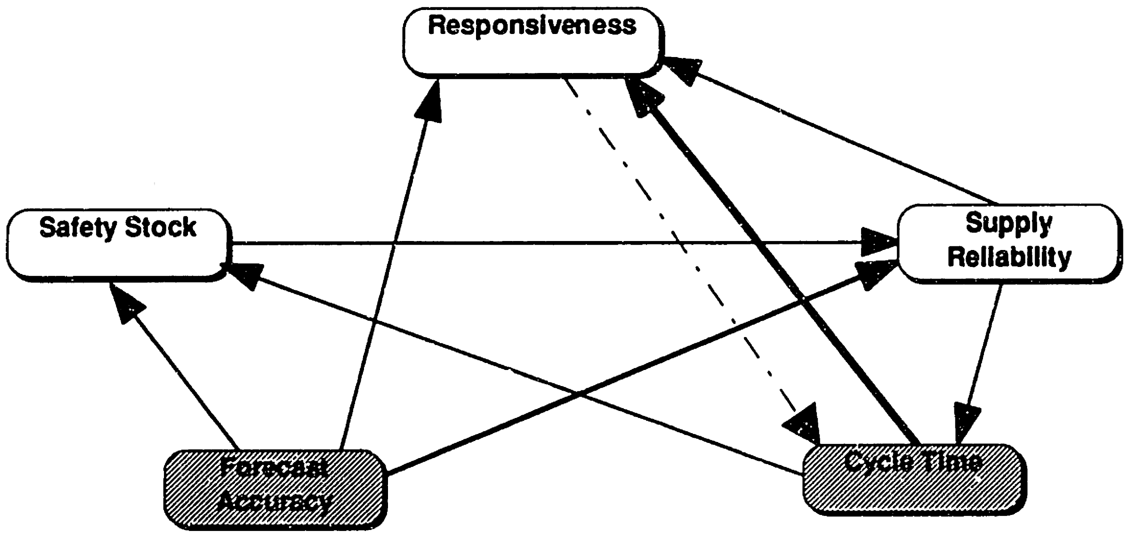
- The *cycle time* impacts the pipeline *safety stock*. The time required to move material through the pipeline will determine the total amount of inventory that is effectively present within the pipeline at any point in time. If the amount of safety stock present in the pipeline correlates with the total level of inventory stored throughout the pipeline, then *cycle time* can impact *safety stock*. The degree of impact of the *cycle time* on *safety stock* is assumed to have a medium level of 3.

- The pipeline *cycle time* has a strong impact on the pipeline *responsiveness*. In a "make to order" pipeline, the time required to move products through the pipeline has a strong influence on the time that it takes to process and fulfill a customer order. The degree of impact of *cycle time* on *responsiveness* is thus assumed to have a high level of 5. *Responsiveness*, in turn, could have a marginal impact on *cycle time*, if a policy geared to find improve the responsiveness were able to shorten the *cycle time*. This influence was however assumed to be weak, and set at a level of 2.

- Finally, *forecast accuracy* has a significant impact on the pipeline *supply reliability* and *safety stock* . Demand variability will impact the reliability with which customer orders are fulfilled. The degree of impact of *forecast accuracy* on *supply reliability* is assumed to have the high level of 4. At the same time, it can impact the amount of safety stock that is maintained in order to protect against a shortfall of supply. The degree of impact of *forecast accuracy* on *safety stock* is therefore assumed to have a medium level of 3.

With these assumptions, the structural analysis matrix is completed and the results are entered into the system grid for direct impacts. The result, captured in chart 2.1, the system grid for direct impacts, shows that both the elements *forecast accuracy* and *cycle time* are located in the *predominant* element field[ii]. Thus, based on these elements' direct interactions, it can be assumed that changes in these elements will significantly impact the overall pipeline system. These elements can be contrasted with the *dependent* elements *safety stock* and *responsiveness*, which are likely to be heavily influenced by the other elements. Finally, the *supply reliability* element is *ambivalent* in the sense that it can exert influence on the system by means of *safety stock* , *cycle time, and responsiveness* while it can also be influenced by the system due to changes in *safety stock* and *forecast accuracy*. Based on these results, a diagram listing the direct impacts is shown in figure 2.6.

[ii] In section 2.2.2, the following characteristics of elements were outlined: *Predominant* elements exert a strong influence on other elements, while experiencing only little influence from other elements. *Ambivalent* elements are heavily influenced by other elements while they are also capable of strongly influencing other elements. Finally, *dependent* elements are highly influenced by most other factors in the system while changes in these elements are unlikely to impact the system.



Element	*Objective*
A. Safety Stock	Low
B. Reliability	High
C. Cycle Time	Low
D. Responsiveness	High
E. Forecast Accuracy	High

Figure 2.6: Evaluation of pipeline elements based on direct impacts.

In the next step, the elements are analyzed based on their indirect system linkages. As stated in 2.2.3, the input for this step is provided by the structural analysis matrix, while the results are captured in the final MICMAC matrix of figure 2.4 and in the system grid for indirect linkages in chart 2.2. After this step, the nature of two elements has shifted. Based on the indirect linkages within this system, the element *responsiveness* is no longer a *dependent* element, but rather a *buffering*[iii] element which is neither capable of influencing the system nor of being significantly influenced by the system. This is why it is likely to be disregarded when attempting to either

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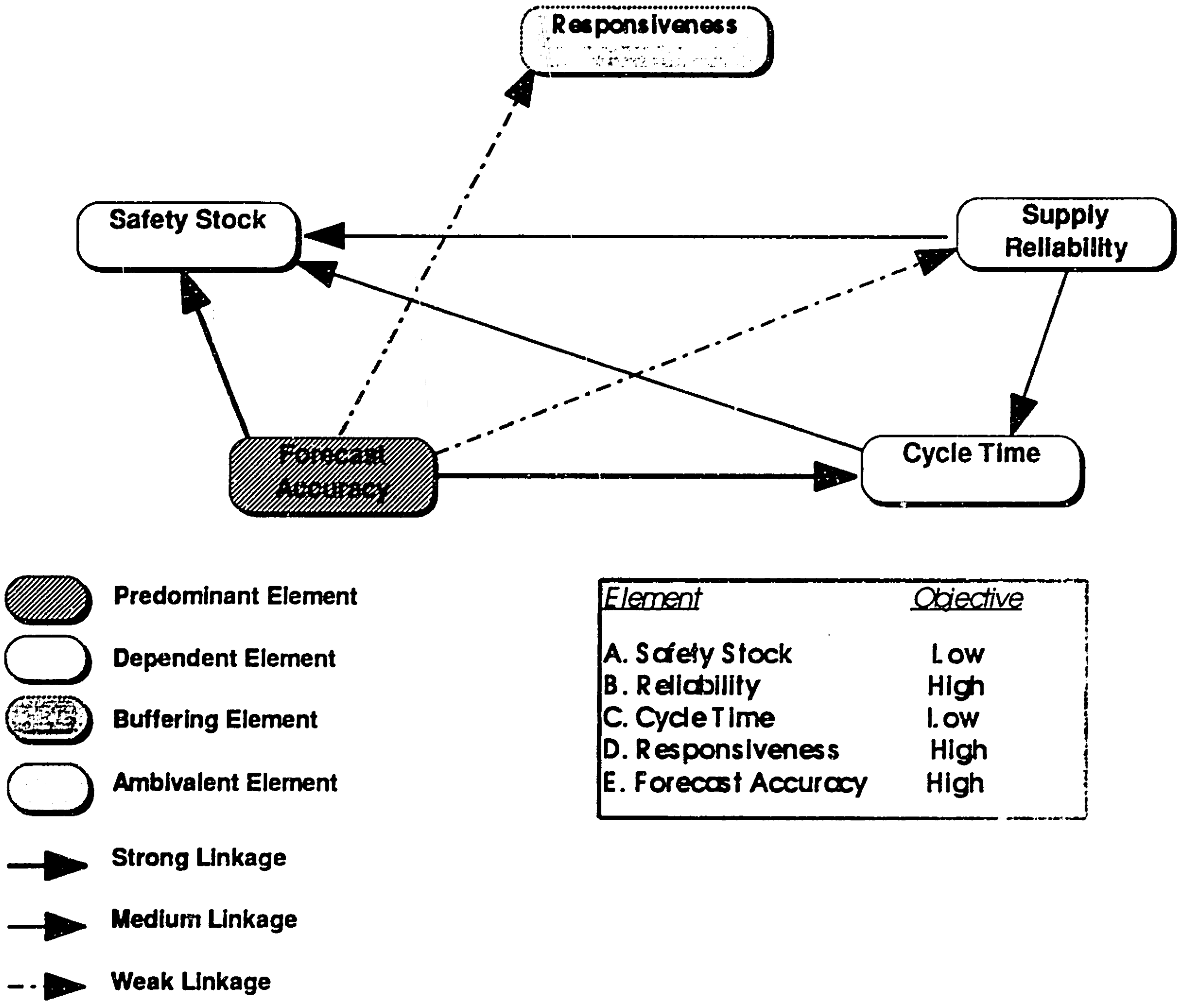
[iii] As mentioned in section 2.2.2, buffering elements experience only a marginal influence from other factors, have however only little ability to influence the rest of the system.

change the system or measure system changes. Moreover, *cycle time*, initially considered a *predominant* element, has turned into a *dependent* element. This is apparently due to a strong influence that the elements *forecast accuracy* and *supply reliability* exert on *cycle time* by means of indirect linkages. Thus, a change in *cycle time* will be unlikely to change the system by means of indirect linkages as much as it will be influenced by other elements, and the only *predominant* element left is *forecast accuracy*. The elements *safety stock* and *supply reliability* remain unchanged. Based on these results, a diagram listing the indirect linkages is shown in figure 2.7.



Element	Objective
A. Safety Stock	Low
B. Reliability	High
C. Cycle Time	Low
D. Responsiveness	High
E. Forecast Accuracy	High

Figure 2.7: Evaluation of pipeline elements based on indirect linkages.

The understanding of the system that has been gained up to this point can be summarized as follows: it is likely that lasting changes throughout the system can be achieved by means of changes in the *forecast accuracy* element. Changes in the *cycle time* element are likely to have an immediate impact on the system, but might not achieve lasting changes. The element *safety stock* could serve as a good indicator of system changes. (This would imply that safety stock policies are continuously adjusted such that they reflect the current situation). It will be necessary to plan changes to the *supply reliability* element carefully if it is used to intervene in the system since it can cause significant changes to the system, while at the same time it can be easily changed. Finally, the *responsiveness* element does not appear very suitable either for measuring the system or for making changes to the system. It should be noted that, while *forecast accuracy* appears to be a strong influencing factor within this set, other elements might have an even stronger influence on product pipelines. For example, Pohdehl[35] shows that if the element *product complexity* is considered in a structural analysis examining a similar set of elements, it is likely to exert a stronger influence on the system than *forecast accuracy*. A definition of *product complexity* and a discussion of the issue of omitting it from the overall analysis of a pipeline system is given in section 3.3.3.

While these results might merely reflect well known and researched aspects of pipeline management, it should be noted that this example includes only a small, illustrative set of elements. Other studies[36] have shown that a larger set of elements with a more comprehensive coverage of direct impacts could lead to more detailed and useful results. Moreover, a review of applications of the scenario analysis in section 5.2.2. shows that it finds a large usage for high level analysis of more complex systems, where the analysis of influencing factors might not be as straight forward.

The assumptions that were made to determine the system interactions were described in section 2.4.1. The interactions between these factors were analyzed in section 2.4.2 such that those factors with the greatest impact on the system could be found. The results indicate that a better understanding of the system impact of changes in the accuracy of forecasts and the impact of changes in the length of the cycle time appears important. The simulation of these impacts is described in section 2.4.3.

2.4.3 Simulating system interactions

This section analyzes the impacts of both an improvement and a deterioration of *forecast accuracy* and *cycle time*. Both forms of change are considered in this example due to the circumstance that, while managerial policies are usually geared to improve an element, it is also necessary to understand the impact of the deterioration of an element due unexpected external events. All elements in this example can thus be assumed to either improve or deteriorate over time. Given the two elements that are analyzed in the context of this simulation, four possible courses of action can occur. These are analyzed in section 2.4.3.1. The impact of these changes on three possible initial system states is shown in section 2.4.3.2.

2.4.3.1 CHANGES EXPECTED TO OCCUR IN SIMULATION

The interactions outlined in this section are captured in the α-matrix of the Kane simulation, described in section 2.3. These interactions cover the first and second order impacts of the changes that are assumed to occur. Indirect impacts of a higher order are not reflected in the α-matrix, because these will not be easily identifiable. These changes will be covered instead by values of the β-matrix, which represents the system impacts that are caused by the rate of change of each element. All α-matrices resulting from the assumptions made below are shown in appendix 2.1. The direction of each impact was determined from the assumptions that were made in section 2.4.2. In this step, it is necessary to reconstruct the precise course of action that can be assumed to occur within the system. Thus, it is necessary to understand the direct impacts within the system, and not the indirect linkages between elements. While the MICMAC results provided an extension to a general analysis of the nature of the system elements, they are not useful as an input for the KSIM analysis.

<u>Change 1:</u> Increased *forecast accuracy* within the system.
From figure 2.6, it could be assumed that an improved *forecast accuracy* would directly lead to a decrease in *safety stock* and to an increase in *supply reliability*. The decrease in *safety stock* could however lead to a decrease in *supply reliability*. On the other hand, the increased *supply reliability* could not only lead to an increased *cycle time* and to a lower *responsiveness*, but also to a further decrease in *safety stock*.

Change 2: Reduced *forecast accuracy* within the system.

As mentioned above, it might be important to understand the impact of changes in demand variability that could decrease the ability to anticipate orders correctly. From figure 2.6, it could be assumed that a reduced *forecast accuracy* would directly lead to an increase in *safety stock* and to a decrease in *supply reliability*. The increase in *safety stock* could however lead to an increase in *supply reliability*. On the other hand, the decrease in *supply reliability* could lead to an increased *cycle time*, a lower *responsiveness*, and to a further increase in *safety stock* .

Thus, a change in *forecast accuracy* is likely to initiate two dynamics within the system. Changes in *supply reliability* appear to be influenced both by counteracting changes of *forecast accuracy* and of *safety stock* . At the same time, changes in *safety stock* appear to be influenced by changes of *forecast accuracy* and of *supply reliability*. It is thus not clear, how *safety stock* and *supply reliability* will act over time.

Change 3: Decreased cycle time.

From figure 2.6, it could be assumed that reducing the *cycle time* would directly lead to a decrease in *safety stock* , an increase in *supply reliability*, and an increase in *responsiveness*. A decrease in *safety stock*, in turn, could lead to a decrease in the *supply reliability*. At the same time, an increase in *supply reliability* could lead to a decrease in *safety stock* , a further decrease in *cycle time* and an increase in *responsiveness*.

Change 4: Increased cycle time.

Again, it might be important to understand the impact of external changes that could necessitate a longer *cycle time*. From figure 2.6, it could be assumed that increasing the cycle time would directly lead to an increase in *safety stock* , a decrease in *supply reliability* and a decrease in *responsiveness*. An increase in *safety stock* , in turn, could however lead to an increase in *supply reliability*. At the same time, a decrease in *supply reliability* could lead to a further increase in *safety stock* , a further increase in *cycle time* and a decrease in *responsiveness*.

Thus, a change in *cycle time* is likely to initiate two dynamics within the system. The element *safety stock* appears to be influenced both by reinforcing changes of the element *cycle time* and of the element *supply reliability*. At the same time, changes of the element *supply reliability* appear to be influenced by counteracting changes of the element *cycle time* and of the element *safety stock.* It is thus not clear, how *supply reliability* will act over time.

The beta matrix for all simulations is shown in figure 2.5. Both the α and the β matrices were assumed to have an equal level of influence on the simulation process. Thus, both the α and the β multipliers were set at 0.5. A sensitivity analysis showed that the specific level of the multipliers merely shifts the simulation results in time, but does not change the overall results.

2.4.3.2 INITIAL VALUES FOR SIMULATION

The initial values for the Kane simulation are shown in table 2.1. In the contrived example of this chapter, three different possible pipeline system states are developed. Each state is represented by the situation of a pipeline within a specific manufacturing facility. Facility 1 can be assumed to face a situation where a high *forecast accuracy* coincides with a long *cycle time* and a low level of *safety stock.* Facility 2 faces a situation where a low *forecast accuracy* coincides with a short *cycle time,* and a somewhat low level of *safety stock* . Finally, facility 3 faces a situation where a low *forecast accuracy* coincides with a somewhat short *cycle time* and a high level of *safety stock* . In all cases, the elements *supply reliability* and *responsiveness* do not appear to be unusually high or low.

Element	Safety stock	Reliability	Cycle time	Responsiveness	Forecast Accuracy
Facility 1:	0.2	0.5	0.9	0.6	0.8
Facility 2:	0.4	0.6	0.1	0.6	0.2
Facility 3:	0.8	0.5	0.4	0.6	0.2

Table 2.1: Initial values for simulation

These values effectively approximate the results of a benchmarking study, to be described in-depth in section 3.3, in the sense that the measured values are normalized on a scale from 0 to 1, based on the high and the low values obtained from the study. This approximation implies that a low (or high) value within the benchmarking group corresponds to a low (or high) value within the simulation. It should also be noted that the upper and lower bounds within this simulation generally represent feasible limits that may be based on long term operating policies or physical constraints. The simulation thus does not provide concise quantitative estimates as much as it attempts to indicate the general direction of changes.

When analyzing these situations, the following five simulations appear to be of interest for decision makers at each facility: Facility 1 would be interested in understanding the impact of a decrease in *cycle time*, while it would also be concerned about the impact of a lower *forecast accuracy*. Facility 2, in contrast, would be interested in understanding the impact of an increase in *forecast accuracy*, while it would also be concerned about the impact of an increase in *cycle time*. Finally, facility 3 would be interested in understanding the impact of an increase in *forecast accuracy*.

These five changes are captured in the following five simulations. It was assumed that these changes would not be sudden, but rather represent gradual changes that occurred over a longer time period. Thus, all simulations were run over a duration of ten periods. After each period, it could be assumed that all system elements had sufficient time to adjust to any system changes, such as changes in safety stock policies that reflected changes in the supply reliability. The impacting element was changed continuously by means of having this element impact itself in each period. This was done by entering a "feedback" value for this element into the diagonal of the α-matrix. In all cases this matrix element had the value 2. Given that the length of the simulation was ten periods, each impacting element would be likely to reach the upper or lower bound of its (normalized) range of possible levels. In order to observe merely a limited change in this element, the duration of the simulation should be shortened accordingly. The simulation results are captured in charts 2.1 through 2.5 in appendix 2.1 and are described below.

2.4.3.3 SIMULATION RESULTS

Simulation 1: Reducing *forecast accuracy* at facility 1

The initial impact of a decrease of *forecast accuracy* at facility 1 was a strong increase in *safety stock* and a moderate decrease in *supply reliability*. The decrease in *supply reliability* led, as expected, to a marginal increase in *cycle time* and a decrease in *responsiveness*.

After 3 periods, *safety stock*, steadily increasing at a high rate, impacted *supply reliability* such that it stopped decreasing any further, and, after 4 periods, started increasing over the final 6 periods. Thus, after the fifth period, a further change in *supply reliability* was apparently less dependent on a further decrease in forecast accuracy than on a further increase in *safety stock*. *Safety stock* increased at a decreasing rate throughout the 10 periods and further increases in *supply reliability* eventually had a stronger enhancing impact on *safety stock* than the inhibiting impact of a further decrease in *forecast accuracy*. *Cycle time* continued to increase at a marginal rate throughout the 10 periods. Finally, *responsiveness* decreased throughout the 10 periods as the high level of cycle time had a stronger inhibiting impact on this element than the enhancing impact of any further increase in *supply reliability*.

At the end of 10 periods, facility 1 appeared to be in a position where a low *forecast accuracy* coincided with a long *cycle time* which had led to a low level of *responsiveness*. However, it now had high levels of *safety stock* that assured a high *supply reliability*.

Simulation 2: Improving *forecast accuracy* at facility 2

The initial impact of an increase in *forecast accuracy* at facility 2 was not only a strong decrease in *safety stock*, but also a slight decrease in *supply reliability*. The latter change led to a marginal decrease in *cycle time* and to a slight increase in *responsiveness*. After 2 periods, the initial decrease in *supply reliability*, that had been apparently caused by the inhibiting impact of a strong decrease in *safety stock*, was reversed by the enhancing impact of further increases in *forecast accuracy*. After period 3, *supply reliability*, influenced at this point only by increases in *forecast accuracy*, started to increase at a decreasing rate and nearly reached its upper limit after 10 periods. After period 4, both *cycle time* and *safety stock* dropped to its lower limit and remained there throughout the final 6 periods. *Responsiveness*, only influenced by increases in *supply reliability* after period 4, gradually increased at a decreasing rate, and nearly reached its upper limit in period 10.

At the end of 10 periods, facility 2 appeared to be in a position where a high *forecast accuracy* coincided with high levels of *supply reliability* and *responsiveness*, along with low levels of *cycle time* and *safety stock*.

Simulation 3: Improving *forecast accuracy* at facility 3:

The impact of an increase in *forecast accuracy* at facility 3 occurred in a manner that somewhat resembled the changes experienced by facility 2. The changes at facility 3 were however strongly influenced by the high initial values of *safety stock* and *cycle time.* Thus, the strong decreases in *safety stock,* that were caused by an increase in *forecast accuracy,* impacted *supply reliability* such that this element dropped from an average level almost completely down to its lower limit after 4 periods. After period 4, the further increases in *forecast accuracy* apparently started to offset the inhibiting impact of decreases of *safety stock* on *supply reliability,* such that it increased over the final 5 periods and nearly reached its upper limit after 10 periods. *Safety stock* dropped to its lower limit after 7 periods. Moreover, *cycle time* decreased continuously throughout the simulation and reached an average value in period 10. The decrease in *cycle time* coincided with a marginal increase in *responsiveness* throughout the simulation which reached an upper limit after 10 periods.

At the end of 10 periods, facility 3, much like facility 2, appeared to be in a position where a high *forecast accuracy* coincided with high levels of *supply reliability* and *responsiveness*, along with low levels of *cycle time* and *safety stock.* However, as the simulation chart could show, it reached this position in a very different manner. In particular, the initial inhibiting impact of a decrease in *safety stock* on *supply reliability* was not experienced at facility 2. This situation might occur in a facility that is highly dependent on high levels of safety stock and does not coordinate changes in operating policies correctly.

Simulation 4: Reducing *cycle time* at facility 1

The initial impact of a decrease in *cycle time* was a decrease in *safety stock*, an increase in *responsiveness*, and an increase in *supply reliability.* The increase in *supply reliability* led to further decreases in *safety stock* such that it declined to its lower limit after 2 periods and remained at this level over the final 8 periods. Supply reliability increased at a decreasing rate throughout the simulation and reached its upper limit after 6 periods. Responsiveness increased rapidly throughout the simulation and reached its upper limit after 7 periods. The *forecast accuracy* remained unchanged throughout the simulation.

At the end of 10 periods, facility 1 appeared to be in a position where a decreased *cycle time* had led to a relatively high level of *supply reliability* and *responsiveness*, but also to a low level of *safety stock*. It should be noted though that at the end of 10 periods, *supply reliability* appeared not to have increased as much as could have been expected from a policy, geared to reduce the cycle time.

Simulation 5: Increasing *cycle time* at facility 2

The initial impact of an increase in *cycle time* was an increase in *safety stock*, and a decrease in *responsiveness*. The increase in *cycle time* led however also to an increase in *supply reliability*, apparently due to the fact that the initial increase in *safety stock* had a stronger enhancing impact on *supply reliability* than the inhibiting impact of an increase in *cycle time*. Further increases in *cycle time*, impacted *supply reliability* such that it increased at a decreasing rate. Thus, the enhancing impact of further increases in *safety stock* were somewhat off-set. After 10 periods, *supply reliability* peaked nearly at its upper limit, while safety stock was somewhat below its upper limit, however still increasing. Finally, *responsiveness* decreased throughout the simulation and dropped to its lower limit after 7 periods. The *forecast accuracy* remained unchanged throughout the simulation.

At the end of 10 periods, facility 2 appeared to be in a position where increases in *cycle time* had led to a low level of *responsiveness*. The long *cycle time* coincided with a high level of *safety stock*, which ensured a high level of *supply reliability*.

2.5 DISCUSSION OF THE STRUCTURAL ANALYSIS

At this point, it appears important to point out the strengths and weaknesses of the structural analysis. A major drawback of the structural analysis is its assumption that opinions, experience, and other forms of "soft" input can be formulated mathematically such that an accurate system model can be devised using deterministic interactions. This assumption implies, in particular, that complex interactions can be described by a looped network of binary interactions, and that the pair wise relationships portrayed by the input matrices adequately represent causal interactions.

Several limitations also exist on a mathematical level for these approaches. A major limitation of the analysis of the interaction matrix of section 2.2.1 is that the capability of an element to act as a driver of system performance is judged, based on the net impact that it has on the variables that are influenced by this element. Thus, a ranking of the predominance of elements is highly dependent on the set of elements that are included for consideration. Moreover, the simulation of section 2.3 assumes that increases and decreases of variables follow a sigmoidal type growth, rather than an exponential growth. Thus, it assumes that realistic bounds can be placed on the variables, automatically limiting reaction rates as the variables approach their upper or lower limit. It also assumes that a dynamic simulation can be done by weighting each impact proportionately to the strength of the interaction and to the relative size of the element producing the interaction. Thus, all other things equal, it assumes that a variable will produce a greater impact on the system as it grows larger. Harris[37] points to the issue that a mathematical model using this assumption is irreversible, and therefore generally inconsistent with the behavior of systems.

On the other hand, the usefulness of the structural analysis is based on three issues. As mentioned in section 2.3, the simple and self-consistent manner, in which the system evolves from a knowledge of the binary interaction of its components makes KSIM one of the few dynamic models that that can be constructed and used in relatively little time and with few resources.[32] Moreover, Porter *et al.*[34] note that KSIM should be viewed as much a process as a product. The benefit of KSIM accrues not only from operating it and analyzing the results but also from building the model, since this phase facilitates the structuring of the discussion of a complex system. Thus, during the construction phase, experience, opinion and judgment can be incorporated along with "hard" data in order to provide a comprehensive system model. Further, a completed model allows alternatives to be quickly formulated and their consequences to be assessed. This final issue coincides with the premise of Kane, who sought to develop a simple approach to visualize the interaction of competing variables in a graphic fashion that was readily understandable for decision makers.[32] Thus, given the model's simplicity, it is important to verify the policy impacts that are forecasted just like the model itself. Only when the system behavior seems reasonable should a degree of confidence be placed in the results.

CONCLUSION

Section 2.1 outlined methods to select a relevant set of system elements, section 2.2 outlined methods of scenario analysis that can be used to identify major drivers of system performance. These are the structural analysis matrix, system grids, and the MICMAC method. Section 2.3 outlined a simulation model to analyze the system impacts of changes in system elements. Section 2.4 applied these methods and the simulation model to a case study, and section 2.5 discussed the limitations and benefits of these models.

Chapter 3 THE FIVE-BOX MODEL

INTRODUCTION

Chapter 3 describes a system interaction model developed at the Digital Equipment Corporation (DEC) and applies it to data from a benchmarking group. This model characterizes the interactions between five pipeline performance measures within DEC's organization and is termed the "Five-Box model". Section 3.1 describes a predecessor model and section 3.2 describes the equations that are applied within this model. Section 3.3 introduces results of an automotive industry benchmarking group, uses them as input data for a somewhat modified version of the 5-Box model, and shows the results of a sensitivity analysis of major interactions within the model.

3.1 THE INVENTORY - LEAD TIME - SERVICE MODEL

Quantitative system interaction models were developed at DEC well before the 5-Box model. The predecessor to the 5-Box model was based on well-known relationships, shown in equation 3.1, to determine the amount of safety stock required to meet a specific fill-rate with a random demand and a random replenishment lead time.

$$\text{Safety stock} = \Phi^{-1}(\text{Fill rate}) * \sigma_c \qquad [3.1]$$

with:

$\Phi^{-1}(x) \equiv$	The inverse cumulative probability of the normal distribution.
Fill rate ≡	The fraction of random orders that should be serviced within the replenishment cycle time.
$\sigma_C \equiv$	The standard deviation of the expected lead time demand. (Units)

The standard deviation of the demand over the replenishment lead time, σ_c, can be described by the relationships that are shown in figure 3.1. Figure 3.1 outlines the depletion of a stockpile that is managed by a continuous review policy. Nahmias[38] defines a continuous inventory review policy as a policy that records demands as they occur such that the level of on-hand inventory is known at all times. It shows the impact of random fluctuations of demand over the lead time, and random fluctuations of the lead time, on the total depletion of inventory between an order entry in any period t and the order arrival in the subsequent period t+1. The safety stock needs to account for both variations. A more detailed description of this situation is provided by Magee.[39]

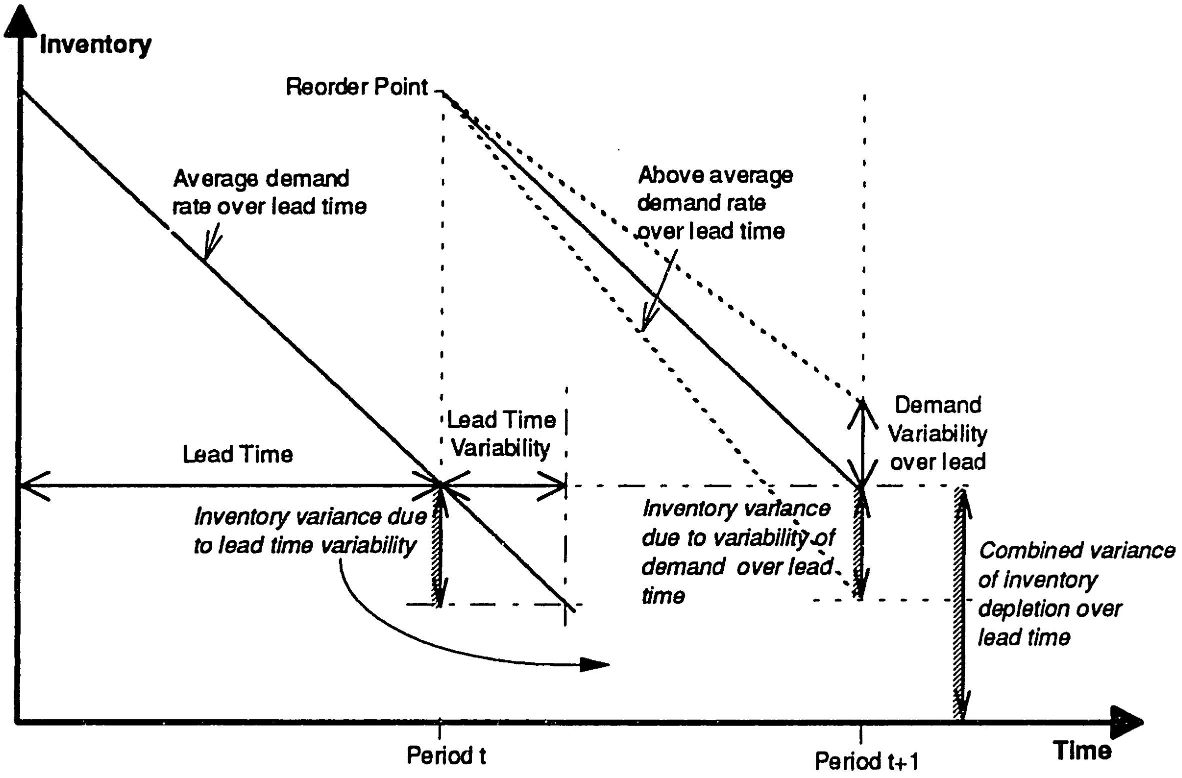


Figure 3.1: Impact of independent fluctuations in lead time and demandrate over the lead time on inventory depletion within a reorder interval

The situation of random demand and a random replenishment lead time can be represented as the sum of a random number of independent identically distributed random variables. Drake[40] shows that the expected value of this sum is equal to the product of the expected value of each distribution:

$$E(r) = E(n) * E(x) \qquad [3.2]$$

where:

$x \equiv$ random variable

$n \equiv$ number of independent experimental values of x

$r \equiv$ sum of n independent values of x

Moreover Drake[40] derives the variance of this sum by differentiating the *s* transform for the probability density function of *r* to get:

$$\sigma_r^2 = E(n) * \sigma_x^2 + [E(x)]^2 * \sigma_n^2 \qquad [3.3]$$

An intuitive derivation of equations 3.2 and 3.3 is shown in appendix 3.1. Applied to the situation of random demand over a random lead time, equation 3.3 can be used to determine the variance of the joint periodic demand / lead time distribution:

$$\sigma_c^2 = \overline{(\text{Lead Time})} * \text{Var (Demand)} + (\overline{\text{Demand}}^2)\ \text{Var}(\overline{\text{Lead Time}}) \qquad [3.4]$$

with:

Demand ≡ Periodic demand in terms of inventory units (dimensionless).
Lead Time ≡ The replenishment time required to service a request for additional inventory expressed in terms of the number of periods used to measure periodic demand (dimensionless).

Substituting the square root of equation 3.4 for the value of σ_c, equation 3.1 can be rewritten as:

$$\text{Safety Stock} = \Phi^{-1}[\text{Fill rate}] * \sqrt{\overline{(\text{Lead Time})}\ \text{Var (Demand)} + \overline{(\text{Demand})}^2\ \text{Var (Lead Time)}} \qquad [3.5]$$

According to Banks,[41] the periodic demand rate can be interpreted as an integer value. This dimension can be justified if each period is understood as an event, and the periodic demand rate signifies the number of units of inventory that are depleted during the occurrence of this event. Moreover, the lead time can be understood as a scaling factor to determine the number of events occurring within a replenishment lead time. This leads to the conclusion that, contrary to the descriptions of Stock,[42] Hill,[43] and Stevenson,[44] the variable "lead time" in equation 3.5 does not have a time dimension, but is rather a dimensionless conversion factor which scales the periodic demand rate in terms of demand over the lead time.

At DEC, equation 3.5 was embedded in a FORTRAN program, termed the "inventory / lead-time / service level" (ILS) model, which could account for a normal distribution of all input variables. The model prompted the user for any combination of five of the six variables used in equation 3.5, and subsequently returned the value that the sixth variable was expected to have. The ILS model was implemented at the company's network gear plant in Augusta, Maine, which at that point had a delivery performance of 60%-70% compared to a target of 95%. The ILS model showed that an additional 2-4 weeks of safety stock inventory would be needed for this target. This result was implemented and subsequently the delivery performance rose to 95%.

The next step was to extend the results at the Augusta facility from parameters, that were important for the plant and work-cell level, to interactions occurring on the product pipeline level. This required a focus on additional measures, such as delivery reliability and order response time. An additional limitation of the ILS model was that it could not account for the situation of several interlinked production stages within the product pipeline. Thus, the ILS model was left as a planning tool at the manufacturing plant level while a different tool was developed for product pipeline planning.

During the development of this new tool, a set of service performance measures were connected to the ILS measures by means of the average product pipeline cycle time, as shown in the "Bubble diagram" in figure 3.2. The average cycle time was defined in section 2.4.1 as the time that material spends in the product pipeline, from the raw material stage to the point at which it leaves the pipeline as part of a completed customer order. Assuming steady state conditions, the average cycle time could be used to compute, how much inventory was present in a product pipeline at any given point in time. It could also reflect the product pipeline supply reliability to the extent that it was correlated with the time required to complete a customer order. The formal relationship between these measures was introduced in the 5-Box model.

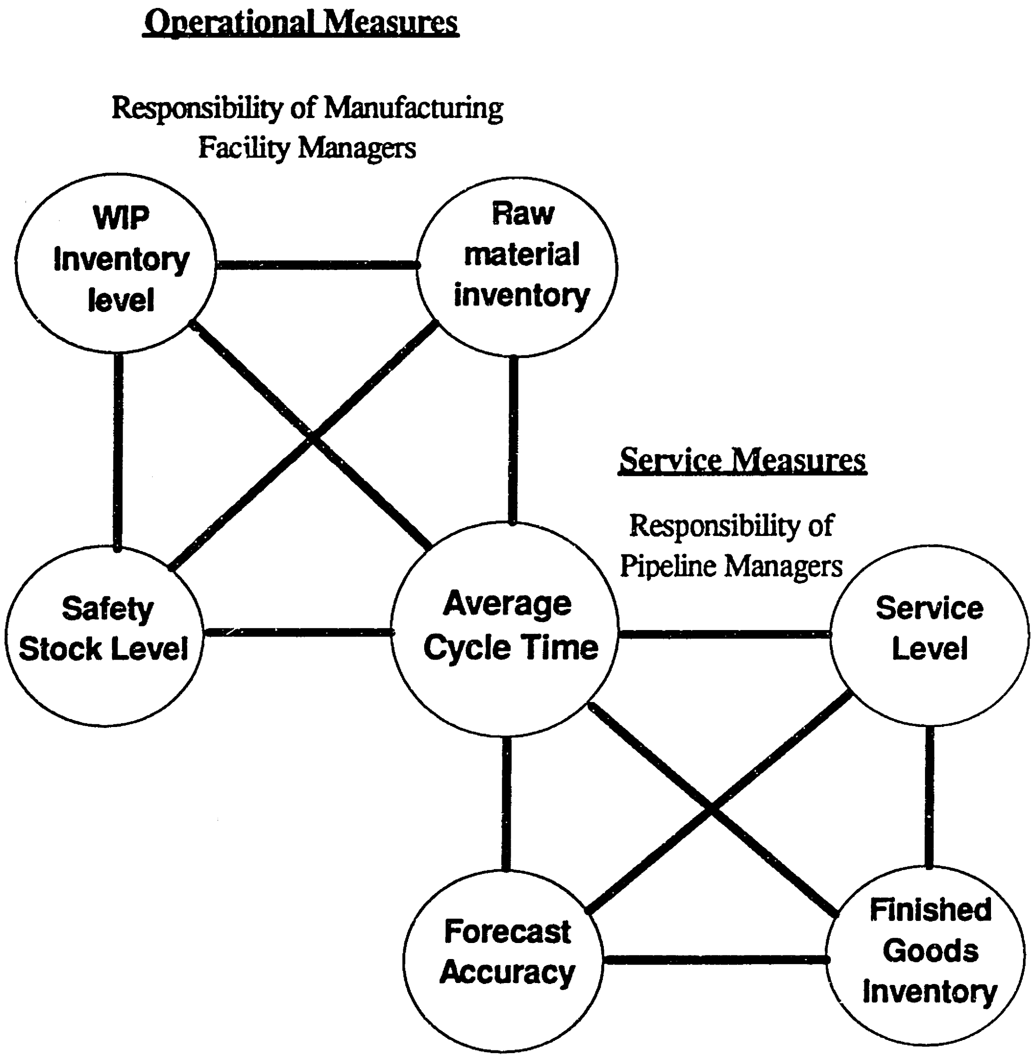


Figure 3.2: The DEC "Bubble" Diagram

3.2 DESCRIPTION OF THE 5-BOX MODEL

Section 3.2 outlines the 5-Box model which accounts for interactions between pipeline measures. Section 3.2.1 provides an overview of these measures, sections 3.2.2 through 3.2.6 give a detailed explanation of the manner in which they are applied within the model, while section 3.2.7 outlines some applications of the model.

3.2.1 Overview of measures

The 5-Box model accounts for the relationships between product pipeline measures. It can be used tc formulate pipeline plans which simultaneously consider measures of significance for Finance and Marketing. These measures can be described as follows:

Measure 1: The *forecast accuracy* is determined from the level of "forecast error." The forecast error can be defined as the discrepancy between the actual demand for those products covered by the 5-Box model [D] and the mean forecasted demand for these products within the forecast period [$\mu(x)$] divided by the forecasted demand: $[D - \mu(x)] / \mu(x)$. As the 5-Box has been used to set quarterly budgets, the forecast period can be assumed to be 3 months.
Measure 2: The *weighted average cycle time* (WACT) is the cumulative lead time required to acquire and transform material into a finished product that can be used to fulfill a customer order. The cycle time is averaged by value over all products, whose pipelines had been combined for modeling purposes.
Measure 3: The measure describing the reliability of shipments to DEC's customers is termed internally "*predictability*." This measure is defined as the percentage of defect-free orders that were shipped on or before the order fulfillment date committed to customers. Throughout this chapter, it will be referred to as supply reliability.
Measure 4: A second service measure at DEC is the *"responsiveness"* of a group of products that are combined within the model. This measure can be defined as the percentage of products with order response times quoted to customers, that are lower than those of comparable competitor products.
Measure 5: The product pipeline *inventory* includes raw material, inventory in-transit, work-in-process, and finished goods inventory located at multiple inventory storage and production stages within a product pipeline. This definition includes both safety stock and process stock located at each point.

While predictability and responsiveness are primarily indicators of product pipeline service performance (or promised performance), forecast accuracy, inventory, and cycle time evaluate the efficiency of pipeline operations. Sections 3.2.2 through 3.2.6 provide a more detailed analysis of the individual measures.

3.2.2 Forecast accuracy

To accommodate a situation, in which the concise forecast error cannot be determined as shown in section 3.2.1, the 5-Box model uses the following approach to derive the mean and standard deviation of a normally distributed forecast error. The forecast input is entered in the form of a "bandwidth" of expected demand over the forecast horizon. The upper side of this bandwidth represents an "upside capability" of the entire pipeline to support unforecasted excess demand before on-time shipments are affected. Similarly, the lower side of the bandwidth accounts for the "downside capability," showing what percentage of demand shortfall would be acceptable before the current inventory led to excessive levels of working capital tied up in inventory. Finally, the percentage of the total forecasted demand that is expected to fall within, above, and below the bandwidth is used to determine the mean and standard deviation of the forecast distribution.

The 5-Box model assumes that the variability of forecasted demand will not only determine the level of finished goods safety stock that is made available for distribution, but also the level of safety stock that is maintained in form of production inputs and raw material throughout the entire pipeline. The level of the total "pipeline safety stock" is based on the fill rate, at DEC also known as the "forecast error coverage," that is determined by having the user specify the target percentage of "demand" throughout the forecast horizon that is intended to be serviced. Demand in this context apparently implies number of orders, as the model then proceeds to calculate, how much safety stock - at DEC termed "upside flex" inventory - will provide a type I service. Nahmias[38] defines a type I service as the probability of not stocking out within the lead time. If several periods are observed, a type I service measures the proportion of periods in which all demands are met. It should be noted, that the 5-Box model uses this forecast error distribution only for the purpose of periodically reevaluating safety stock levels throughout the pipeline. In the 5-Box model, it is assumed not to be correlated with the variability of demand for finished goods inventory at the final production stage during the replenishment lead time.

3.2.3 Weighted Average Cycle Time

As defined in section 3.2.1, the weighted average cumulative cycle time (WACT) is the amount of time that products spend in the pipeline, in the form of raw material, work in process inventory, and as finished goods, before they are used to meet demand. The cycle time of each product line is "weighted" by the value of this product line relative to the combined value of all product lines analyzed in the model. It is used in section 3.2.6 to compute the level of pipeline safety stock.

3.2.4 Supply Reliability

As mentioned in section 3.2.1, supply reliability is defined as the percentage of defect free orders delivered on or before the committed shipment date. According to Copacino,[45] such orders can be defined as "perfect orders." The supply reliability in the 5-Box model is determined by the probability that finished goods inventory is sufficient to accommodate the replenishment lead time demand variance, and the probability that a defect free product can be shipped within the quoted lead time:

Supply Reliability = F(Service level of finished goods inventory, Order fulfillment process time reliability, Manufactured product quality)

The three components of supply reliability are addressed in order:

3.2.4.1 (Finished goods) inventory service level

The level of finished goods inventory at the final production stage of the 5-Box pipeline, before goods are delivered to distribution channels, determines the type I service that is provided to the distribution channels by means of finished goods inventory. In the 5-Box model, it is termed the *inventory service level* as this is the level of supply reliability that is achieved by having finished goods inventory available. Given this definition, the 5-Box model effectively assumes two separate fill rates within the pipeline: the fill rate that is maintained to meet the overall variability of demand over the (quarterly) forecast horizon, and the fill rate that is provided at the finished goods storage point of the final assembly stage in order to cover the lead time demand variability. While the finished goods safety stock will be based on the variability demand of demand throughout the forecast horizon, the *inventory service level* shows the fill rate that this safety stock level will achieve, given the demand variability throughout the replenishment lead time at the final stage. The lead time for the replenishment of finished goods is assumed to be fixed. Thus, the inventory service level is based only on the amount of demand variation within the replenishment lead time at the final stage. Based on Lewis[46] it can be shown that he formula for the variance of lead time demand presented in equation 3.4 thus changes to:

$$\sigma^2 = \text{Var (Periodic demand)} * \text{Average replenishment lead time in periods} \qquad [3.6]$$

Entering equation 3.6 into equation 3.1 and solving for the fill rate leads to equation 3.7:

$$\text{Fill rate} = \Phi\left[\frac{\text{Finished goods safety stock}}{\sigma\text{ (Periodic demand)} * \sqrt{\text{Replenishment lead time in periods}}}\right] \qquad [3.7]$$

It should be noted that the variables in equation 3.7 are, like the variables in equation 3.5, dimensionless. Given equation 3.7, it somewhat unusual that the 5-Box model actually applies the entire level of finished goods inventory towards the determination of the inventory service level. This issue could be explained with the assumption that the stockpile is replenished on a continuous basis.

At DEC, the inventory service level was usually near perfect, as it was generally not possible to stock out of finished goods. If finshed goods inventory was insufficent, lead times would be extended such that they covered the replenishment lead time. However occasionally, large orders for otherwise slow moving products arrived, where the lead time was quoted before it was realized that there was not enough inventory at hand to fill the order.

3.2.4.2 Order fulfillment process reliability

The 5-Box model assumes that the supply reliability is impacted by both the level of finished goods inventory and the reliability of the order fulfillment process. Thus, a low "process reliability" can lead to an imperfect pipeline supply reliability, even in the presence of sufficient inventory. In this context, process reliability is measured by the percentage of orders fulfilled within the lead time quoted to the customers. At DEC, the response time includes the "release to manufacturing time," the time required for a final configuration of products, and any intermediate storage time. Process reliability depends both on the lead-time quoted to the customer and on the distribution of the response time that is required to fulfill an order. The response time is assumed to be normally distributed:

$$\text{Response time} \approx N(\text{Quoted Lead time, Response time variance}) \qquad [3.8]$$

Thus, the process reliability can be modeled as follows:

$$Process\ Reliability = \Phi\left\{\frac{Quoted\ Lead\ Time - Response\ Time}{\sqrt{Response\ Time\ Variance}}\right\} \qquad [3.9]$$

3.2.4.3 Perfect Product Percentage

While not explicitly mentioned in the 5-Box model, the third factor determining the ability of a product pipeline to supply defect free products on time, is the ability of Manufacturing to produce defect free products. Thus, it might be necessary to include the average percentage of products that are manufactured without defects.

To summarize, the determination of supply reliability depends on the inventory service level, the process reliability, and the reliability of any other significant support functions. In the 5-Box model, the ultimate reliability of the product pipeline supply is determined by the product of the three factors listed above, as shown in equation 3.10. Further factors that are likely to impact the supply reliability can be added by factoring them into equation 3.10.

$$\text{Reliability} = \text{"Inventory Service Level"} * \text{Process Reliability} * \text{"Perfect Product" \%} \qquad [3.10]$$

3.2.5 Responsiveness

As defined in section 3.2.1, responsiveness is the percentage of items on "Competitive lead-time Menus." Responsiveness levels are computed by determining all lead times that are quoted to customers and comparing them with lead times that are quoted by competitors for comparable products. At DEC, this percentage is measured each week and averaged over the quarter to calculate the responsiveness measure. This measure incorporates both marketing and operational issues that are likely to impact the responsiveness of a pipeline on a week to week basis. These are *supply constraints* and *forecasting constraints*. The fraction of *supply constrained* items reflects the percentage of orders delayed due to the absence of key parts required from suppliers. The fraction of *forecasting error* constrained items reflects the expected percentage of orders that are not covered by the pipeline inventory fill rate, described in section 3.2.2.

Both constraints are assumed to extend the actual order fulfillment lead time beyond the quoted lead time for all products affected by these constraints. As equation 3.11 shows, the 5-Box model incorporates these constraints by multiplying the percentage of "competitive quoted lead time" (QLT) items with the product of the percentage of products affected by these constraints:

$$\text{Responsiveness} = \frac{\text{No. of items on "competitive" QLT}}{\text{Total number of items measured}} * \text{Supply constrained fraction} * \text{Forecast error constrained fract.} \qquad [3.11]$$

It should be noted that this definition of responsiveness is specific to DEC. It might be more useful for a general version of this measure to weigh the "competitive" quoted lead times by product value or by sales volume.

3.2.6 Inventory

As noted in section 3.2.1, the 5-Box model distinguishes between baseline inventory, present in the product pipeline even if there is no forecast error, and safety stock, used to cover forecast errors. Examples of baseline inventory, also described in Magee[39] as process stock, are items such as "work in process" and inventory used to cover supplier lead times. The "safety stock %" expresses the level of safety stock as a percentage of total inventory located at any point in the pipeline.

The total amount of inventory that is present throughout the entire 5-Box model pipeline at any point in time is determined by means of Little's formula.[47] Applied to the product pipeline, Little's formula states that the amount of inventory in the system (or length of the queue) is equal to the product of the rate at which units are processed by the system (equal to the service rate) and the time that a unit spends in the system (or waiting time). The safety stock in the 5-Box pipeline can then be computed as the safety stock percentage of total pipeline system inventory - which is the product of the mean forecasted demand rate over the cycle time and the weighted average cycle time (WACT):

$$\text{Total pipeline safety stock} = \text{Safety stock \%} * \text{Forecasted rate of demand} * \text{WACT} \quad [3.12]$$

As shown in figure 3.3, the 5-Box model uses a conceptual pipeline model that represents a general manufacturing pipeline configuration containing several production stages and a distribution stage with inventory in-transit, raw material stock, work-in-process inventories (WIP) and finished goods stock (FG). As figure 3.3. shows, the total level of inventory is determined from the amount of process stock and the amount of safety stock for each form of inventory at each stage. When determining pipeline safety stock, the model prompts the user to determine the percentage of total safety stock that should be allocated to each form of inventory at each stage. For the purpose of computing inventory holding costs, the model assumes that safety stock can be held at any stage of the product pipeline, provided that the production line is properly configured. To assure a proper configuration, the model allows the user to enter additional safety stock for products that are sourced from suppliers on long lead times. While this feature captures some aspects of inventory management, it is not likely to provide comprehensive guidelines as to what a properly configured pipeline represents.

	Production (stage 1)				*Final assembly (stage 2)*				*Distribution*	*Product Totals*
	In-transit	Raw mat.	WIP	F.G.	In-transit	Raw mat.	WIP	F.G.	F.G.	
Inventory "If no Forecast Error:" (Process stock)										
Manufacturing Inv. ($)	$	$	$	$	$	$	$	$	$	$
Weeks of supply										Weeks
Days of supply										Days
Inventory "to cover Forecast Error:" (Safety Stock)										
Long Lead Time %	▨	%	▨	▨	▨	%	▨	▨	▨	%
% Safety stock	▨	%	▨	%	▨	%	%	%	%	%
Manufacturing Inv. ($)	$	$	$	$	$	$	$	$	$	$
Supplier Inv ($)	▨	$	▨	▨	▨	▨	▨	▨	▨	$
Total Safety Stock										Weeks
Total Inventory:										
Manufacturing Inv. ($)	$	$	$	$	$	$	$	$	$	$
Weeks of supply										Weeks
Days of supply										Days

Figure 3.3: The conceptual 5-Box pipeline

Moreover, while this approach might lead to an accurate determination of inventory holding costs, it does not capture the full impact of any change in the level of safety stock that is maintained throughout the pipeline on the supply reliability. Merely finished goods safety stock at the final production stage has an impact on the supply reliability as described in equation 3.7. Changes in finished goods safety stock at earlier production stages will impact supply reliability only if the user specifies that semi-finished goods can be shipped from earlier stages directly to customers. This issue is addressed in section 4.2.

3.2.7 Applications of the 5-Box Model

Applying this model to pipeline operations at DEC showed that the amount of finished goods safety stock maintained at DEC was so large that inventory shortage was almost never a problem and supply reliability of DEC's product pipelines was near perfect. Moreover, the 5-Box model provided a general insight into the trade-off between pipeline safety stock and quoted lead times. If all orders were serviced by means of finished goods inventory and safety stock was reduced such that a deviation of actual demand from forecasted demand exceeded the level of safety stock, then the delivery lead-time that was quoted to customers needed to be lengthened in order to account for the replenishment of finished goods. Moreover, the 5-Box model could show that an alternative to greater safety stock and longer quoted lead times was an improvement of demand forecasts.

The 5-Box model was used at DEC as a decision support tool to set quarterly budgets and to facilitate planning throughout the year. It demonstrated the general relationships between the five measures outlined above, enabling DEC to test the feasibility of high level combinations of business objectives, and the impact of changes in factors that were capable of influencing the pipeline performance. From an organizational viewpoint, it supported, for example, the assertion that it was not possible to maintain low safety stock levels throughout the pipeline while maintaining a high level of pipeline supply reliability and that inaccurate forecasts provided by marketing had a highly negative impact on pipeline inventory levels.

3.3 APPLYING THE 5-BOX MODEL TO DATA FROM AN AUTOMOTIVE INDUSTRY BENCHMARKING PROJECT

Section 3.3 describes the application of the 5-Box model to data of a benchmarking project of five manufacturing facilities in the automotive industry. Section 3.3.1 provides a general introduction to the benchmarking project, 3.3.2 describes the data set obtained from the project, and outlines the assumptions and the changes made to the 5-Box model. Section 3.3.3 constructs some possible situations for each manufacturing facility by changing one measure and observing changes of all other measures. Finally, section 3.3.4 shows the major interactions within the model by means of sensitivity analyses.

3.3.1 Short Background on the data source

In the spring of 1994, a manufacturing benchmarking round table, consisting of five assembly facilities from four major German automotive manufacturers, was launched.[48] The intent was to look for ways in which all participants could increase the productivity and effectiveness of their operations by comparing processes within automotive manufacturing pipelines. Like other process benchmarking projects, it started with an outline of the scope of the process to be benchmarked. The initial process definition was quite broad, starting with the initial production of a new car model - "job 1" - and extending over customer orders up to the delivery of completed vehicles. This process was divided into four *sub-processes:*[48]

Sub-process 1: *Material flow processes,* such as transportation and storage, which ensure material availability throughout the pipeline.

Sub-process 2: *Information processes* (control activities) such as production program planning, routing, order processing, and other forms of pipeline coordination.

Sub-process 3: *Change processes* which are initiated in order to revise the structure of existing pipelines or the pipeline outputs. Change processes introduce new production arrangements or product versions.

Sub-process 4: *New product processes* that are needed in order to determine the structure of a new product pipeline. Such processes include the planning and coordination of all shipments, procedures, and systems associated with the start-up of new products. While closely related to *change processes*, they were viewed as a separate process due to the fact that they usually require a large number of high level decisions.

The group focused its measurements on sub-process 1 since information flows, product changes, and new product introduction are considered supporting processes that merely ensure a smooth flow of goods through the pipeline system. Recent publications such as Buxbaum[49] however point to examples in which the design of the product pipeline is actually based on improvements in the logistics information pipeline.

The models in chapters 2 and 3 focused on short and medium term interactions between measures of the flow of material through the pipeline. This is why the benchmarking project group data appears applicable to these models. When examining data by means of these models, it is assumed that all contributions provided by the "supporting" processes of information flow, model change, and new product introduction, are reflected in the performance of the material flow process measures.

The benchmarking group developed a framework to compare the participants' order fulfillment material flow process, i.e. the process that starts with the customer order and ends with the shipment of a finished vehicle. Note that, unlike the US automotive industry, a large part of the vehicles manufactured in the German automotive industry are made to order. An internal Audi report[50] has estimated that 65% of all vehicles are manufactured to orders. This situation implies that German automotive industry pipelines face a two-fold demand: orders that can be serviced from finished goods stock, and custom orders that need to be manufactured on an individual basis. A "make-to-order" system contrasts however with the current 5-Box model, which assumes that all demand can be serviced from finished goods inventory. Section 3.3.2.3 outlines those changes that were made to the 5-Box model to account for "make-to-order" flows.

Appendix 3.2 lists the benchmarking project data for the measures described above. Before discussing the assumptions that were required by the model, the following limitations of the data should be mentioned. While the lack of some inputs might appear to lessen the relevance of the actual context, it should be noted that this chapter is more concerned with the general interactions that the 5-Box model is capable of describing rather than the implications that these might have for each facility participating in the project.

- Although two final assembly facilities had compiled data on nearly every measure listed above, some measures were missing and a great deal of uncertainty existed with regard to their logistics and manufacturing costs, and their cycle times. Thus, they were omitted from the 5-Box analysis.
- The benchmarking study only looked at the production of one vehicle, not at a set of products that could be "weighted" based on their value. This meant that the weighted average cycle time reflected only the average cycle time that assembly inputs for vehicles produced at each facility spent in the pipeline. This also meant that the data offered no "percentage" of products that were offered on competitive lead times, which rendered the 5-Box measure *responsiveness* quite meaningless.
- The study only observed the production process at the final assembly, not at interconnected operations within a complete product pipeline. Thus, only the final stage of the conceptual 5-Box pipeline could be constructed.
- The manufacturing costs were assumed to consist entirely of material costs logistics costs, and value-added labor costs. The value added labor costs were approximated from the product of the "net manufacturing time per unit" (NMTU) and an approximate value of the hourly labor cost in the German automotive industry. The NMTU measure denoted the number of net productive value-added labor hours that were invested in the production of a vehicle. This approximation might not yield exact measurements of the total value of pipeline inventory, but has no bearing on the results of section 3.3.3, or on the sensitivity analysis of section 3.3.4, since all inventory measurements are in done in terms of "days of inventory."

Using the data of the remaining three facilities, the following measurements and assumptions for the 5-Box model were done.

3.3.2 5-Box case study assumptions

This section outlines the benchmarking measurements and the assumptions that were necessary to supplement these measurements and to modify the 5-Box model. In particular it will look at the assumptions and measurements done for the forecast accuracy, the cycle time, the supply reliability, the responsiveness, the inventory, the manufacturing costs, and the product complexity at each facility in the benchmarking study.

3.3.2.1 (BOX 1) Bandwidth of monthly forecast accuracy

No facility had been able to obtain accurate forecasts for the monthly production schedule. Thus, the actual monthly production volume could not be matched with forecasts in order to determine forecast accuracy. Any information of the forecast accuracy therefore needed to be compiled, based on a perception of the forecasted demand. From the information that had been gathered, facilities two and three appeared to experience the same degree of forecast accuracy while facility 1 had a higher forecast accuracy due to a more stable level of demand from its distribution channels.

Using the "bandwidths" provided by the 5-Box model, an upper and a lower bandwidth was set at +/- 20% of the mean demand forecast, which is assumed to be evenly distributed. For facility one, 90% of the monthly demand is assumed to be within the bandwidths, while facilities two and three are assumed to each have 60% of the monthly demand within the bandwidths. The determination of the forecast accuracy in this manner leads to standard deviations of monthly demand forecasts that are 23% of output for facilities two and three and 6% of output for facility one. Finally, the pipeline fill rate was set at 90%.

3.3.2.2 (BOX 2) Total Cycle Time

Orders for raw materials were placed on a continuous basis in order to assure a steady supply. Thus, material was assumed to enter the pipeline when delivery arrangements were made with suppliers. Material left the pipeline, when a finished vehicle exited the manufacturing facility. Thus, the total cycle time that material would spend in the pipeline was approximated from the sum of the production schedule lead time, the lead time that was required to enter a vehicle into the production schedule, the average lead time that was required by suppliers, and the average time that was required for manufacturing.

3.3.2.3 (BOX 3) Supply Reliability

In this case study, the percentage of on-time shipments provided by a manufacturing facility is based on two factors. (1.) the ability of the manufacturing process to deliver defect-free products to customers and (2.) the ability of finished goods safety stock to service random requests from the distribution channel. Thus, it is necessary to segment these two forms of demand. Based on the study mentioned in section 3.3.1, it was assumed that two thirds of all orders represent specific customer orders, whereas the remaining one third are serviced from finished goods inventory. The supply reliability of the 5-Box model - that is the percentage of orders that are shipped on-time - can be revised such that it weights both demand segments based on their share of total orders. In the following, it is assumed that if a finished goods inventory is sufficient to meet demand, this demand can be serviced on time. If not, a separate "finished goods inventory delivery time reliability" would need to be added to the model. Equation 3.13, used to determine the supply reliability at each facility of this case study assumes that both channels do not cross. This means that "make to order" requests cannot be serviced with finished goods safety stock , and that orders for the finished goods inventory cannot be met by means of an additional production run. Thus the supply reliability can be written as:

$$\text{Supply reliability at each facility} = 0.34 * \text{Inventory Service Level} + 0.66 * \left[\text{Process Reliability} * \text{Perfect Product \%}\right] \quad [3.13]$$

The process reliability is determined from the cumulative probability that the response time of the production process is shorter than the quoted lead time. In this study, the response time is the time that is required to finish a vehicle, once a vehicle has been scheduled for production. The quoted lead time for orders ranges from 30 days for Manufacturer One to 25 days for Manufacturer Two. Since no manufacturer had information on the response time variability, an average variability of one half of the order response time at all three facilities was estimated and verified by checking the results of supply reliability measurements shown in appendix 3.2. These measurements had determined the percentage of orders that were delivered to the customer on the promised week and the percentage of orders that completed assembly within the week that had been planned by the production schedule.

Moreover, the percentage of perfect products, as described in section 3.2.4, is factored into equation 3.13 to determine the supply reliability of the "make-to-order" channel by assuming that the order, if defective, will require reworking such that it is delayed beyond the quoted lead-time. In this case study, the perfect product percentage was complemented by an additional measure: the cost of expedited component shipments that were necessary to avoid an interruption in production. This cost could be used as a measure of the accuracy of the parts shipment schedule. It would however need to be added to the manufacturing costs and not to the supply reliability of the 5-Box model, since it does not impact the final delivery of a vehicle to customers.

As mentioned, the finished goods inventory in the manufacturing facility services the distribution channels and dealerships. When determining the finished goods inventory service level by means of equation 3.7, the 5-Box model assumes that both the replenishment lead time for the finished goods inventory and the variability of demand over the replenishment lead time are fixed. Equation 3.7 assumes a continuous inventory review policy and a fixed production batch size.

In this case study, the replenishment lead time is assumed equal to the order response time. Given the uncertainty involved with the production of a vehicle, it can be assumed that the replenishment lead time is more accurately approximated by the order response time distribution. Thus, equation 3.7, used to determine the inventory service level, needs to be revised such that the standard deviation of lead time demand, shown in equation 3.6, includes the square root of the lead time demand variance. Equation 3.6 is thus effectively replaced by equation 3.4, which denotes the distribution of lead time demand, given a variable periodic demand and a variable lead time. Moreover, it can be assumed that the variability of demand over the replenishment lead time is not independent of the accuracy of demand forecasts over the forecasting horizon. As the first analysis of section 3.3.5 verifies, the variability of lead time demand in equation 3.6 can be set at approximately twice the rate of the standard deviation of demand over the forecast horizon, determined in section 3.3.2.1. This adjustment assures that changes in the forecast accuracy are reflected in the fill rate at the finished goods stock pile.

3.3.2.3 (BOX 4) Responsiveness

A "competitive" lead time within the German automotive industry is assumed to be the prevalent industry standard of six weeks. Based on the lead times that are quoted by all three manufacturers, all facilities are supplying their vehicles faster than this competitive lead time. However, section 3.3.2.2 pointed out that the benchmarking study captured merely one average quoted lead time for all vehicles. Thus, the "responsiveness" measure carries little meaning in all further analysis.

3.3.2.4 (BOX 5) Inventory levels

In the benchmarking study, measurements of the level of inventory that was located throughout the final assembly stage of the manufacturing process started with assembly material in inbound transportation and ended with finished vehicles waiting for distribution. When determining the level of safety stock for this case study, the "percentage of safety stock," described in section 3.2.6, that was located at each point of the pipeline, was determined from the following assumptions: inventory in inbound transportation contained no safety stock, while safety stock constituted 50% of total inventory at the incoming goods dock, and 25% of inventory in production or waiting for distribution. These amounts were subtracted from the total inventory that had been measured in the study in order to set the "base stock" at each point could be set. Given the total level of inventory measured at each of the final three points, this assumption allocated 70% of all safety stock to the incoming goods dock, 20% to inventory in production, and 10% to inventory waiting for distribution. While this approach reflects the best estimates of the participants who had measured the inventory, this method might not yield safety stock levels for raw material, work in process, and finished goods that correctly account for dynamics such as the variability of the local replenishment lead time and demand. Methods to address this limitation are shown in section 4.2.

3.3.2.5 Product complexity

The benchmarking project finally included measures of the product variety and "complexity" of the production process by means of a "complexity matrix." This matrix depicted the size of each facility, the number of suppliers, the number of separate production lines, and the vector of vehicle options. The variety that was associated with each vehicle was measured in terms of the number of options that were available to the customer and the number of possible manufacturing combinations. This measure is not included in the 5-Box model. Thus the implication of omitting it from the further analysis is addressed.

Cooper[51] and Bennett[52] give a good overview of the impact that product variety has on the cost and supply reliability of the order fulfillment process within product pipelines in the automotive industry. These articles confirm that variety and process complexity exert a significant influence on the structure and management of the product pipeline. However, they also note that changes in the level of process complexity and product variety in the product pipeline can be achieved only throughout the process of developing product pipelines for new products, or when restructuring existing pipelines due to product changes. Thus, process complexity and product variety can be viewed as external parameters that have a strong impact on the pipeline, but cannot be influenced by decision makers within pipeline operations on a daily basis. It would thus not be possible to speak of a true "interaction" between these measures and the other 5-Box measures.

A summary of the major inputs for the model is provided in table 3.1. A detailed description of the inputs is shown in Appendix 3.1, the 5-Box models that resulted from these inputs are listed in Appendix 3.2.

3.3.3 5-Box case study results

The results of the initial case study inputs are summarized in table 3.1. This table lists the most relevant measures and four representative situations including changes in some input variable. These are analyzed to study the ramifications of changes in the input variables:

	Current Situation:			*Possible Situations:*			
Metric:	Facility 1	Facility 2	Facility 3	Facility 1	Facility 2	Facility 2	Facility 3
Inventory (days)	13.4	14.8	20.5	30.7	14.8	**256.4**	12.6
Avg. Cycle Time (days)	75	27.2	34.5	75	27.2	27.2	34.5
Demand Variance	6%	24%	24%	**24%**	24%	24%	**6%**
Supply Reliability	50%	54%	46%	46%	42%	**55%**	46%
Finished Goods Inventory (days)	1.18	1.33	1.56	2.91	1.34	**25.50**	0.77
Inventory Service *Level*	53%	53%	53%	55%	53%	93%	52%
Response Time (days)	24.2	15.5	22.5	24.2	**22.5**	**22.5**	22.5
Process Reliability	70%	90%	70%	70%	60%	68%	70%

Table 3.1: Using the 5-Box model to construct possible situations for each facility

Situation 1: The variance of the forecast accuracy for facility 1 is increased from 6% to 24%. Due to this change, the inventory required to maintain a 90% fill rate increases from 13.4 days to 30.7 days. Since the safety stock of finished goods inventory is assumed to be 10% of the total pipeline safety stock, it increases from 1.18 to 2.91 days, which leads to an increase of the inventory service level from 53% to 55%. A comparison with the other facilities shows that, given the length of the cycle time at facility 1, its pipeline inventory levels are highly dependent on a stable demand over the forecast horizon.

Situation 2: The variance of the forecast accuracy for facility 3 is reduced from 24% to 6%. This leads to a reduction in total pipeline inventory from 20.5 to 12.6 days. Here too, the finished goods safety stock is assumed to remain at 10% of the total pipeline safety stock and finished goods inventory decreases from 1.56 to 0.77 days. Subsequently, the inventory service level decreases from 53% to 52%. This result shows that a change in the level of inventory at facility 3 is less affected by changes in forecast accuracy than facility 1. The reason for this can be traced to the shorter total pipeline cycle time of facility 3.

Situation 3: The response time of facility 2 is increased from 15 5 days to 22.5 days. Thus, the process reliability decreases from 90% to 60% and the supply reliability decreases from 54% to 42%. Looking at this result, it is of interest to determine the amount of additional finished goods inventory that facility 2 would have to keep in stock in order to compensate for this decline in supply reliability. Thus, the amount of pipeline inventory that would be required in order to maintain the supply reliability at its original value of 54% is determined. In this situation, an inventory service level of 93%, requiring 25.5 days of finished goods inventory, would be needed to restore the overall supply reliability to its original level. Given that finished goods inventory receives 10% of the overall pipeline safety stock, the overall pipeline inventory will need to increase from 14.8 to 256.4 days of supply. This result shows the magnitude of increase that pipeline inventory is required to have in order to compensate for a 40% increase in production cycle time. It can be noted that this result is based on the somewhat strong assumptions that total supply reliability is determined to 34% by changes in the inventory service level and that these changes are on to a marginal extent by changes in finished goods inventory.

3.3.4 Sensitivity analysis

An analysis of the impact that is created by changes in an input parameter allows a better understanding of the dynamics that are captured in the 5-Box model, and of the modifications proposed in section 3.3.2.3. This analysis is based on the diagram in figure 3.4, which shows the interactions captured within the 5-Box model.

While the continuous lines in figure 3.4 reflect the interactions captured in the 5-Box model that were outlined in section 3.2, the dotted lines refer to the following interactions that are likely to occur in a "make to order" system, such as that analyzed in the case study in section 3.3. These interactions are in particular the impact of changes in the order response time and the response time variability and the impact of changes in the forecast accuracy on the inventory service level, such as outlined in section 3.3.2.3. In addition, the length of the average cycle time might have some impact on the lead time quoted to customers. This impact is however likely to be based on the perception of the person setting the quoted lead times and cannot be measured directly. Finally, figure 3.4 captures the issue that a "make-to-order" system is likely to show some correlation between the average response time and the average time that material will spend in the pipeline.

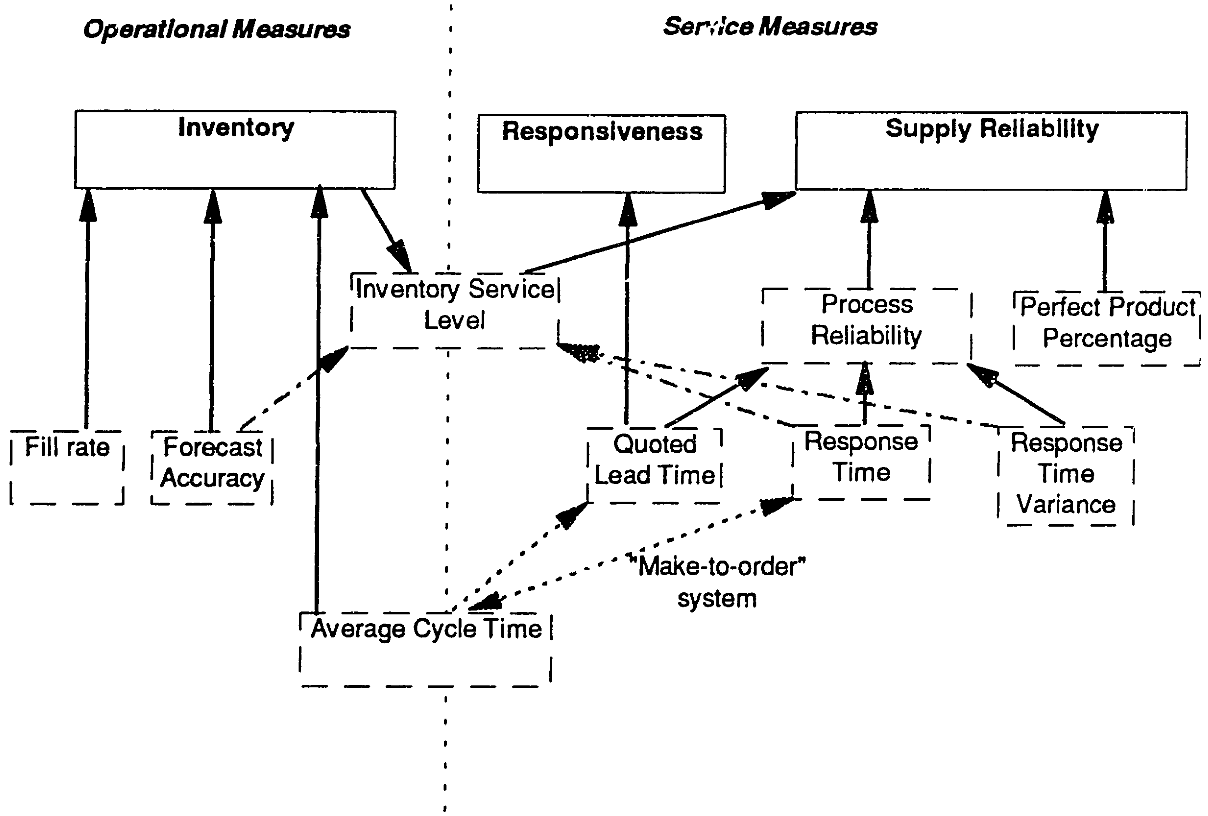


Figure 3.4: Major interactions within the 5-Box model

Based on figure 3.4, the following seven analyses are intended to capture all significant chains of influence within the 5-Box model. The resulting charts are listed in appendix 3.3.

Analysis 1: The impact that changes in the demand variance over the forecasting horizon have on the level of inventory and supply reliability at each manufacturing facility, without adjusting the finished goods demand variability for changes in the forecast accuracy.

	Facility 1		Facility 2		Facility 3	
Average cycle Time	75 Days		27.2 Days		34.5 Days	
Demand Variance	0%	90%	0%	90%	0%	90%
Safety Stock (Days of sup.)	0	87	0	32	0	40
Total Inv. (Days of supply)	10	97	7	39	16	55
Inventory Service Level	53%	97%	53%	68%	53%	73%
Pipeline supply reliability	46%	61%	54%	63%	46%	56%

Table 3.2: Impact of changes in the demand variance from 0% to 90%

This analysis shows that the increase in demand variability will increase pipeline safety stock, and thus the inventory service level. This result is based however on the original assumption of the 5-Box model, that demand at the final production stage is independent of the overall pipeline demand variability. In general, it is unlikely for these two sources of demand variability to be independent. Thus, the demand variability of the finished goods stockpile was adjusted such that it reflected changes in the uncertainty that the entire pipeline was facing. By setting the weekly demand variability at the final production stage at twice the rate of the standard deviation of the forecast accuracy, it can be shown that the inventory service level remains nearly unchanged with changes in the level of forecast accuracy. Now, a shift in forecast accuracy changes both the amount of safety stock that is maintained throughout the pipeline and the degree of demand variability at the final production stage. This adjustment is maintained throughout the following measurements.

Analysis 2: The impact that changes in the required pipeline fill rate have on inventory days of supply, and thus on the overall pipeline supply reliability.

	Facility 1		Facility 2		Facility 3	
Response Time	24.2 Days		15.5 Days		22.5 Days	
Response Time Variance	12.1 Days		7.8 Days		11.3 Days	
Fill rate	50%	99.9%	50%	99.9%	50%	99.9%
Safety Stock (Days of supply)	0	22	0	45	0	45
Total Inv. (Days of supply)	9	31	8	53	10	55
Inventory Service Level	52%	56%	51%	59%	51%	57%
Pipeline supply reliability	45%	46%	53%	56%	45%	48%

Table 3.3: Impact of changes in the pipeline inventory fill rate from 50% to 99.9%

The results captured in table 3.3 show that increasing the overall fill rate will increase the amount of pipeline safety stock in a manner that is dependent on the overall demand variability. The measurements to show the impact of a change in the safety stock on the inventory service level confirm what could be expected from equation 3.5. Changes in the inventory service level determined both by the length of the replenishment lead time (in this situation, the order response time) and by the lead time variability (the response time variability). The inventory service level of facility 1, with a long response time, and a high response time variability, is impacted to a lesser extent by changes in the level of pipeline safety stock than the inventory service level of facility 2, with a short response time and low response time variability.

Analysis 3: The impact that changes in the average cycle time have on inventory days of supply in the pipeline, and thus on the overall supply reliability.

	Facility 1		Facility 2		Facility 3	
Demand Variance	6%		24%		24%	
Avg. cycle Time (Days)	10	75	10	75	10	75
Safety Stock (Days of sup.)	1	6	4	24	3	24
Total Inv. (Days of supply)	9	15	12	32	13	34
Inventory Service Level	52%	53%	52%	56%	51%	54%
Pipeline supply reliability	45%	45%	53%	54%	45%	46%

Table 3.4: Impact of changes in the average cycle time from 10 days to 75 days

Table 3.4 shows that the increase in inventory that coincides with an increase in cycle time is dependent on the demand variability at each facility. The slope of the increase for facility 1, facing a demand variability of 6%, is smaller than the slope of the increase for facilities 2 and 3, each facing a demand variability of 24%. The impact of a change in the safety stock on the inventory service level, and thus on the overall pipeline supply reliability occurs in the same manner as discussed in the previous analysis.

Analysis 4: The impact that changes in the order response time have on the process reliability, and thus on the overall pipeline supply reliability, given a fixed quoted lead time.

	Facility 1		Facility 2		Facility 3	
Quoted lead time	30 days		25 days		28 days	
Response time variance	15 days		12.5 days		14 days	
Response time (days)	10	36	10	36	10	36
Order response reliability	100%	38%	100%	28%	100%	34%
Pipeline supply reliability	59%	32%	59%	28%	59%	31%

Table 3.5: Impact of changes in the response time from 10 days to 36 days

Table 3.5 shows that the decrease in order response reliability is larger at facilities two and three than at facility 1. This result can be explained by equation 3.9, which shows that the level of change of the order response process reliability that is created by changes in the order response time depends both on the variability of the response time distribution and on the time that is quoted to the customer.

Analysis 5: The impact that changes in the response time variance have on the process reliability, and thus on the overall pipeline supply reliability, given a fixed response time and a fixed quoted lead time.

	Facility 1		Facility 2		Facility 3	
Quoted lead time	30 days		25 days		28 days	
Response time	24.2 days		15.5 days		22.5 days	
Resp. time variance (days)	2	16	2	16	2	16
Order response reliability	100%	65%	100%	72%	100%	65%
Pipeline supply reliability	59%	42%	59%	47%	59%	43%

Table 3.6: Impact of changes in the response time variance from 2 days to 16 days

An increase in response time variance impacts the order response reliability such that it decreases at a decreasing rate and asymptotically approaches a lower limit, dependent on the specific pipeline that is modeled. As it could be expected from equation 3.9, the results captured in table 3.6 show that a change in the variance of the order response time impacts the order response process reliability in a manner that is dependent on the difference between quoted lead times and mean order response. The decrease of order response reliability is high at facilities 1 and 3, each having a difference between quoted lead times and mean order response times of approximately 6 days. However, the decrease is lower at facility 2, having a difference between the quoted lead time and the mean response time of approximately 10 days.

Analysis 6: The impact that changes in the quoted lead time have on the process reliability, and thus on the overall pipeline supply reliability, given a fixed response time.

	Facility 1		Facility 2		Facility 3	
Response time	24.2 days		15.5 days		22.5 days	
Response time variance	10 days		10 days		10 days	
Quoted lead time (days)	10	50	10	50	10	50
Order response reliability	12%	99%	24%	100%	13%	100%
Pipeline supply reliability	22%	58%	26%	59%	23%	59%

Table 3.7: Impact of changes in the quoted lead time from 10 days to 50 days

The results captured in table 3.7 reflect equation 3.9 as they show that the impact of changes in the quoted lead time on the order response process reliability and on the overall pipeline supply reliability a change in order response reliability is dependent on the response time at each facility. Facilities 1 and 3, each with high order fulfillment response times, have lower initial levels of supply reliably than facility 2. These changes are analogous, however opposite to the impact of changes in the order response time.

Analysis 7: As mentioned, the average cycle time that material spends within the pipeline can be assumed to be strongly correlated to the amount of time that is required to manufacture a vehicle. This analysis therefore observes the result of the assumption that any change in the order response time will simultaneously change the average cycle time. While analysis 4 shows that an increase in the order response time changes the order response reliability, analysis 3 shows that changes in the average cycle time impacts the 5-Box inventory service level. Moreover, equation 3.13 shows that changes in the overall pipeline supply reliability are based on changes in both the inventory service level and on changes in the order response reliability.

	Facility 1		Facility 2		Facility 3	
Quoted lead time	30 days		25 days		28 days	
Response time variance	15 days		12.5 days		14 days	
Response time (days)	10	36	10	36	10	36
Average cycle time (days)	10	36	10	36	10	36
Inventory service level	58%	52%	53%	52%	52%	51%
Order response reliability	100%	38%	100%	28%	100%	34%
Pipeline supply reliability	59%	38%	58%	29%	58%	31%
Total inventory (days)	12.5	14.2	13.1	21.4	16.5	24.3

Table 3.8: Simultaneous changes in the average cycle time and the mean order response time

As could be expected from analysis 3 and 4, table 3.8 shows that an increase in the response time causes the order response process reliability to decrease and the total pipeline inventory to increase. Moreover any increase in the inventory service level caused by an increase in pipeline inventory is far less than the decreases in order response process reliability. Thus, it can be concluded that in the situation of a linkage between the average cycle time and the order response time, the ability to decrease the order response time will be highly beneficial both from a service and from a financial viewpoint. This analysis could also show however that the impact of such a change depends on various pipeline parameters.

In particular, within this case study, a change in the manufacturing time will lead to the least changes at facility 1, and to the greatest changes at facility 2, both from a service level and from a financial viewpoint. This can be explained by the circumstance that facility 1 requires less safety stock throughout its pipeline and is less reliant on a fast order response time, since it has the longest quoted lead time. Facility 2, on the other hand, requires a higher level of safety stock and offers a shorter quoted lead time. Thus, changes in the length of time that material spends in its pipeline has a strong impact on the total level of pipeline inventory, and a reduction in order response time of a facility with a short quoted lead time will have a strong impact on the facility's process reliability.

CONCLUSION

Chapter 3 reviewed and applied metrics interaction models at DEC. Section 3.1 described the "Inventory lead time Service" model. Section 3.2 described the equations used in the 5-Box model. Section 3.3 described an automotive industry benchmarking group data set that is modeled with the 5-Box model. Finally, section 3.3.4. showed some sensitivity analyses that were conducted with the data.

Chapter 4 GENERAL EXTENSIONS TO THE 5-BOX MODEL

INTRODUCTION

The 5-Box model is defined by its developers[53] as a "high level" pipeline planning tool. As shown in chapter 3, the 5-Box product pipeline spans over a set of manufacturing stages which procure raw material, transform this material into intermediate products, assemble finished goods, and distribute these goods to customers. It models this product pipeline as one entity that is required to maintain one aggregate level of safety stock in order to provide a specific level of service reliability. When applying this model to manufacturing pipelines, two of the underlying assumptions are troublesome.

First, the 5-Box model assumes that given a fixed order response time and a fixed response time variability, changes in the supply reliability can only be achieved by means of changes in the level of finished goods inventory. On the other hand, if demand exceeds the level of inventory, it assumes that quoted lead times will need to be extended.[54] The amount, by which the quoted lead times are extended will reflect the ability of Manufacturing to compensate for unexpected shifts in demand on short notice. Among other approaches, such as changing the production schedule in the situation of multiple products, this can be achieved by maintaining surplus manufacturing capacity. Thus, the degree to which quoted lead times need to be extended may depend to some extent on the amount of excess manufacturing capacity within the pipeline. Recent publications, listed in section 4.1.1, indicate that investment in additional manufacturing capacity will not only decrease the impact of random surges in demand on the manufacturing lead time, but also reduce manufacturing lead time variability and, depending on its cost, can provide a more efficient alternative to the deployment of further inventory throughout the pipeline. Section 3.3 showed that if the order response time is assumed to be equal to the manufacturing lead time, the 5-Box model can account for the fact that a decrease of the manufacturing time variability will lead to an increase in pipeline supply reliability. However, the model does not capture changes in inventory that could be achieved through a change in the level of manufacturing capacity within the system.

Second, the 5-Box model might not provide efficient guidelines to set inventory levels throughout each production stage. While fillrates are usually established in order to determine the the level of safety stock at the inventory storage point that faces demand, the 5-Box model assumes, as mentioned in section 3.2, that an "overall pipeline" safety stock can be effectively allocated throughout the pipeline. This allocation is done by setting safety stock "percentages," shown in figure 3..3, at points throughout the pipeline that are expected to store safety stock. The user is prompted first for the existing level of process stock present at an inventory storage point, and then for the percentage of overall pipeline safety stock that should be placed at this point. In order to assure a "correct" pipeline safety stock set-up at all points, the model accounts for additional safety stock required at each stage to cover extended supplier lead times and refers users to the ILS model, outlined in section 3.1, for further analysis. It can be noted however, that the ILS model is not capable of incorporating important aspects of pipeline performance that may be reflected in the level of safety stock that is set. In particular, it does not reflect the possible tradeoff between inventory holding costs, stockout costs, and costs of transporting goods between successive production stages, and it does not cover possible impacts of the pipeline network. Moreover, using the 5-Box method to determine safety stock levels throughout the pipeline might not provide an accurate modeling of the impact of changes in the forecast accuracy on pipeline inventory. Setting safety stock "percentages" implies that a change in forecast accuracy will correspond to a linear change in the level of safety stock at each point throughout the pipeline. This assumption could be valid in specific pipeline arrangements, but cannot be considered generally applicable. Lee *et al.*[55] point out that if safety stock levels are determined in such a general manner, unanticipated pipeline bottlenecks could emerge. These bottlenecks can be caused by the model's inability to account for "local" dynamics such as delayed replenishment lead times between production stages. Likewise, this approach could lead to excessive inventory at other locations so that working capital is needlessly tied up. Section 4.2 outlines models to address these issues.

Two additional limitations of the 5-Box model can be mentioned at this point. First, the nature of customer demand and of the order response time are assumed to be normally distributed. Mentzer[56] has shown however that the assumption of normality is frequently violated. This is why in the case of low order volumes, Keaton[57] suggests a gamma distribution of demand over the forecasting horizon. In the case of a "make to order" system with short response times, the response time has been found by Magee *et al.*[58] to resemble a log-normal distribution. Moreover, publications such as Zinn,[59] dispute the assumption that the nature of lead time demand variability is independent of the lead time duration by demonstrating the impact of autocorrelated customer demand. These issues are not addressed in detail in this chapter as a greater attention is given to the general interaction between the measures rather than to their specific nature.

Second, the model assumes that the reliability of pipeline operations can be completely defined by measures of *overall supply reliability* and the *fill rate*. While these are important aspects, they could be extended with further measures to provide a more comprehensive picture of the level of reliability. Petrovic,[60] for example, lists the *ready rate*, the *expected number of backorders*, and the *logistic delay time* as important performance measures in multi echelon inventory systems. The *ready rate* can be defined as the probability that an item that is observed at a random point in time has zero back orders, while the logistic delay time can be defined as the end user equipment downtime that occurs due to defective products. Moreover, the model assumes that customer service standards can be completely determined by the pipeline *responsiveness*. However, according to La Londe,[61] further measures such as service quality and after-sales service constitute a major part of the level of service perceived by the customer, and are thus additional measures that should be used to set standards for pipeline performance. The issue of lacking performance measures will be revisited in section 5.1.

4.1 INVENTORY - MANUFACTURING CAPACITY TRADEOFFS

Section 4.1.1 motivates the first extension by describing the circumstances within which a tradeoff between finished goods inventory and manufacturing capacity can be found, while section 4.1.2 outlines general approaches to determine an improved allocation of finished goods inventory and manufacturing capacity.

4.1.1 Motivating inventory - manufacturing capacity tradeoffs

The tradeoff of finished goods inventory vs. manufacturing capacity usually emerges during the process of designing product pipelines or of reevaluating existing manufacturing configurations. At this point, decision makers are capable of making simultaneous decisions on the level of finished goods inventory to maintain at a production stage, the amount of labor to hire, and the number of manufacturing lines to purchase for this production stage.

In situations of highly cyclical and/or random demand, capacity planning decisions are likely to lead to inefficient manufacturing arrangements, if they do not account for the value of pipeline inventory assets that they entail. Such decisions are inclined to prioritize a high utilization rate of manufacturing equipment and could thus require excessive levels of finished goods inventory to meet demand fluctuations. For example, with a cyclical demand, low cost of additional production capacity and high cost of holding inventory, it might be desirable to maintain idle production lines that are only used in periods of peak demand rather than to "build" inventory in anticipation of demand spikes.

In the situation of a pipeline facing random demand fluctuations, where orders can be serviced within the production and distribution lead time, excess capacity is capable of supporting the concept of "postponement." Postponement describes a pipeline arrangement that delays the final assembly of a product up to the point at which it is actually ordered by a customer. According to Lee,[62] this concept is particularly important for manufacturers that intend to offer a large product variety and that accrue obsolete inventory if finished products are not sold shortly after they were manufactured. In this situation, intermediate inventory has the advantage of being "generic" since it can be used to produce the product that was ordered, while finished goods safety stock would need to maintain distinct characteristics.

According to Krajewski,[63] the concept of a "protective" capacity has gained relevance with recent advances in manufacturing methods. The introduction of JIT manufacturing arrangements within the product pipeline has led to a reconsideration of the effective costs of holding inventory and of obsolescent finished goods inventory. Moreover, "lean manufacturing" methods[64] address the issue of reducing the overhead costs of idle capacity. Lean manufacturing methods attempt "to produce and distribute products in half the overall expense,"[65] by striving to minimize all investments that are incurred throughout the life cycle of these products. Savings have been found in particular by means of approaches to "manufacture only those products that are necessary," by reducing the capital cost of new equipment acquisitions, and by increasing the flexibility of production labor.[66] Both JIT and "lean manufacturing" pipeline arrangements may thus be likely to maintain "slack" capacity, instead of excess inventory in order to assure that only those products, that have been demanded, are produced and shipped. Moreover, Steele,[67] Atwater,[68] and Goldratt,[69] describe further situations, in which slack capacity provides an acceptable alternative to inventory. The results of their research confirm that adding slack capacity will lead to a reduction in order response time variability while allowing a pipeline to operate on lower inventory levels. They point out however, that the value of capacity slack is highly dependent on the nature of the industry and usually requires a long term view because of the future revenue that is necessary to offset the current cost associated of acquiring and maintaining capacity slack.

4.1.2 Models of inventory - manufacturing capacity tradeoffs

Schonberger,[70] McClain *et al.*,[71] Billesbach,[72] Inman and Mehra,[73] and Zipkin[74] have extensively discussed the potential reduction in finished goods inventory that can be achieved by a lower order response time variability in the context of JIT or "stockless production." However, little research has been done to determine the reduction of finished goods inventory that would result from a more efficient configuration of inventory and manufacturing capacity investments.

Given a deterministic cyclical demand, the general tradeoff between finished goods inventory and investments in manufacturing capacity can be modeled in terms of modified aggregate production scheduling programs. Aggregate production planning models such as Hanssman,[75] and Haeling[76] have considered capacity shifts, however have modeled these merely as changes in the work force level. This limitation is primarily done in order to analyze investments with approximately the same time frame and to maintain a linear objective function. The advantage of linear models is that they can be easily extended to cover production processes with several stages. A comprehensive overview of multi-stage linear planning models is provided in Johnson and Montgomery.[77] Moreover, the first production scheduling model geared to balance the investment in additional seasonal stock with the investment in additional capacity was developed by Hax and Meal,[78] who develop a "seasonal planning submodel" for the situation of cyclical demand. This program, too, only minimizes the sum of inventory costs and possible additional labor overtime costs.

Bemelmans[79] proposes the introduction of measures of the capacity investment that is tied up in inventories in order to "set safety stock levels more efficiently and to achieve an improved coupling of production schedules with material flow coordination decisions."[79] While the author compares various production scheduling programs that consider this "capacity investment aspect" of inventory, he does not seek programs to find an optimal tradeoff between these measures. Moreover, Billington *et al.*[80] note that although many authors have proposed various production scheduling models that consider constraints of a facility capacity, none have employed an optimization model that explicitly determines the optimal capacity investment.

A review of hierarchical production scheduling programs indicates that manufacturing capacity and inventory decisions are usually taken separately, based on different criteria. Hax[81] shows that production line purchases are usually long term decisions that are based, among other issues, on the ability to maximize equipment utilization. In contrast, safety and seasonal stock are usually based on production scheduling programs which attempt to minimize production costs, given the available production capacity levels. If the situations that have been outlined in section 4.1.1 apply and it is reasonable to combine such short term and long term investments, then production schedules and inventory levels can be determined at the same time as manufacturing line purchasing decisions. The decision to expand the level of manufacturing capacity by means of additional production lines can then be included in the objective function of an aggregate production scheduling program.

Colgan[82] analyzes alternative shop-floor configurations for the manufacturing process of PC modules consisting of surface mount technology and module assembly to determine an optimal "return on operating assets." The return on operating assets can be defined as the quotient of profit resulting from production operations and the cost of production capacity and inventory. His analysis of one production stage shows that an optimal return on operating assets requires increased levels of slack capacity as demand cyclicality increases. A limitation of this analysis is however the issue that the objective function is fractional and likely to be non-linear. An extension of this program to cover multiple production stages might lead to an unmanageable running time.

A somewhat more simple measure to compare the profitability of alternative investments in production capacity investment while considering the necessary investment in inventory is by looking at the *residual income* from capacity expenditures.. The *residual income* can be introduced as the profit before interest expense and taxes minus a capital charge. As shown in equation 4.1, the capital charge is calculated from the product of a percentage rate, also known as the "weighted average cost of capital" (WACC) for the particular company and intended investment, and the necessary level of investment in production capacity and inventory assets. The capital charge thus represents the opportunity cost of the invested capital. Brealey and Meyers[83] provide a detailed description of the weighted cost of capital, along with methods to determine it.

$$\begin{aligned}&\text{Residual Income} = \text{Profit from operations} - [\text{Cost of capital} * \text{Investment}]\\&= [\text{Revenue} - \text{Cost of operations}] - [\text{WACC} * (\text{Inventory assets} + \text{Capacity expenditures})]\end{aligned} \qquad [4.1]$$

In an aggregate production scheduling program, the residual income can be maximized by minimizing the cost of manufacturing operations while meeting a sufficient level of demand. In a multi stage product pipeline, such an optimization model could have the following form:

Objective: Minimize the cost of manufacturing operations and the level of investments in manufacturing capacity and inventory:

Subject to: Servicing customer according to the fill rate in each period
A feasible production process at each facility
A limited production capacity purchasing budget

In the case of cyclical demand, Bitran *et al.*[84] note that it is important to set a time horizon for the programming formulation such that the optimization covers a full demand cycle. The inclusion of multiple manufacturing stages is facilitated by assuming a separable objective function that sums over all production stages included in the optimization. An example of a possible multistage problem formulation to optimize the residual income from capacity investments is listed in appendix 4.1.

It should be noted though that the applicability of [illegible]ults from such an analysis is limited by the fact that capacity investment decisions might be guided by multiple objectives. Hill,[85] Stevenson,[86] and Vollman[87] list additional issues that are likely to be considered in capacity planning decisions such as the rate of product design changes, or the rate of technological changes. In certain situations, these criteria could outweigh the objective of achieving an optimal residual income on manufacturing investments. Finally, it can be noted that higher level investment decisions are likely to aggregate a manufacturing capacity vs. inventory tradeoff into a broad "portfolio analysis" of product pipeline operations. According to Naylor,[88] a portfolio analysis supports the process of deciding in which businesses a company should be in and how much funding to allocate to these businesses.

If however an analysis that is geared to optimize the residual income of manufacturing capacity expenditures were to be extended such that it evaluated all operations throughout a multi-stage product pipeline, it would be no longer possible to assume a separable objective function. A separable objective function presumes that the entire pipeline can be treated as a set of independent business units, except for the fact that all compete for the same capital resources. However, given the interdependent nature of product pipelines, it might not be possible to treat each production stage as a separate profit center. Hirschfield[89] therefore views the ultimate objective of any model geared to find optimal investment decisions throughout a pipeline as the maximization of overall pipeline profitability.

4.2 MODIFYING INVENTORY LEVELS WITHIN THE 5-BOX PRODUCT PIPELINE

As mentioned above, the 5-Box model does not consider "local" methods of determining safety stock within a pipeline. Rather, it assumes that a central decision maker using the model is capable of setting process and safety stock levels at each point, such that the overall level of pipeline supply reliability is maintained. Lee and Billington[55] define a management structure that allows the determination of operating policies at each stage of a pipeline based on the material and demand status of the entire pipeline as a "centralized pipeline control." This arrangement would assume that inventory decisions at all Manufacturing and Distribution stages can be modeled as a single entity by a central set of decision makers. While this assumption may be suitable for the situation of pipelines at DEC, La Londe[90] notes that this does not reflect a common pipeline arrangement. Even leaders in the development of inter-company operating ties, such as Baxter Corporation, manage a majority of their product pipelines based on a traditional, decentralized control structure.[91] Lee and Billington[55] contrast decentralized control with centralized control by describing decentralized control as a situation where each stage in the pipeline makes decisions based on "local" information. Cohen *et al.* maintain that a consideration of the "local" lead times and demand uncertainties at each production stage facilitates a reasonable translation of overall pipeline safety stock levels and overall pipeline supply reliability into efficient operating policies at each stage. This point is confirmed by Billington[92] and Davis,[93] who outline the benefits of a successful implementation of decentralized pipeline models. The 5-Box model is likely to gain greater applicability if its inventory levels reflect an understanding of the transportation costs, lead times and demand uncertainty within each individual production stage and between successive production stages throughout the product pipeline: issues that the ILS model might not sufficiently capture.

The rest of section 4.2 therefore shows models that assist in the determination of safety stock levels at each production stage within decentralized product pipelines, based on the demand for input material and finished products, the operating cost, and the replenishment lead times. Section 4.2.1 outlines approaches to compute safety stock levels and shipment sizes between successive stages based on the total logistics cost of operations. Moreover, section 4.2.2 outlines a model to set safety stock levels that reflect the dynamics of an integrated production-inventory storage stage such as the one modeled in the conceptual 5-Box model pipeline.

4.2.1 Minimum logistics cost models

"Local" inventory levels are usually influenced by the tradeoff between the cost of holding inventories, and the cost of stocking out. They are also influenced by the size of shipments between successive storage points, which, in turn, are influenced by the cost of making frequent shipments and the cost of holding inventories. The 5-Box model attempts to model the first tradeoff by suggesting that the user observe the inventory holding costs associated with various pipeline fill rates in order to "perform what-ifs to find the best balance for the business."[55] The 5-Box model however completely neglects the second tradeoff as it counts transportation costs merely as "value added costs" towards the computation of total pipeline costs. If the costs of goodwill and lost sales associated with a stockout can be quantified, then the optimal fill rate - and thus optimal inventory levels - can be determined for each inventory storage point. Section 4.2.1.1 demonstrates how the transportation - inventory cost tradeoff and a precise estimate of stock out costs can be used for an exact determination of safety stock levels and shipment sizes in a single link between two storage points, while section 4.2.1.2 shows the impacts that the product pipeline network can have on the determination of the optimal single link shipment size, and thus on the level of safety stock at each storage point.

4.2.1.1 TRANSPORTATION - INVENTORY TRADEOFFS ON A SINGLE LINK

Shipping large loads infrequently between successive stages in the pipeline reduces the ordering cost per item, because the fixed cost of the shipment can be spread over more items. However, larger shipments increase the inventory holding cost per item because of the added time required to produce and consume larger shipments. Alternatively, shipping smaller orders, more frequently, results in a higher ordering cost per item, but reduces the inventory holding cost per item. With variable demand, and continuous review, this tradeoff is resolved by the economic order quantity (EOQ) Q^*, and the optimal reorder point, s^*. The EOQ is based on the Wilson lot-size model,[94] which is used to compute the number of units that need to be produced in one batch given a setup cost, a carrying cost, and a sales rate, such that the total unit costs are minimized. This production lot size model is used in section 4.3.2.2.

Total logistics costs can be defined as the sum of transportation, ordering, stock-out costs and inventory carrying costs. For a continuous review inventory policy with a stochastic demand and lead time, the average annual cost of holding, set-up, and shortages can therefore be formulated such as in Nahmias:[38]

$$TC = \frac{A\bar{D}}{Q} + \frac{K\,\bar{a}(s)\,\bar{D}}{Q} + VW\left[\frac{Q}{2} + s - \bar{L}\,\bar{D}\right] \tag{4.2}$$

where:

TC : average annual logistics cost ($)
Q : reorder quantity (units)
A : ordering costs ($/order)
s: reorder point (units)
$\bar{D}$: expected annual demand rate (units/year)
$\bar{a}(s)$: expected shortage per cycle time (units)
$\bar{L}$: average lead time between orders (days)
K : per unit stock out cost ($/unit)
V : per unit value of the commodity ($/unit)
W: annual inventory carrying cost (%/year)

The three components of the logistics cost, from left to right, can be described as follows:

Component 1: Annual ordering cost

The average annual ordering cost is determined by the product of order set-up and transportation costs per order and total annual orders. This component will decrease as the shipment size increases.

Component 2: Annual stock-out cost

The average annual stock-out cost is the product of the cost per stock-out and the number of stock-outs per year. This component will decrease as the shipment size increases.

Component 3: Inventory carrying cost at the storage location

The average annual inventory carrying costs at the storage location are determined by the product of the annual inventory carrying cost and the value of the average level of inventory at the storage location. The average level of inventory at the storage location is determined from the sum of process stock and safety stock. The safety stock is the expected level of inventory on-hand just before an order arrives and is given by the difference between the reorder point and the expected level of lead time demand. This cost component will increase with the shipment size.

The optimal reorder quantity (or shipment size), Q^*, and the optimal reorder point, s^*, that minimize equation 4.2 can be found in the following manner. Scarf[95] shows that the total logistics cost function is non-linear, unconstrained and usually convex. Thus, Q^* can be found at the minimum of equation 4.2:

$$Q^* = \sqrt{\frac{2\,\overline{\mathrm{D}}\left[\mathrm{A} + \mathrm{K}\,\bar{\mathrm{a}}(s^*)\right]}{\mathrm{V\,W}}} \qquad [4.3]$$

Equation 4.3 shows that the optimal shipment size depends on the optimal shortage per cycle $\bar{\mathrm{a}}(\mathrm{s}^*)$, and thus on the reorder point s^*, that generates the lowest combination of inventory carrying costs and stock-out costs. Assuming a normally distributed demand over the forecast horizon, Nahmias[38] shows that the safety stock will be set such that the cumulative probability of stocking out within an order cycle, given reorder point s^*, is equal to the quotient of inventory carrying costs of the reorder quantity and the product of per unit stock out costs and daily demand.

$$1 - F(s) = \frac{Q * (VW)}{K * \overline{D}} \qquad [4.4]$$

General methods that determine the optimal shipment size and reorder point with continuous review systems, such as in Nahmias[38] are known as (Q, R) policies. Appendix 4.2 illustrates a six step solution procedure to find Q^* and s^* for equation 4.2, assuming a strictly convex total logistics cost function. As mentioned, the level of safety stock can be determined from the reorder point s^* by subtracting the expected demand over the replenishment lead time. Using these models, the safety stock "percentages" of the 5-Box model could now be revised, such that they assured a minimal total cost of ordering, storing, and shipping material and goods between successive stages. These percentages would be determined by adding up the "local" safety stock levels throughout the pipeline, and computing the percentage of total safety stock that should be allocated to each point.

4.2.1.2 TRANSPORTATION -INVENTORY TRADEOFFS WITHIN THE PRODUCT PIPELINE NETWORK

As mentioned, these results do not recognize, that product pipelines usually do not consist of merely one origin and destination, but rather of a network of "points" that produce, warehouse and distribute products. Daganzo[96] terms pipelines "large scale manufacturing systems with a *many points to many points* logistic process that conveys multiple raw materials to their destination markets." Products that are stored at a plant or warehouse may have several points of consumption in the following stage. Likewise, they might be produced with input materials that are sourced from several points. A common pipeline network structure is the combination of an assembly type inbound network and an arborescent distribution network. An assembly type manufacturing setting implies a multistage inbound network, where one finished good is produced from several input materials. Thus, a node in this network may have several supplying nodes. On the other hand, an arborescent distribution network implies that all distribution locations are supplied from one central point. Thus, a node will have at most one supplying node. This network structure is shown in figure 4.1.

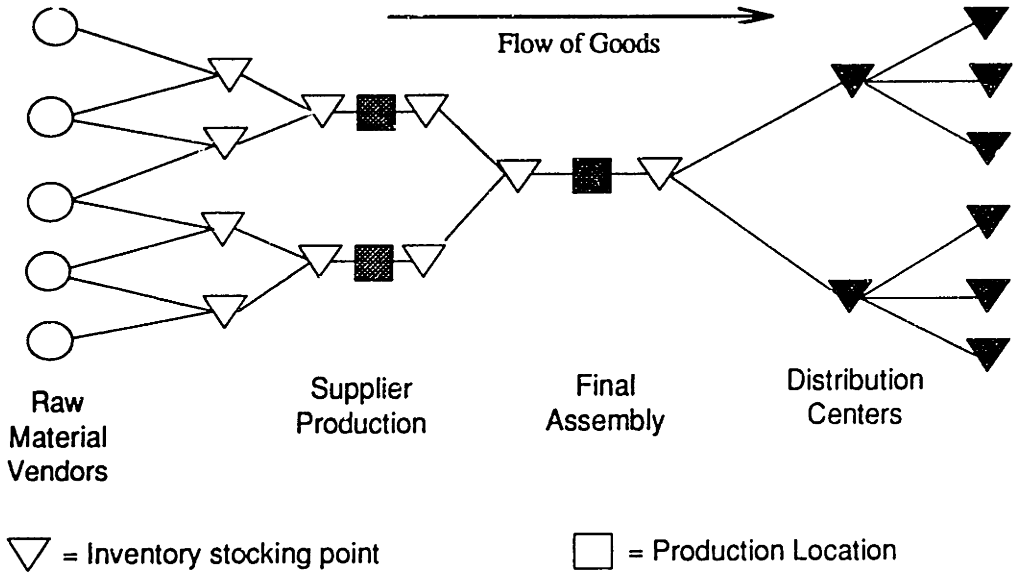


Figure 4.1: Assembly type manufacturing structure with arborescent distribution network

In a network, there are two decision variables: (i) shipment sizes or frequencies on the network links and (ii) the routes over the network. The rest of this section describes the manner in which the route that is selected for each shipment will impact the amount of material shipped on each link within the product pipeline network. In particular, it will look at the network of inbound shipments, since this is the primary focus of the 5-Box model.

The subnetwork of inbound shipments supplying one assembly plant can contain several supplier plants and warehouses to be used as transshipment points, giving four possible routing options:

Option 1: Making only direct shipments from the suppliers to the assembly plants

Option 2: Making all shipments via the warehouses

Option 3: Making direct shipments between some plant pairs, shipping via the warehouses for others, and using a mixture of these two options for yet others.

Option 4: "Peddling," that is delivering items from a supplier or the warehouses to several assembly plants in one truck load.

In the situation of one warehouse, that serves as a consolidating point for shipments to one assembly plant, such a subnetwork could be represented in the following manner:

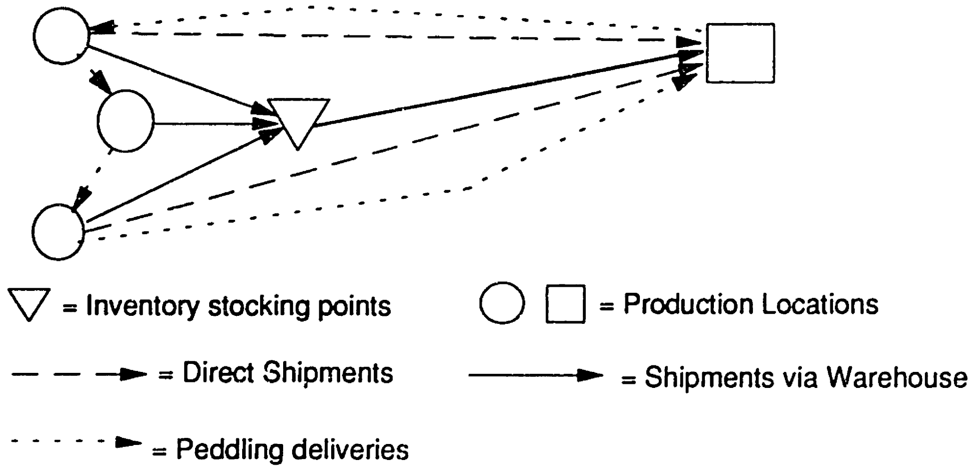


Figure 4.2: Shipping options for inbound shipment network

Each of these routing options involves different transportation costs and will therefore affect the optimal shipment size Q^*, which, in turn, will impact the flow on each individual link. A similar analysis could also be constructed for the outbound distribution network.

Equation 4.2 uses the assumption of Magee, et al.[58] that freight charges can be approximated by a parameter that depends only on the distance. However Burns *et al.*[97] and Blumenfield *et al.*,[98] show that optimal link shipment sizes vary with the square root of the flow. They also show that the minimum logistics cost per unit time on the link increases with the flow at a decreasing rate until there is sufficient flow to justify full conveyance loads, at which point costs approximately increase in a linear manner. These results imply a concave cost per unit time and flow. The result of this scale economy leads to the conclusion that routing and shipment size decisions for all origins and destinations are interrelated. Network costs can be minimized only if optimal routes and shipment sizes are determined simultaneously.

Given that the total link cost is not a convex function of flow, the routing decisions cannot be evaluated with standard mathematical programming techniques. Blumenfield *et al.*[98] propose an enumerative procedure based on the observation that fixed shipment sizes on each link will lead to a linear increase in the total cost per unit of flow. Given this assumption, they prove that the total inbound network can be decomposed into independent sub-networks such as the network outlined in figure 4.2. The resulting procedure can be described as follows: (i) generate a variety of fixed shipment-size combinations on the inbound links, (ii) determine the optimal shipping strategy on each subnetwork for each shipment route - shipment size combination, (iii) sum up the resulting minimum costs on all subnetworks for each route-size combination, and finally, (iv) select the optimal substrategy on each subnetwork that results in the minimum overall cost.

This procedure is practical if there are only a few inbound links, and thus only a few shipment-size combinations to be considered. However, as the number of inbound links increases, the shipment size combinations will increase significantly. More complex networks are analyzed by Burns *et al.*[97] by expressing the customer location in terms of density. Thus the authors avoid the need to specify a detailed network and the corresponding flows. Their research concludes that the EOQ of section 4.2.1.1 yields minimal logistics costs for direct shipments, while in many cases the optimal shipment size for a peddling routing strategy is a full truckload. The inventory-transportation cost trade-off for a peddling strategy however also depends on the number of customers that are on the route. Moreover, based on the concavity of the link cost functions, it can be maintained that shipping some products direct, and some via an intermediate warehouse will always be more costly. A comprehensive overview of these approaches is given in Daganzo.[96] Among other limitations of network approaches, it is important to note the issue that the assumption of a deterministic demand does not allow the computation of specific safety stock levels. Thus, these procedures can be merely used to adjust the optimal shipment quantity of methods in section 4.2.1.1 and not to determine optimal stocking policies.

Part 4.2.1 outlined approaches to determine the level of safety stock that should be maintained at each production stage, and the optimal shipment size between a pair of production stages within the pipeline based on a minimal total logistics cost. Applying these approaches to the conceptual 5-Box pipeline outlined in section 3.2.6 leads to the issue of how to split this inventory correctly into raw materials, "work in process" inventory, and finished goods inventory at an integrated inventory storage-production stage. This issue can be resolved if it can be assumed that raw materials are likely to be stored the incoming goods dock of such a stage, "work in process" inventory is likely to be maintained at the production lines of such a stage, while finished goods inventories are likely to be maintained at the finished goods stock piles of such a stage. Section 4.2.2 thus outlines an approach to apply the EOQ method of section 4.2.1 towards the determination of inventory levels at each of these three inventory storage points within a stage.

4.2.2 Determining inventory levels at each point of an integrated storage-production stage

In the context of the 5-Box model conceptual pipeline, a major limitation of the methods in 4.2.1 is that they cannot determine optimal stocking policies at specific inventory storage points within the production stage such as at the finished goods stock pile and as work-in-process inventory. They rather focus on the coordination of transportation efforts to minimize inventory holding and transportation costs within the pipeline network. Accordingly they emphasize the shipment size and schedule while assuming a simplified picture of manufacturing, especially with regard to the issues of production lead time and capacity. Moreover, they do not consider production lead time uncertainty, a key component of the order response time uncertainty in the 5-Box model.

The following conceptual model of a production stage can thus be used to illustrate the dynamics of a manufacturing stage within the 5-Box model product pipeline shown in figure 3..3:

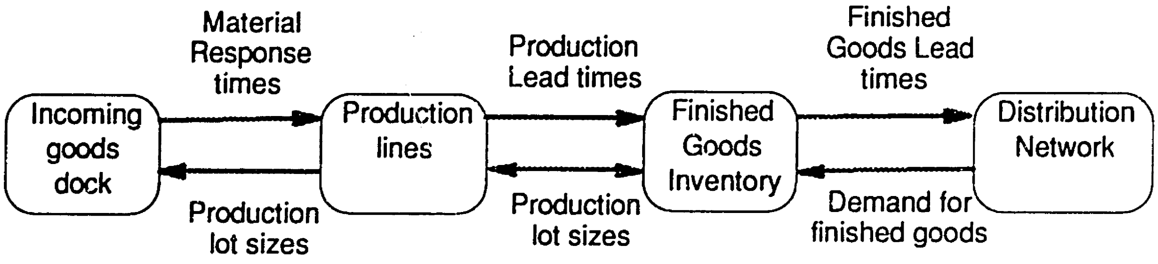


Figure 4.3: Inventory points within each production stage

Given the configuration in figure 4.3, each stage in the 5-Box model could have different inventory policies that could be advantageous within a production stage. It might be preferable to make a high level of raw material available to the manufacturing stage, but have only a low level of finished goods. On the other hand, it might be preferable to maintain a high level of finished goods, but make only little raw material available to manufacturing. Within the conceptual pipeline of the 5-Box model, either policy will most likely result in different pipeline inventory holding costs, however provide an identical level of supply reliability. This is the case, if the policies are modeled such that the total amount of pipeline inventory is unchanged, and the stage being modeled is not the final assembly stage before the distribution network. It can be expected however that each option will actually require changes at other inventory locations in order to assure an unchanged overall pipeline supply reliability. Such dynamics can be captured by a model that includes both production policies and inventory storage policies.

An initial approach to connect production operating policies with finished goods stocks is presented in Garish and Graves,[99] who consider a one product batch facility with stochastic demands for finished goods. Williams[100] extends this model with heuristics for a multi-echelon production and distribution structure, but assumes a deterministic production lead time. This simplification is eliminated by Karmarkar[101] and Zipkin,[102] who model the relationship between production lead times and manufacturing lot-sizes by means of an M/G/1 queuing relationship. The results of Garish and Graves[99] are extended by Williams,[103] who assumes that the finished goods inventory operates under a (Q,R) continuous review, inventory policy. Cohen and Lee[104] develop a model that synthesizes the research of Karmarkar and Williams by capturing both the lead time uncertainties between manufacturing stages and within each manufacturing stage. This makes the model applicable for the determination of production inventory and finished goods inventory. They integrate the production stage into a network that models multiple inputs for each assembly stage that feeds a distribution network with finished goods. The key linkage between manufacturing and distribution is the manufacturing lead time. This lead time is assumed to be the replenishment lead time for the distribution part of the network. The authors assume that in this situation, the replenishment lead time is constant and equal to the mean manufacturing lead time.

Drawing from these models, it is possible to develop an integrated approach to determining inventory levels and replenishment quantities based on a knowledge of the nature of product demand, of inventory holding, stock-out, and (fixed) order costs and of probabilistic production and replenishment lead times at each production stage of the 5-Box model. Along the lines of the Cohen and Lee[104] model, a heuristic listed in appendix 4.3, attempts to set efficient inventory levels in a pipeline that contains multiple input materials and multiple finished goods. Each production stage is embedded in an assembly type manufacturing network setting that connects to an arborescent type distribution network. This heuristic proceeds by finding efficient inventory levels at a production input material, WIP, or finished goods storage point based on the level of supply reliability that is required by the next down stream storage point. These "local" levels of supply reliability thus serve as linkages between the storage points within each stage, and between successive stages.

This heuristic is thus likely to yield a more reasonable approximation of fill rates that would be required throughout the pipeline, given a specific overall pipeline supply reliability. These could be determined by setting the overall pipeline supply reliability to be the supply reliability of the final stage captured in the heuristic, which is likely to be the distribution network. Based on this reliability provided to the final customer, upstream stages in the pipeline can be connected by using the down stream distribution service level of one stage as the material availability level of the subsequent stage. Clark and Scarf[105] maintain that such a recursive determination of the local service and inventory levels leads to near optimal results in serially connected product pipelines. Moreover, Rosling[106] shows that, under certain initial conditions and assuming that a single final good is produced, the assembly network structure can be reduced to a serial one. Thus, a recursive determination of the local service and inventory levels could also apply to pipelines with an assembly type network structure.

While this heuristic might be too complex in terms of computations and data collection efforts to extend the general tradeoffs captured in the 5-Box model, it could be applied to assure that efficient and effective fill rates are found within each production-inventory storage stage throughout the pipeline. Lee and Billington[55] report the successful implementation of a related heuristic to facilitate the product pipeline design process at Hewlett Packard. A limitation of this model that should be mentioned is that it represents the cost of ordering and shipping items from one stocking location to another as fixed. Thus, the problem of shipping costs as a non-linear function of the shipment quantity, outlined in section 4.2.1.2, is assumed away.

CONCLUSION

This chapter introduced extensions of the 5-Box model that would need to be taken into consideration for a more comprehensive understanding of the product pipeline system. In particular, section 4.1 looked at the issue of tradeoffs between manufacturing capacity and finished goods inventory in a capacity constrained pipeline. Section 4.2 looked at methods that could set efficient "local" process stock and safety stock levels at each inventory stocking point throughout the 5-Box pipeline. They could thus improve decisions made with the 5-Box model by translating them into efficient operating policies throughout decentrally managed product pipelines.

Chapter 5 MODEL EVALUATION AND IMPLEMENTATION ISSUES

INTRODUCTION

This chapter evaluates the ability of the models outlined in chapters 2 and 3 to analyze the product pipeline system. The evaluation is based on construction criteria outlined in section 5.1. Section 5.2 evaluates the models based on implementation issues. Section 5.2.1 describes a general set of implementation issues, while 5.2.2 outlines the usefulness of these approaches for specific functions within the organizational structure. Finally, section 5.2.3 evaluates the models' ability to support performance measurement systems and suggests guidelines for the selection of additional performance measures.

5.1 SYSTEM MODEL CONSTRUCTION CRITERIA

This section describes three criteria for the construction of models of system interactions within product pipelines. These criteria are *comprehensiveness*, *causal orientation*, and *accuracy*. Section 5.1.4 applies these three criteria for an evaluation of the two system interactions models.

5.1.1 Model comprehensiveness

The objective of a *comprehensive* model is to cover all significant tradeoffs within the system. According to Mentzer,[107] the most significant tradeoffs in product pipeline performance can be found between measures that reflect efficiency and measures that reflect effectiveness. Therefore, a system model for product pipelines can be considered *comprehensive*, if it incorporates measures of both efficiency and effectiveness. Efficiency, the measure of how well resources are utilized, is described primarily by operational and financial measures. Effectiveness, the extent to which stated goals are accomplished, is primarily described by non-financial measures such as the service level provided and time-related measures.

Based on the above definition, the general transformation model, outlined by NEVEM,[108] is an example of a *comprehensive* pipeline model, since it can incorporate many efficiency and effectiveness measures, and connects these by a set of parameters reflecting performance. The transformation model, shown in figure 5.1, captures the conversion of inputs into finished goods or services. It models three categories of measures: inputs, situational parameters, and outputs.

The efficiency of the transformation process is determined by comparing the inputs with the quality and quantity of pipeline output that they provide. The effectiveness of the process is determined by the extent to which the transformation process realizes stated output norms. All measures that have a bearing on the transformation process are entered as situational parameters. Situational parameters describe the circumstances under which the transformation process has occurred. These parameters can thus impact both pipeline efficiency and effectiveness. A similar transformation model is proposed by Caplice,[24] who reduces all effectiveness measures to the ability of a pipeline to complete the delivery of a product to the final customer precisely according to prespecified requirements. While the transformation model can include as many situational parameters as are desired, it provides no means to explain the impact of the situational parameters. Thus, it provides no analytic linkage between the level of efficiency and effectiveness. Moreover, it cannot explain any interactions that may occur among the input or output measures

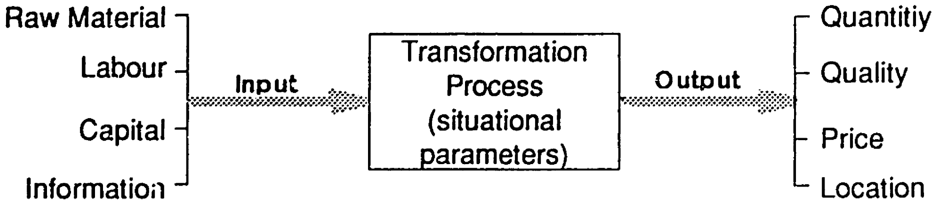


Figure 5.1: The general transformation model [108]

5.1.2 Causal orientation of model

A system interactions model is *causally oriented* if it incorporates a complete set of factors that influence the interactions that are analyzed. For example, a causally oriented system model will seek to explain changes of the measure "supply reliability" with changes of the measure "cycle time variance," and continue by explaining these changes with changes of the measure "production time variance." The model may therefore establish that a *root cause* for increases in "supply reliability" is the reduction in "production time variance." A system interactions model with a high level of causal orientation will therefore be likely to include a large number of root causes driving system interactions.

5.1.3 Accuracy of model

A system interactions model is *accurate* if it describes interactions accurately. This definition implies that an *accurate* model will provide a precise estimate of the interactions that are expected to occur between system measures. In general, a system interactions model with a good internal comparability of performance measures is likely to be accurate. A model has a good internal comparability if it can identify the manner, in which the different dimensions of performance captured by the model can be traded off between each other. A model with a good internal comparability is thus likely to incorporate measures with compatible units, such as exclusively financial measures. It can therefore be contrasted with a highly *comprehensive* model, which is likely to contain measures with incompatible units, such as both time-based and financial measures. Thus, a tradeoff can be made between the ability to construct an *accurate* model and the ability to construct a *comprehensive* model. This trade-off is confirmed by the issue that the compilation of concise information on system interactions usually requires substantial data collection efforts and may be expensive.

5.1.4 Model evaluation and conclusion

The *comprehensiveness* of the structural analysis is based on the number of measures included in the system, outlined in section 2.1, provided that they sufficiently cover measures of efficiency and effectiveness and provide an adequate linkage between these two categories. Moreover, the analysis of system interactions in section 2.2 provides a set of factors that may influence the pipeline performance. It is therefore possible for the structural analysis approach to be both *comprehensive* and *causally oriented.* However, as mentioned in section 2.5, the interactions between system elements are based on subjective inputs and are measured by a set of time independent parameters. While the simulation of section 2.4 provides some qualitative

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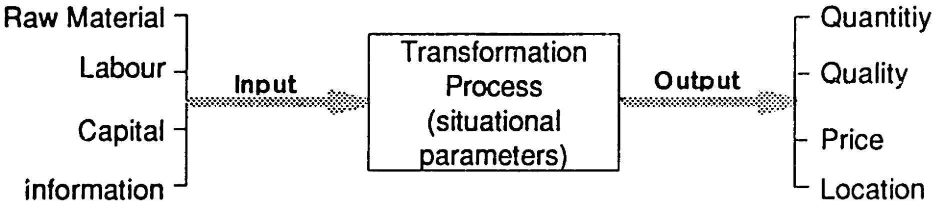

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The 5-Box model tried to create a better understanding of the relationship between measures of significance for Marketing and Finance. It covers both measures of pipeline effectiveness and a financial measure that can assist in the determination of pipeline efficiency. In this sense, the model is *comprehensive*. However, a major limitation of the model is its assumption that the five measures used are the only key drivers of product pipeline performance. As mentioned in section 4.1, the measure of pipeline inventory holding costs may not fully capture the financial performance of a product pipeline. Chapter 4 also described how the 5-Box model might not be able to provide a complete set of pipeline effectiveness measures. Therefore, the *comprehensiveness* will be determined by the extent to which a pipeline's effectiveness is reflected in its responsiveness and reliability while its efficiency is determined by the amount of inventory holding costs that are incurred. Section 3.2 showed how the 5-Box model models various components of supply reliability and responsiveness, and that it incorporates the most significant locations of safety stock within the pipeline. The model's *causal orientation* is however limited to these factors. Finally, section 3.3 shows that the 5-Box model provides a good analytical modeling of the interaction between the 5-Box measures such that the model can be considered reasonably *accurate*.

A review of both models' *comprehensiveness*, *causal orientation*, and *accuracy* shows that each model stresses different construction criteria. While the structural analysis emphasizes *comprehensiveness* and *causal orientation*, the 5-Box model makes a greater effort to assure the *accuracy* of a few select interactions. Thus, the models appear to be useful for different sets of decision makers. A detailed discussion of the issue of the models' usefulness is provided in section 5.2, which addresses implementation issues surrounding the system interactions models.

5.2 SYSTEM MODEL IMPLEMENTATION ISSUES

This section outlines criteria and issues that should be observed when implementing the structural analysis and the 5-Box model. Section 5.2.1 outlines a general set of implementation issues, while section 5.2.2 identifies the decision making levels within the pipeline management organization, for which the models are likely to be useful. Finally, section 5.2.3 discusses the models' ability to form the basis of a product pipeline performance measurement system and provides guidelines for the selection of additional measures.

5.2.1 General implementation criteria

The implementation of the pipeline system interactions models is facilitated if three criteria are observed. The models should (i) be simple enough to be easily understood, (ii) the product pipeline data required by these models should be readily available, and (iii) the models should provide useful inputs for the decision making process. These issues will be addressed in order.

Both models are fairly simple to understand in the sense that they involve only standard spreadsheet manipulations and are accompanied by quite detailed descriptions. Section 3.3.4 showed, however, that the compilation of input data for the 5-Box model may require large efforts if this data is not readily available. Likewise, the structural analysis requires "expert surveys" and group discussions which may be difficult to organize. Thus, neither model appears to have simple input requirements. The third aspect mentioned, the models' ability to be useful for decision makers, is outlined in section 5.2.2.

5.2.2 Usefulness of models

A system interactions model can be described as "useful" if it can be readily applied as a guide for actions. This attribute is related to *causal orientation*. However, while a strong *causal orientation* would imply that all root causes have been determined, a useful system model only needs to describe the impact of a few key factors, specifically those that can be influenced by the specific decision maker using this model. The set of factors that are able to be influenced by a decision maker of course depends on the decision maker's position within the pipeline management organization. An understanding of a pipeline system interactions model's usefulness therefore requires investigating the decision making structure within the product pipeline management organization. Section 5.2.2.1 outlines such an organizational structure, while section 5.2.2.2 integrates the models into this structure.

5.2.2.1 A GENERAL DECISION MAKING STRUCTURE WITHIN THE PIPELINE MANAGEMENT ORGANIZATION

A taxonomy of managerial decisions within an organization is given by Anthony.[109] He classifies such decisions into three categories: strategic planning, tactical planning and operations control. Based on his guidelines, these three categories can be applied to the product pipeline as follows.

Anthony states that strategic planning decisions within the organization in charge of providing the product or service are mostly concerned with the establishment of managerial policies and the development of resources to satisfy external requirements in a manner that is consistent with organizational goals. These decisions impact the design of the product pipeline and include the following: (i) selection of new product lines and markets; (ii) location and sizing of new plants; (iii) development of logistics networks; and (iv) acquisition of new equipment. These decisions define the competitive position of each product line involved in a pipeline, their growth rates, and, eventually, the overall pipeline success or failure. They are made at fairly high managerial levels, involve large investments, have long term implications, and are affected by both external and internal information. Thus, models to support these decisions would need a broad scope, a long planning horizon, and would have to recognize the impact of uncertainties and risk.

Tactical planning decisions focus on the resource utilization process within the product pipeline, after decisions have been made regarding the amount and location of physical facilities. Tactical decisions allocate resources, such as existing manufacturing capacity and work force levels. Typical decisions in this category include the allocation of manufacturing capacity to product families, the utilization of regular and overtime labor, and the selection of transportation alternatives. These decisions involve a medium range planning horizon and the aggregation of items into product families. Thus, models to support these decisions require the ability to determine an optimal allocation of these resources.

Operations control decisions deal with day to day operational and scheduling issues. They require a more disaggregate level of information than tactical or strategic decision-making. Typical decisions at this level include the following: (i) production sequencing and lot sizing at the item level; (ii) assignment of customer orders to individual machines; (iii) inventory accounting and inventory control activities; (iv) order dispatching, expediting and processing; and (v) vehicle scheduling. Thus, models to support these decisions require a detailed understanding of the operational situation that is observed.

Magee *et al.*[58] add a fourth decision level to this framework, located between strategic and tactical decisions, in order to reflect the particular dynamics of the product pipeline. Decisions made at this level pertain to the deployment and control of inventory within the product pipeline network. These decisions are made after the characteristics of the product pipeline from supplier to customer have been established.

At the level of strategic planning, the choice of product lines to and markets will ultimately determine the structure of the procurement, manufacturing, and distribution processes - that is, the design of the product pipeline. Those management functions that are responsible for the product pipeline performance are linked to the broader organizational strategy both through the assurance of marketplace delivery and through the design of the product pipeline. In general, it can be assumed that the management of the pipeline will be coordinated among functional departments that represent marketing issues, finance issues, and operational issues.

Given these definitions and assumptions, the design and planning of product pipelines should commence with an understanding of the broadest strategic plans of the organization. Thus, Magee *et al.*[58], contend that two issues link the functional departments that are responsible for the product pipeline performance with planners of the broader organizational strategy. First, the pipeline management functions need to assist strategic planners in understanding how the product pipeline can be used to differentiate or distinguish the product or service on the marketplace. Second, management needs to evaluate the impacts of any proposed broad organizational strategy on the pipeline structure and communicate their results. For this task, they need to analyze such issues as whether the competitive advantage gained by providing a superior customer service, such as a one-day delivery time, will be worth the cost.

Moreover, in order to ensure the successful implementation of any broad organizational strategic plan, Magee *et al.*[58] see the necessity to develop consensuses among Operations, Marketing and

Finance throughout the planning process. This relationship is outlined in figure 5.2 in section 5.2.2.2, where the usefulness of the two system interactions models is evaluated.

5.2.2.2 EVALUATION OF THE SYSTEM INTERACTIONS MODELS' USEFULNESS

The Structural Analysis:

Recent surveys by Wilson[110] and Malaska[111] show that scenario analysis, which forms the basis of the structural analysis methods applied in chapter 2, is frequently employed to support corporate strategic planning. This usage apparently derives from the method's ability to analyze interactions within complex, interdependent systems and to identify the most significant factors that influence system performance. In particular, the methods to identify key influencing factors of system performance, outlined in section 2.2, provide planners with a set of parameters that could support the successful implementation of product pipeline design changes. They can also be used for the selection of useful benchmarking measures. The simulation of section 2.3 provides a better understanding of the impact of changes of these factors on the pipeline. Thus, it can assist in visualizing the impact of changes in the broad organizational strategy. Similarly. Shoemaker,[112] Brauers,[113] Whipple,[114] Huss,[115] Leemhuis,[116] Bunn,[117] Schnaars,[118] and Duncan,[119] draw related conclusions in the sense that all authors regard scenario analysis as an effective method for the evaluation of broad organizational strategic plans and as a good tool to promote the understanding of interdependent systems, such as the product pipeline, throughout the organization. The structural analysis could therefore possibly be used as a precursor for more detailed quantitative analyses, once a clear necessity to develop such models emerges. This is why the structural analysis is placed in figure 5.2 between the organizational strategy planning level and the level of management functions that are responsible for the product pipeline performance.

The 5-Box model:

As mentioned in section 3.2.7, the 5-Box model supports "strategic" pipeline design decisions based on its ability to determine the inventory holding cost of a specific pipeline "service level." It thus assures that both Marketing and Finance understand some of the impacts of changes to the pipeline "service level." Based on the discussion of section 5.2.2.1, it can be viewed as a model to facilitate agreement among two of the three functional departments. For the model to support Marketing decisions that are related to the pipeline design however would require the assumption that the level of service can be completely described by the level of supply reliability or by the level of responsiveness.

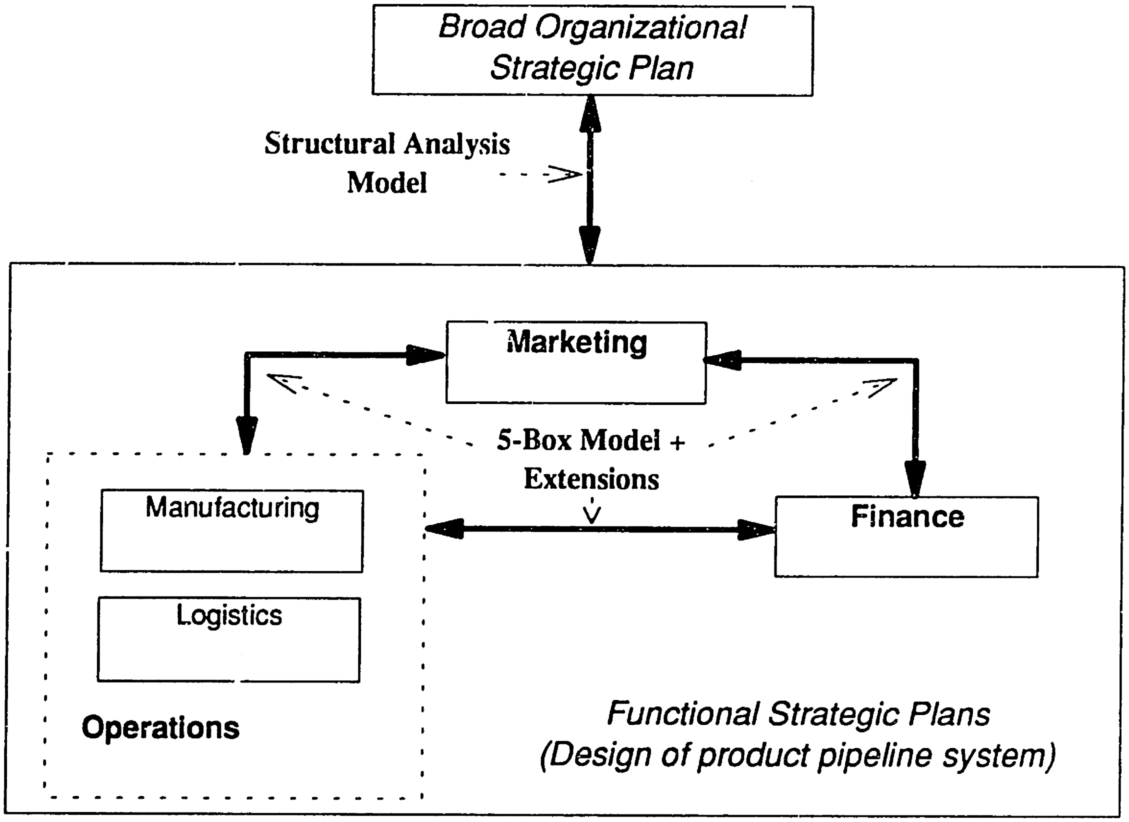


Figure 5.2: Organizational diagram (From Magee *et al.*[58])
and proposed location of system interactions models

The issue that the 5-Box measure of pipeline inventory holding costs might not provide sufficient guidance for Finance during the process of pipeline design could be resolved by the extensions proposed in section 4.1.2. These extensions determine the profitability of alternative levels of investment in manufacturing facilities and of shifts in the production capacity. Moreover, the programming model shown in appendix 4.1 could be useful for tactical production decisions since it can show the amount of output to be produced and finished goods inventory to be maintained in order to meet demand. Finally, the extensions proposed in section 4.2 provide decision support for the fourth decision level, proposed by Magee *et al.*,[58] the deployment of inventory throughout the pipeline network. Thus, they would supply Operations with a set of recommended inventory levels that would result from any changes in the product pipeline design. This is why the 5-Box model along with its extensions can be placed at the center of figure 5.2, relating to all three functions that manage the pipeline.

5.2.3 Applicability of models for performance measurement systems

On a stand alone basis, both models are likely to be applied as planning tools to support management decisions, as outlined in section 5.2.2. Given the models' capability to reflect and simulate interactions between measures, they could also be used to support performance evaluation. This function appears to be important, as a review of Caplice[24] has found a large number of current product pipeline performance measurement systems to be developed without a good awareness of the relationships between those measures that are reviewed. Thus, to the extent that the two system interactions models are *comprehensive*, *causally oriented*, and *accurate*, they could be integrated into existing performance measurement systems.

Alternatively, they could be used as a basis for new performance measurement systems. With this approach, it might not be clear what additional performance measures need to be added to achieve a comprehensive evaluation of pipeline performance. The rest of this section provides guidelines and suggestions for the selection of such additional measures. These guidelines also provide a starting point for the selection of measures that could extend the models into performance measurement systems.

A comprehensive product pipeline performance measurement system is not only concerned with the measurement of an efficient and effective market place delivery of products, but should also reflect how the pipeline performance fits into the "larger picture" - that is, the overall performance of the manufacturing organizations engaged in the pipeline. Thus, if the system interactions models are to be extended into comprehensive performance measurement systems, additional measures will need to be added such that transactions occurring both within the *horizontal* and the *vertical* structure of the product pipeline are captured. A NEVEM work-group study[108] defines the *horizontal* structure of the product pipeline to be the arrangement of all activities, departments, and inventory storage points included in the process of delivering the product to the customer. In contrast, the *vertical* structure of the product pipeline reflects the hierarchical management structure of each manufacturing organization that engages in designing and maintaining the product flow throughout the pipeline. A closer analysis of measures that would need to be added in order to meet these two criteria, follows.

5.2.3.1 MEASURES TO REFLECT THE HORIZONTAL PIPELINE STRUCTURE

While intercompany operating ties have led to important changes in the management of the material and information flow within the product pipeline, Chow[120] notes they have apparently had little impact on performance measurement systems. Since intercompany operating ties have primarily led to performance changes within the horizontal structure of the product pipeline, they require additional performance measures.

It is difficult to compile a specific list of horizontal measures, as most are intended to reflect the specific operating arrangements that have been established within the pipeline. However, recent studies of the Boston Consulting Group[121] and AT Kearney[122] suggest general measures based on delivery time and service quality. In particular, AT Kearney[122] describes the ability of logistics services within the pipeline to deliver "supply quality" with "zero-defects." As shown in figure 5.3, it summarizes the results of a 1992 survey based on three components: cost, time and "supply quality" of the delivered product. "Supply quality," the percentage of errors in the servicing of customer requirements within a specific time period, is nearly identical to the "perfect order" measure outlined in section 3.2.4. The 3-dimensional coordinate of figure 5.3 however allows a visualization of pipeline performance changes along the lines of the transformation model. It relates changes of "supply quality," an effectiveness measure, directly to changes in logistics costs, a measure of operational efficiency, and puts this relation in the perspective of cycle time, a situational parameter.

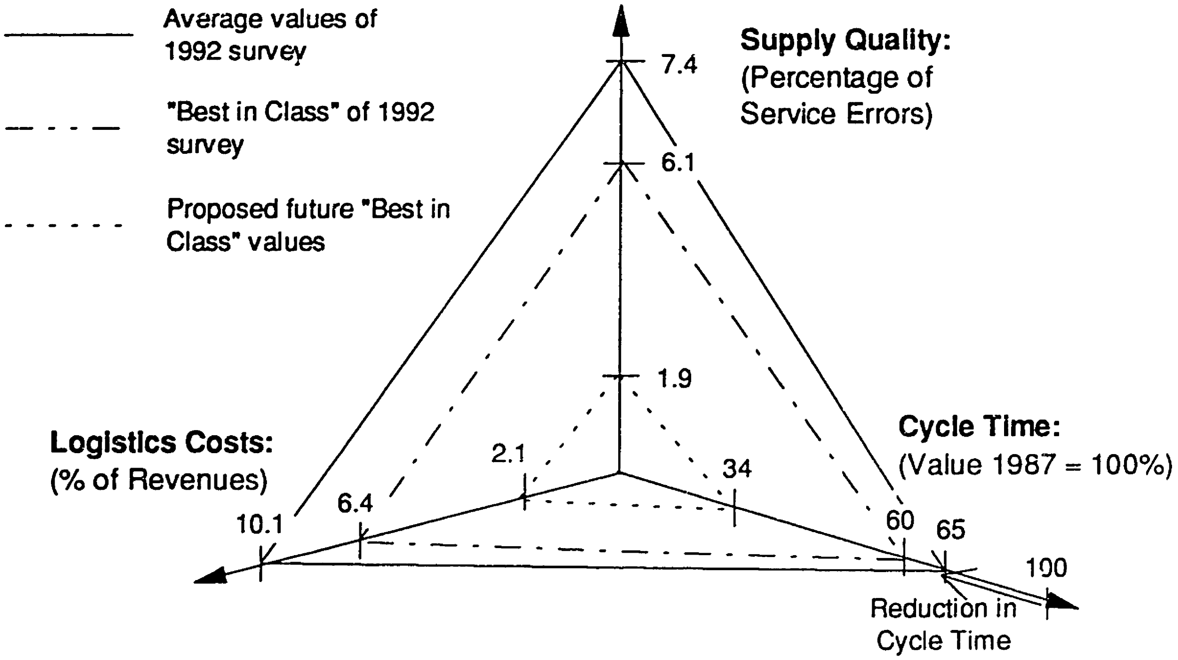


Figure 5.3: Three components of product pipeline evaluation (From AT Kearney[122])

5.2.3.2 MEASURES OF THE VERTICAL PIPELINE STRUCTURE

Vertical performance measurements tie the financial performance of a pipeline into the financial performance of the manufacturing organization engaged in this pipeline. A product pipeline merges the traditional expense centers of manufacturing and logistics with the revenue center of marketing such that an independent profit center is formed including those product lines within the pipeline. The notion of a product line profit center can be extended by viewing the product pipeline as an investment center that relates profits from pipeline sales directly to the capital investments that are required to assure manufacturing and delivery of the product line.

Perhaps the best known hierarchical financial performance measure is the criterion "return on assets (ROA), the ratio of net profit divided by the current and fixed assets. Figure 5.4 relates pipeline profits and pipeline investments to each other by means of the ROA, and shows in particular, how the level of pipeline assets, such as inventory and manufacturing facilities, can be evaluated based on the net profit that these assets generate. The net profit, in turn, is determined by the difference between the cost of total pipeline operations and the profit generated by the products that are delivered to the market through this pipeline. A more detailed description of approaches to determine the profitability of pipeline operations by means of a return on asset analysis is provided in Stock.[123]

Brealy and Meyers[124] contrast the "return on assets" with the "net present value" (NPV) of an investment. The NPV reflects the net contribution of the cash flow resulting from a financial endeavor such as the decision to manufacture and distribute a product or service to the wealth of the investors. The NPV is thus a useful measure for the evaluation of pipeline design changes, or for the decision of whether or not to enter a pipeline arrangement. A modified model of figure 5.4, which condenses common pipeline measures such that they can facilitate the determination of the NPV, is shown in figure 5.5.

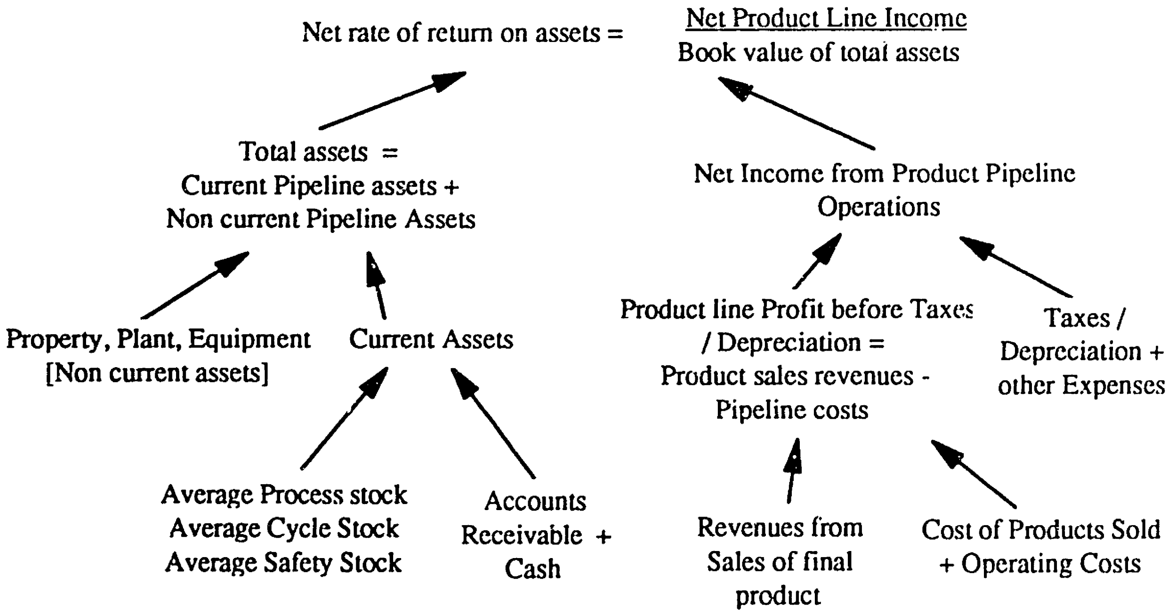


Figure 5.4: The ROA model applied to the product pipeline (Based on Anthony[125])

The measurement structure that is shown in figure 5.5 is of general nature and required some simplifying assumptions that might limit its applicability for certain pipeline organizational structures. The model assumes that the overriding objectives of any organization are the ability to satisfy both customer and shareholder objectives. Moreover it assumes that customer satisfaction is ultimately reflected in the market share of the product that is being delivered to the market, while shareholder satisfaction is ultimately reflected in the ROA or NPV that was achieved by the division in charge of the marketplace delivery of the product. Finally, it assumes that the operational performance is adequately reflected in the average cycle time, the net manufacturing time per unit, the material purchasing costs, the transportation costs, the inventory levels, and the manufacturing capacity levels. All measures have been defined in chapters 3 and 4. Figure 5.5 then aggregates these measures into higher level measures such as *fixed* and *variable product pipeline costs*, and *manufacturing quality*, which in turn contribute to a set of measures of aggregate product pipeline performance.

As outlined in section 5.1, the aggregate pipeline performance is likely to be accurately represented by measures of pipeline effectiveness and an efficiency. In figure 5.5, it is assumed that the pipeline effectiveness is accurately reflected in the percentage of "perfect orders," defined in section 3.2.4, that are generated from pipeline operations. On the other hand, the level of pipeline efficiency is determined from the total costs of pipeline operations. Figure 5.5 then describes how these aggregate pipeline measures contribute to the overall organizational objectives, defined above. Finally, both the accuracy of demand forecasts and the complexity of products within the pipeline are listed as key performance drivers. These measures, defined in sections 3.2 and 3.3, cannot be aggregated into the hierarchical structure, however are assumed to have a strong influence on the performance of the product pipeline.

Figure 5.5 can be used to understand how the sets of measures used in the system interactions models would fit into this vertically integrated performance measurement structure. Since the structural analysis does not have a set of core measures, it cannot be integrated into figure 5.5. However, the 5-Box measures could be integrated in a manner such as shown in figure 5.6. Figure 5.6 will be used for further analysis in section 5.2.3.3.

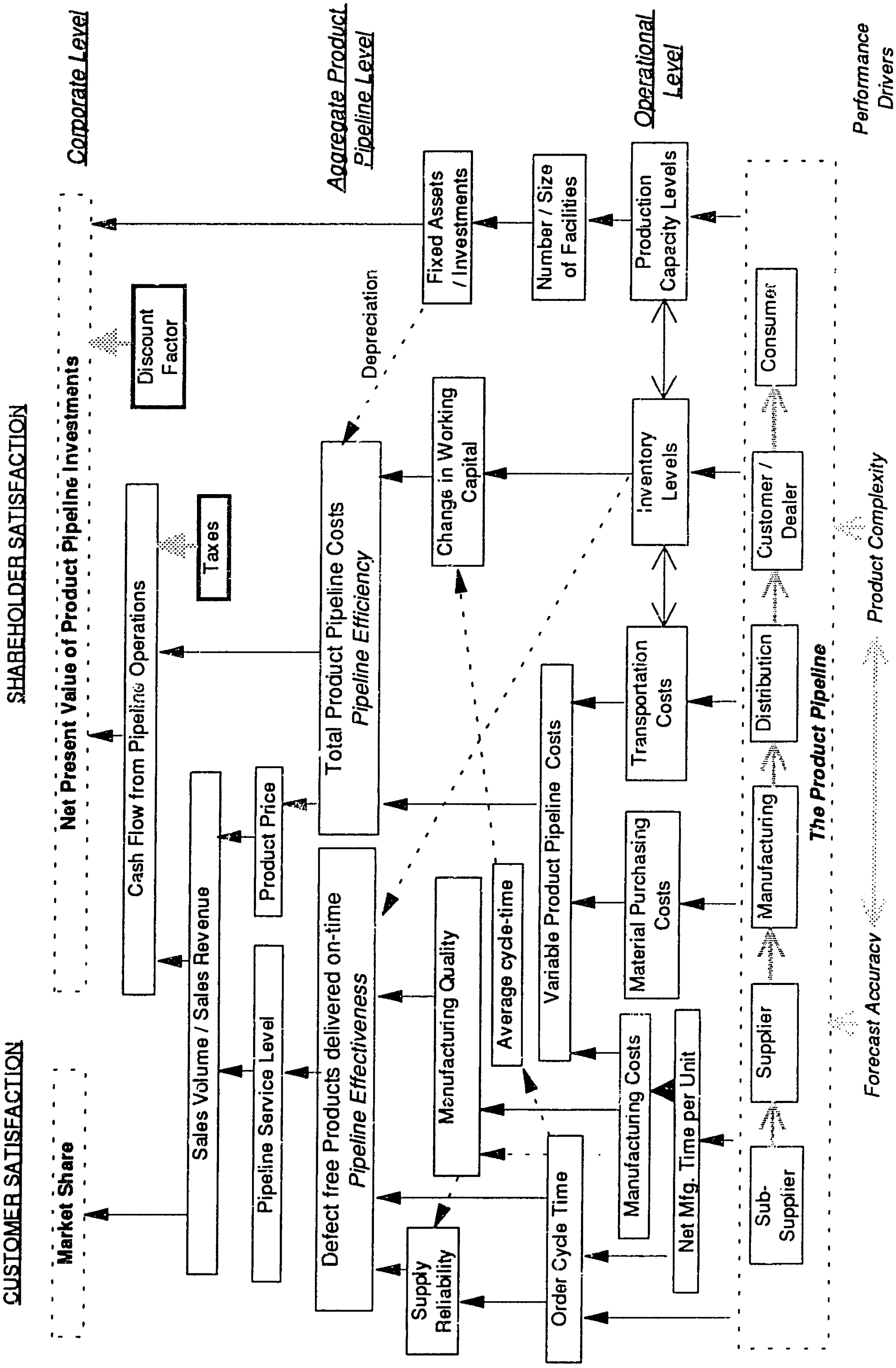


Figure 5.5: Model of the vertical structure of pipeline measurement

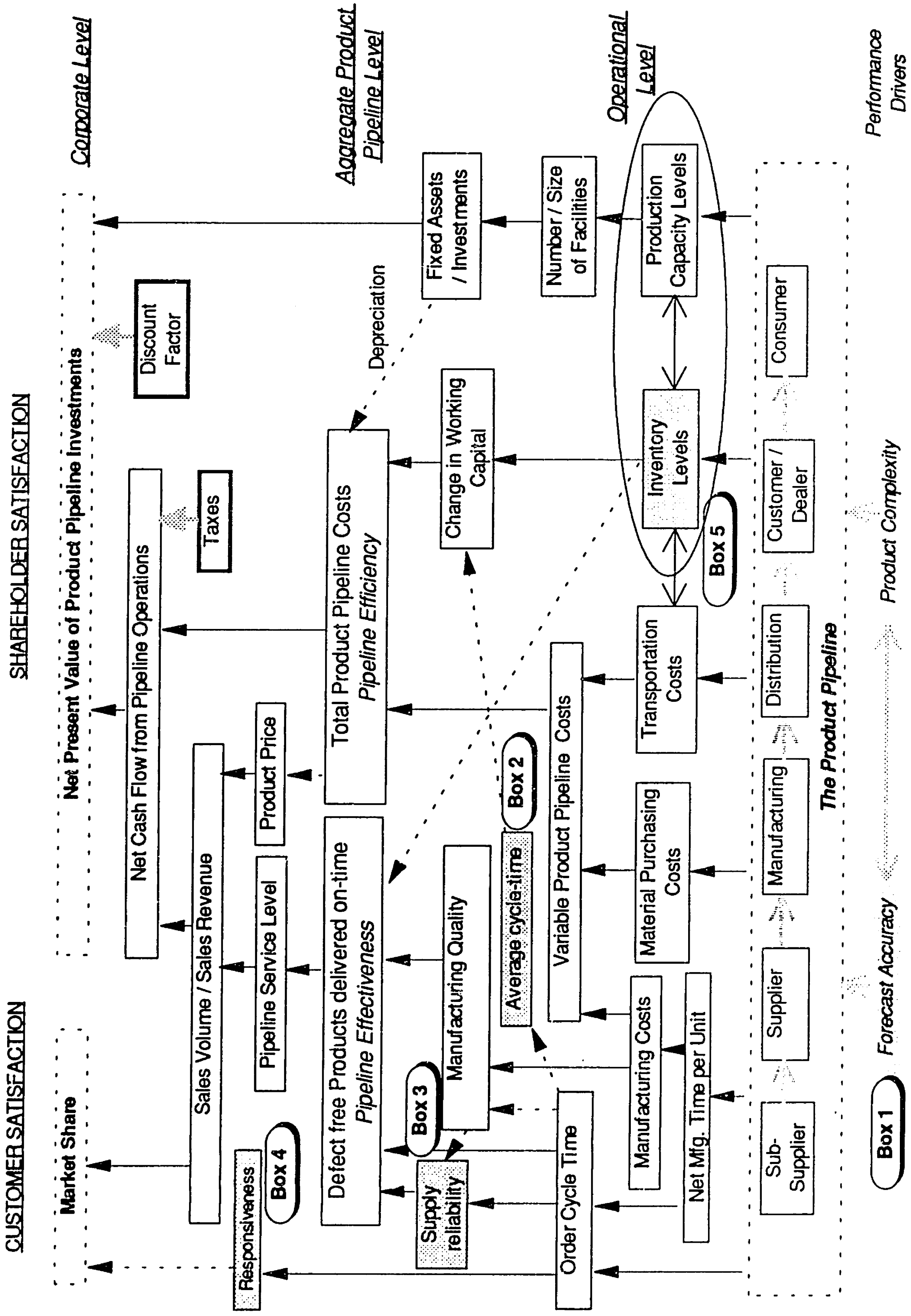


Figure 5.6: Integrating the 5-Box measures into the vertical measurement model

As previously mentioned, this section merely provides a general set of vertically integrated performance measures that may not always be applicable. This section therefore concludes by outlining a recently proposed framework for the selection of measures for a performance measurement system that is both horizontally and vertically integrated. It is termed the "Balanced Scorecard," developed by Kaplan and Norton.[126] The balanced scorecard symbolizes a framework that incorporates strategic, operational and financial measures by seeking to reconcile four "perspectives" of performance measurement: the "customer perspective," the "financial perspective," the "internal perspective," and the "change perspective." The customer perspective captures customer expectation, the financial perspective reflects the demands of financial stakeholders, the internal perspective captures those internal activities and information processes that have the largest influence on external performance, while the change perspective, represented by measures of innovation and learning, captures continuous improvements within the organization. In the pipeline context, the "financial perspective" assures a set of vertically integrated measures, while the "internal perspective" assures a set of horizontally integrated measures. Finally, the "customer perspective" assures a set of measures to improve both the horizontal and the vertical integration of the measurement system.[127]

A review of Kaplan and Norton,[128] Brittlestone[129], and Vitale *et al.*[130] show that the balanced scorecard framework has found widespread usage within the development of performance measures for broad strategic planning within organizations. Accordingly, Gregory[131] points out that the construction of performance measures in this manner, supported by appropriate decision support models, can lead to the development of a "strategic controlling" model. Strategic controlling models provide feedback to decision makers on the overall status of the organization based on current measures and allow them to identify those parameters that should be changed in order to "steer" the organization correctly.

5.2.3.3 USING THE MODELS AS A BASIS FOR PIPELINE PERFORMANCE MEASUREMENT

Given the structural analysis's potential to achieve a high level of comprehensiveness, it could be used to support a performance measurement system that resembles the "Balanced Scorecard" framework described above. Within this framework, the four performance measurement "perspectives" could guide the selection of system elements. However, if implemented in this manner, the structural analysis would not necessarily explain the level at which a measure should be expected to operate, as much as it could provide information on influencing factors and actions that could impact the system performance. This is why it shows only limited applicability for the support of pipeline performance measurement systems.

While the current set of 5-Box measures covers three of the four "balanced scorecard" perspectives, it does not appear to provide a complete coverage of each category. Section 5.1.4 shows that the level of supply reliability and responsiveness might not completely reflect the customer perspective, while section 4.1 shows that the level of pipeline inventory might not completely reflect the shareholder perspective. Finally, forecast accuracy and product cycle time length might not completely reflect the performance of internal processes. However, as mentioned, these measures could form a basis for a more comprehensive measurement system. Figure 5.6 provides an overview of additional measures that could be added to the 5-Box model in order to provide a more vertically integrated measurement of pipeline performance. Most importantly, figure 5.6 shows that it lacks a high level vertically integrated measure. The 5-Box appears to be horizontally well integrated as it can span over several production stages and captures the impact of time based measures. However, additional internal process measures for the distribution segment of the model could assure a greater horizontal integration. Additional external processes measures such as those listed in chapter 4 could be added to also improve the measurement of the performance of pipelines that are managed by intercompany operating ties. Once again, it should be mentioned that these measures cannot be listed on an individual basis because they would be highly dependent on the specific nature of the pipeline arrangements.

CONCLUSION

Chapter 5 evaluated the system interactions models' ability to provide an analysis of the product pipeline system and discussed issues pertaining to the implementation of these models. Section 5.1 evaluated the models by using three system interactions model construction criteria while section 5.2 evaluated the models based on implementation issues. Section 5.2.1 described a general set of implementation issues, while 5.2.2 outlined the usefulness of these approaches for specific functions within the surrounding organizational structure. It points to the possibility that both models could complement one another due to the fact that they cover related, however distinct functions within the pipeline management structure: the structural analysis appears to have a strong applicability for high level planning, whereas the 5-Box model is more applicable for the functions of Finance and Marketing. Finally, section 5.2.3 outlined a set of guidelines for the selection of performance measures that could be used to extend the models into more comprehensive performance measurement systems. It shows that the 5-Box model could serve as a basis for the construction of a more comprehensive pipeline performance measurement system provided that it can incorporate measures such as some of those outlined in figure 5.6.

Chapter 6 CONCLUSION

This thesis has reviewed the need to view the product pipeline as a complex system of interdependent performance measures and outlined approaches to improve the planning and measurement within this system.

Chapter 2 outlined a high level approach to facilitate an analysis of the product pipeline system. It used methods of scenario analysis to identify significant drivers of system performance and simulated the interactions that could occur as a result of changes in these aspects of system performance. These methods were subsequently applied to evaluate the interactions between five aspects of product pipeline performance in the situation of three possible pipeline systems. These methods were thus used to propose policies that were likely to change these systems within this example and to simulate the possible impact of these changes.

Chapter 3 outlined a derivation of the formula to determine the safety stock that is required to meet a variable demand over a variable lead time by providing a derivation of the probabilistic identity underlying the determination of lead time demand. Moreover, it described models at the Digital Equipment Corporation to address the issue of interactions between product pipeline performance measures, that are partially based on this formula. It one of these models, termed the 5-Box model, was subsequently modified in order to analyze data from product pipeline systems that serviced demand partially by means of a "make-to-order" system, partially by means of a finished goods stock pile. The model was further modified such that it could account for replenishment lead time variability for finished goods inventory.

Chapter 4 outlined modifications that could enhance the 5-Box model's applicability for product pipeline analysis. It focused on issues surrounding a tradeoff between inventory and production capacity and on models to determine more efficient levels of inventory throughout the pipeline. In particular, it proposed a mathematical programming model to find an efficient level of capacity throughout a pipeline facing a cyclical deterministic demand throughput multiple interlinked pipeline stages. Moreover, it outlined a heuristic to determine the correct levels of raw material, work-in-process, and finished goods inventory within an integrated production-distribution stage.

Chapter 5 showed an evaluation of the models described in chapters 2 and 3 that was based on their ability to provide an analysis of system interactions that is comprehensive, causally oriented, and accurate. It outlined the usefulness of these models and attempted to identify decision making situations, in which these models could provide meaningful support. Finally, it addressed the issue of integrating the models into performance measurement systems and provided guidelines for the determination of further performance measures that, if included, could increase the models' coverage of pipeline performance.

Appendix:

Appendix 2.1: α - Matrices for the Kane Simulation

Alpha Value Matrices:
(Impact of Row Variables on Column Variables)

1.) Increasing Forecast Accuracy

	1	*2*	*3*	*4*	*5*
1. Inventory	0	-2	0	0	0
2. Reliability	-2	0	-1	1	0
3. Cycle Time	0	0	0	0	0
4. Responsiveness	0	0	0	0	0
5. Forecast Accuracy	-2	2	0	0	2

2.) Reducing Forecast Accuracy

	1	*2*	*3*	*4*	*5*
1. Inventory	0	2	0	0	0
2. Reliability	2	0	1	-1	0
3. Cycle Time	0	0	0	0	0
4. Responsiveness	0	0	0	0	0
5. Forecast Accuracy	2	-2	0	0	-2

3.) Improving Cycle Time

	1	*2*	*3*	*4*	*5*
1. Inventory	0	-2	0	0	0
2. Reliability	-2	0	-1	1	0
3. Cycle Time	-2	1	-2	3	0
4. Responsiveness	0	0	0	0	0
5. Forecast Accuracy	0	0	0	0	0

4.) Reducing Cycle Time

	1	*2*	*3*	*4*	*5*
1. Inventory	0	2	0	0	0
2. Reliability	2	0	1	-1	0
3. Cycle Time	2	-1	2	-3	0
4. Responsiveness	0	0	0	0	0
5. Forecast Accuracy	0	0	0	0	0

Appendix 2.2: Kane Simulation charts

Chart 2.1: The impact of a reduced *forecast accuracy* at facility 1.

Chart 2.2: The impact of an improved *forecast accuracy* at facility 2.

Chart 2.3: The impact of an improved *forecast accuracy* at facility 3.

Chart 2.4: The impact of a reduced *cycle time* at facility 1.

Chart 2.5: The impact of an increased *cycle time* at facility 2.

Chart 2.1: *Reducing Forecast Accuracy at facility 1*

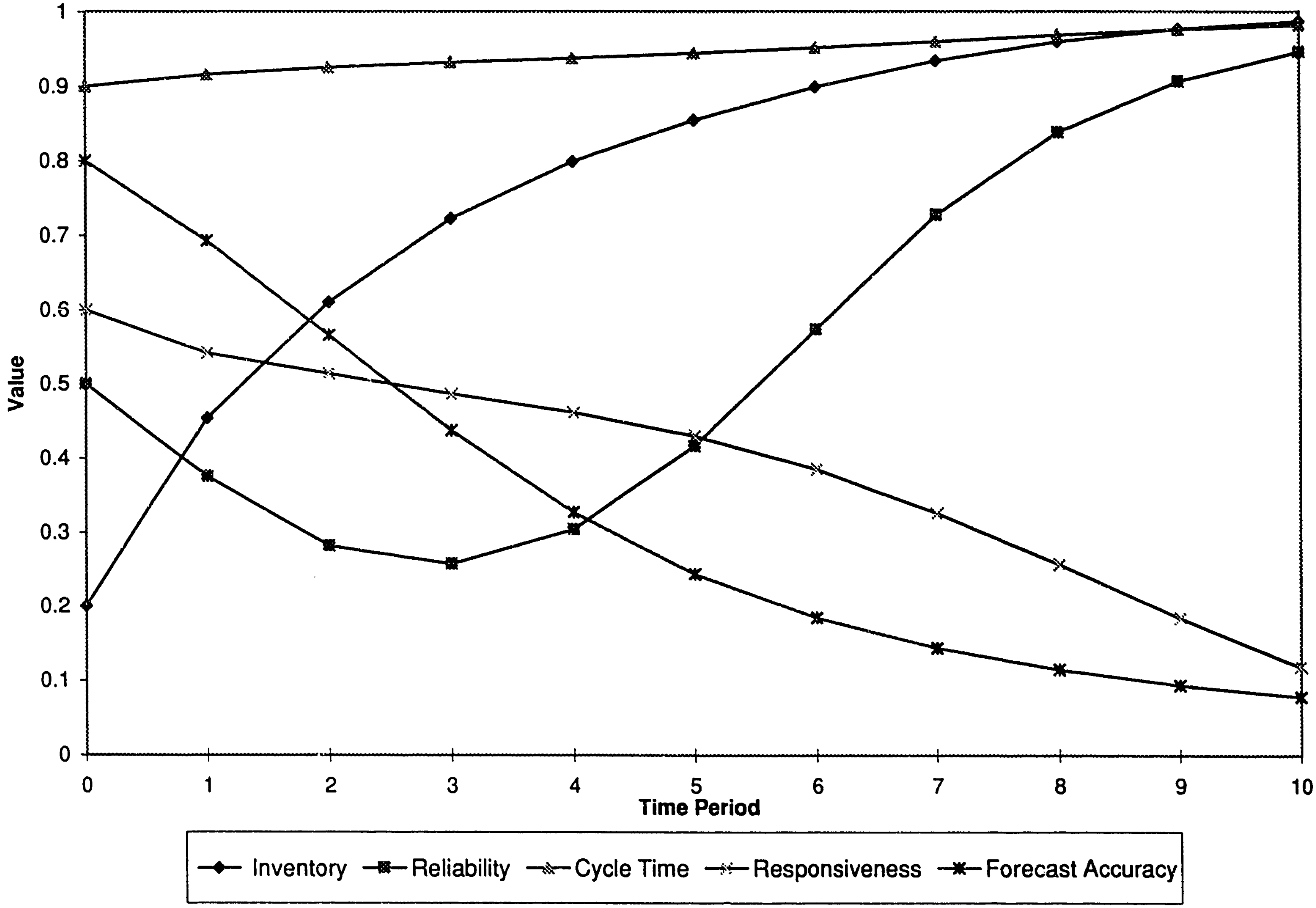


Chart 2.2: *Improving Forecast Accuracy at facility 2*

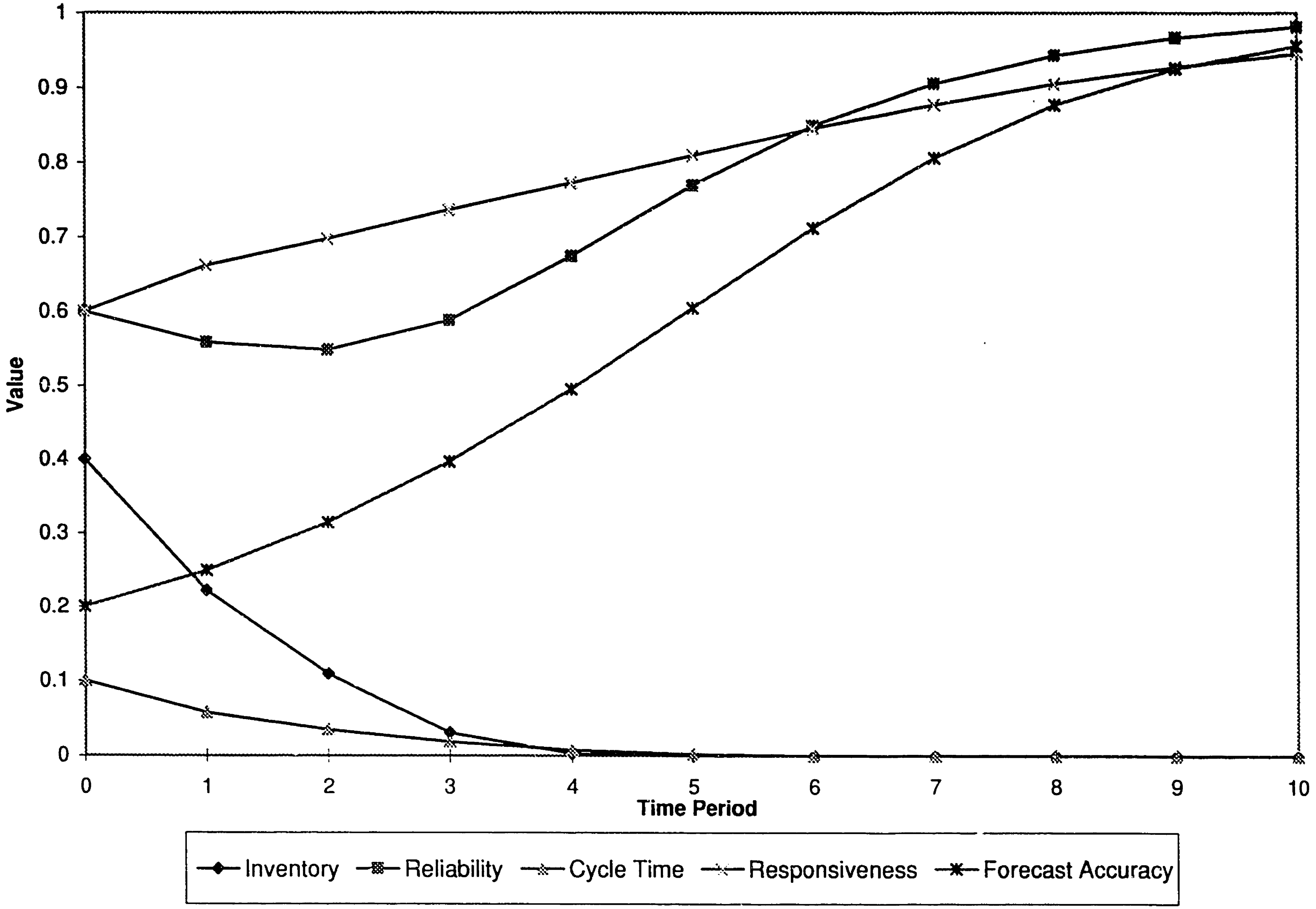


Chart 2.3: *Improving Forecast Accuracy at facility 3*

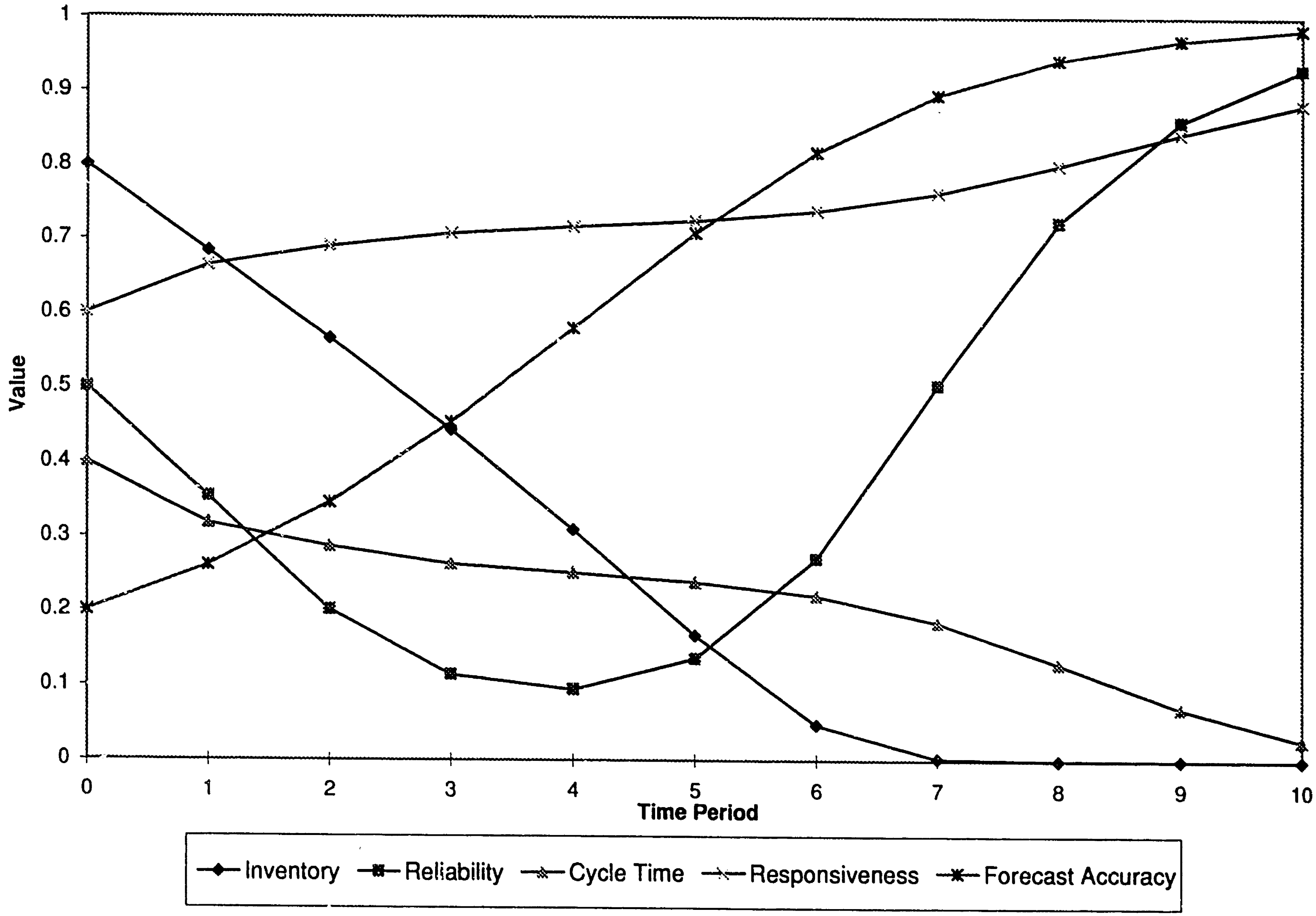


Chart 2.4: *Reducing Cycle Time at facility 1*

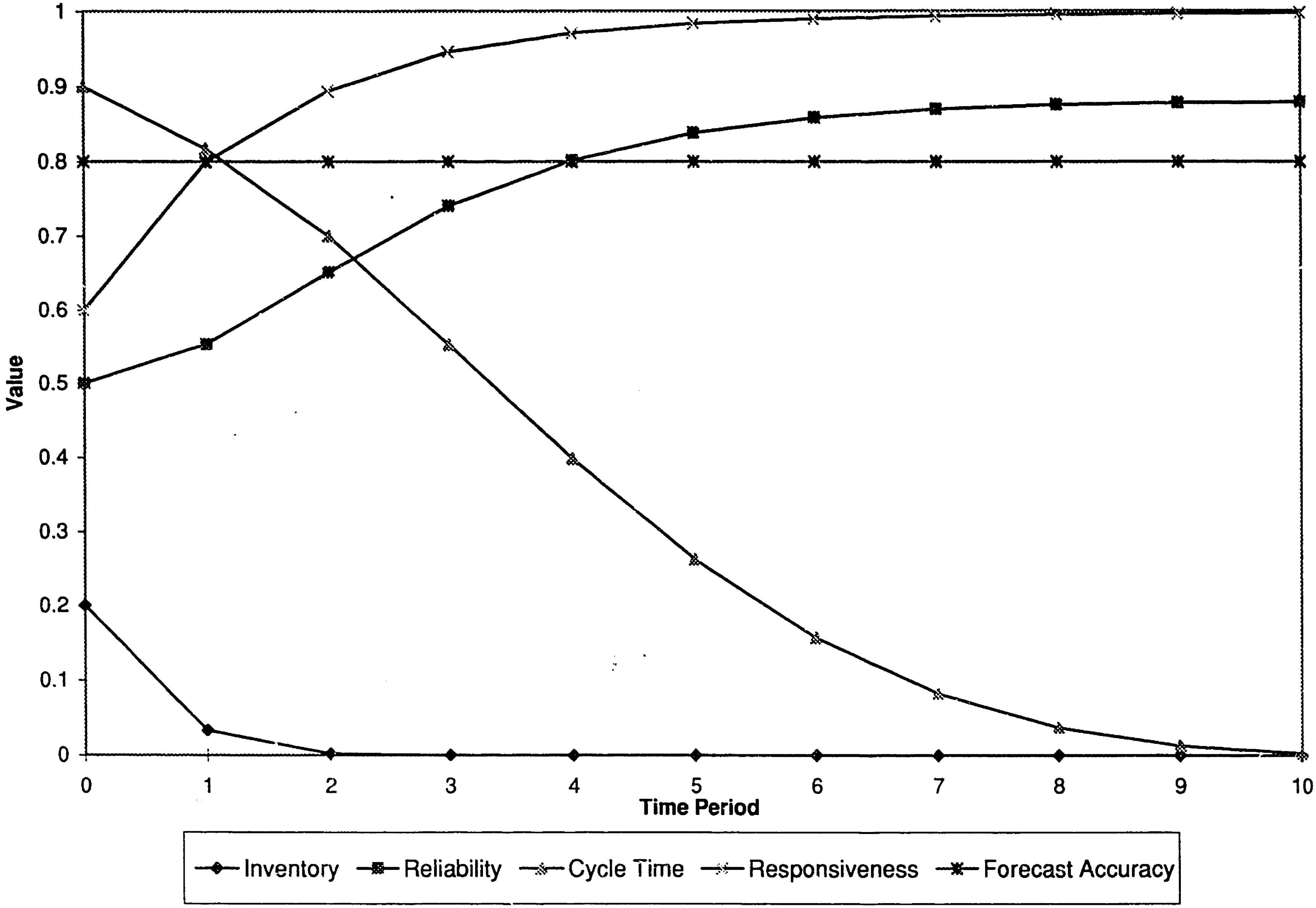
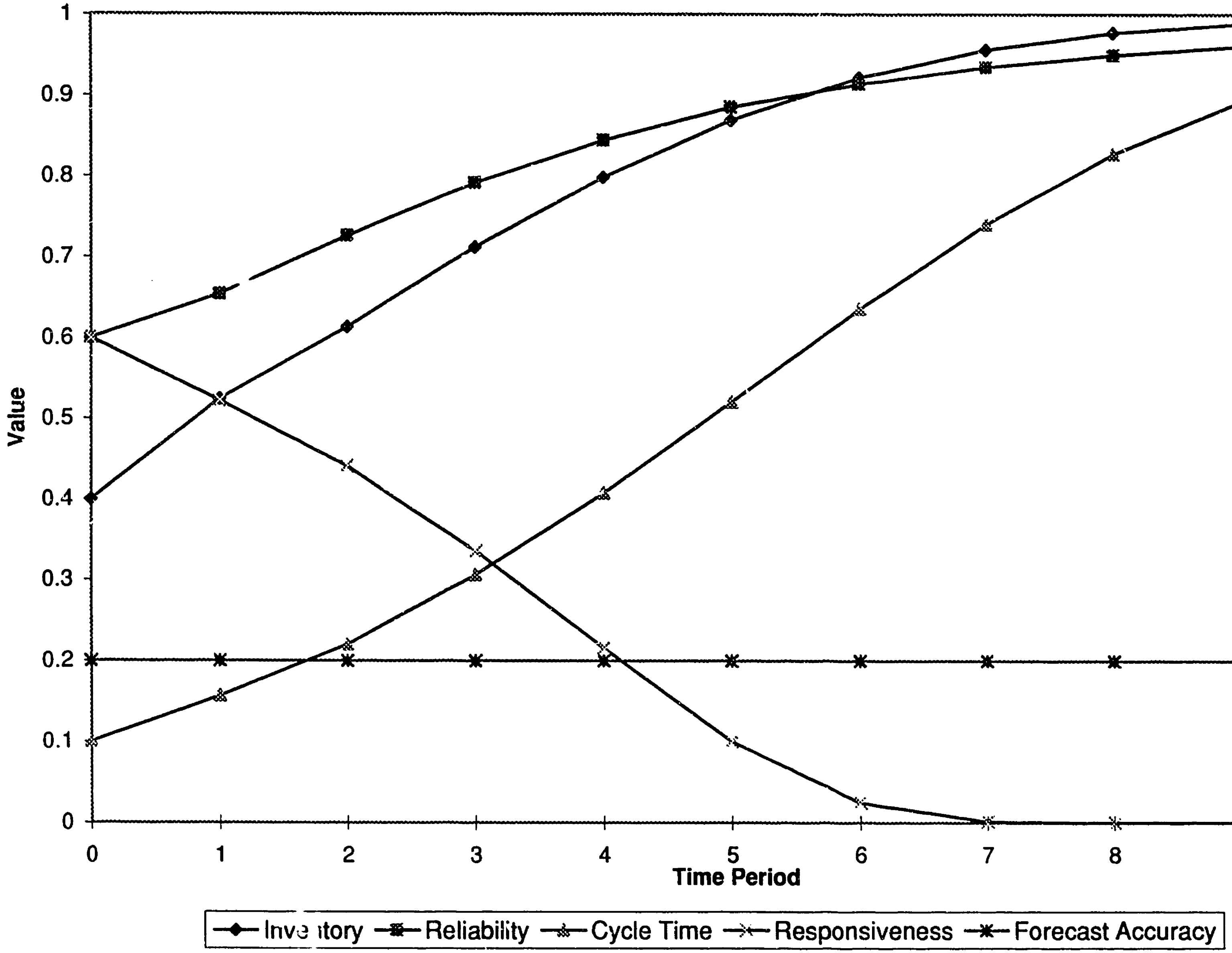


Chart 2.5: *Increasing Cycle Time at facility 2*



Appendix 3.1: Derivation of the expected value and the variance of a random sum of random variables[1]

For the purposes of this derivation, it is necessary to clarify that a random variable can be written as the sum of a (deterministic) expected value, and a purely random component.

$$\text{i.e.: } x = E(x) + \tilde{x}, \text{ where } E(\tilde{x}) = 0, \text{ and } \sigma_x^2 = 0 + \sigma_{\tilde{x}}^2 \qquad [6.1]$$

The sum (r) of a random number n of independent identically distributed random variables x_i can be written as:

$r = x_1 + x_2 + x_3 \ldots. + x_n$, with $x_i \approx$ iid, and n: non-negative, integer valued random variable.

Then the expected value of the sum, E(r), can be written as:

$$E(r) = E(x_1 + \ldots. + x_n) = E\left[E(x_1) + E(x_2) + \ldots. + E(x_n) + \tilde{x}_1 + \tilde{x}_2 \ldots + \tilde{x}_n\right] [6.2]$$

$$E(r) = E\left[nE(x) + nE(\tilde{x})\right] \qquad [6.3]$$

where:

$E[nE(x)] = E(x) * E(n)$ and the second term on the right hand side of equation 6.3 is equal to 0 based on 6.1. The term n is a random variable. Thus, the expected value of a sum of a random number of random variables can be written as:

$$E(r) = E(x) * E(n) \qquad [6.4]$$

The variance of this sum, σ_r^2 , can be derived from equation 6.2, where:

$$r = E(x_1) + E(x_2) + \ldots. + E(x_n) + \tilde{x}_1 + \tilde{x}_2 \ldots + \tilde{x}_n = nE(x) + \tilde{x}_1 + \tilde{x}_2 \ldots + \tilde{x}_n \qquad [6.5]$$

It should be noted that the expected value and random component are independent of one another. The variance of both terms is therefore the sum of the variance of each term:

$$\sigma_r^2 = E^2(x)\,\sigma_n^2 + \mathrm{Var}(\tilde{x}_1 + \tilde{x}_2 \ldots. + \tilde{x}_n) \qquad [6.6]$$

The variance of the random component of the right hand side can be determined as follows:

---

[1] Ayazifar, B. *Recitation Notes* Course 6.431 Probabilistic Systems Analysis, MIT Spring 1995

Let $\tilde{x}_1 + \tilde{x}_2 .. + \tilde{x}_n \equiv \lambda$, then for every r.v.: $\sigma^2_\lambda = E(\lambda^2) - E(\lambda)^2$.

Here: $E(\lambda)^2 = 0$ from 6.1.

Therefore:

$$\sigma^2_\lambda = E(\lambda^2) = E\left[(\tilde{x}_1 + \tilde{x}_2 .. + \tilde{x}_n)^2\right] = E\left[\tilde{x}_1^2 + \tilde{x}_2^2 + \ldots \tilde{x}_n^2 + 2\sum_{i=1}^{n}\sum_{j=i+1}^{n}\tilde{x}_i\,\tilde{x}_j\right] \qquad [6.7]$$

$$= E\left[\tilde{x}_1{}^2 + \tilde{x}_2{}^2 .. + \tilde{x}_n{}^2\right] + 2E\left[\sum_{i=1}^{n}\sum_{j=i+1}^{n}\tilde{x}_i\,\tilde{x}_j\right] \qquad [6.8]$$

Where the second term of equation 6.8 is the product of the expected value of two independent variables:

$$2E\left[\sum_{i=1}^{n}\sum_{j=i+1}^{n}\tilde{x}_i\,\tilde{x}_j\right] = 2\left[\sum_{i=1}^{n}E(\tilde{x}_i)\sum_{j=i+1}^{n}E(\tilde{x}_j)\right] \qquad [6.9]$$

The expected value of $\tilde{x}_i$ and $\tilde{x}_j$ is however 0. Thus, the second term of equation 6.8 is zero and the variance of the random component can be written as:

$$E(\lambda^2) = E\left[\tilde{x}_1^2 + \tilde{x}_2^2 \ldots + \tilde{x}_n^2\right] \qquad [6.10]$$

or:

$$E(\lambda^2) = E(n)\,E(\tilde{x}^2) = E(n)\,\sigma^2_{\tilde{x}} = E(n)\sigma^2_x \qquad [6.11]$$

$$\text{because: } E(\tilde{x}) = 0$$

The variance of the sum of *n* random variables *x* can therefore be written from equations 6.6 and 6.11 as:

$$\sigma^2_r = E^2(x)\,\sigma^2_n + E(n)\,\sigma^2_x \qquad [6.12]$$

Appendix 3.2: Data from automotive manufacturer benchmarking group

[Pages 128-132]

Appendix 3.3: Resulting 5-Box model charts

[Pages 133-138]

Measure 1: Inventory levels [Raw material = RM / Work-in-process = WIP / Finished Goods = FG]
(Working days of inventory)

Location:	Facility 1:			Facility 2:			Facility 3:			Facility 4:			Facility 5:		
	RM	WIP	FG	RM	WIP	FG	RM	WIP	FG	RM	WIP	FG	RM	WiP	FG
Inbound transportation	1			1.4			1			0.8			0.8		
Incoming goods dock	6.8			7.2			8.5			6.6			6.6		
Production		3.2			3.1			8.5			6.6			6.6	
Distribution			2.6			2.5			2.5			2.0			2.0
Total:	7.8	3.2	2.6	8.6	3.1	2.5	9.5	8.5	2.5	7.4	6.6	2	7.4	6.6	2

Total: 13.6 Working days 14.2 Working days 20.5 Working days 16.0 Working days 16.0 Working days

Measure 2: Order Response Time (Working days)

Point	Description	Facility 1	Facility 2	Facility 3	Facility 4	Facility 5
1	Order entry Planning lead time	2	3	13.5	30	30
2	Supplier lead time	12	7.5			
3	Production start to end of production	6.1	2.5	3		
4	End of production to distribution	3.1	2.5	1		
5	Distribution to customer (Dealer)	1		5		
	Net Order Response Time:	24.2	15.5	22.5	30	30
	Total cycle time: [1]	75	27.5	34.5	36	36
	Quoted lead time:	30	25	28		

WIP-
cycle
time

Note 1: Average amount of time required for material to move through pipeline.

Measure 3: Adherence to production program, supply reliability, and perfect product percentage

- The adherance to the production program is measured by comparing the weekly and daily production schedule with the list of vehicles passing the final production inspection. (FPI)

- The Supply Reliability of the distibution channels is measured by comparing the week, in which the dealer committed delivery to the customer with the week, in which the order passed final inspection.

	Description	Facility 1	Facility 2	Facility 3	Facility 4	Facility 5
1	Adherence to weekly program (Production schedule vs. list at PFI: X-1 day to X+3 days)	72.2%	80.0%	68.5%	89.7%	70.8%
2	Adherence to daily program (Production schedule vs. daily list at PFI) [2]	19.5%	18.0%	16.1%	47.5%	20.7%
3	Distribution supply reliability (Production week committed to week of arrival of order at PFI)	[3]	[3]	37.8%	41.4%	39.4%
4	Perfect Product Percentage (Facilities 1-3: Estimates)	60.0%	60.0%	60.0%	67.5%	44.5%

Note 2: This data was not required by the 5-box model, is however listed to illustrate the the high level of production schedule variability that is common throughout the automotive industry

Note 3: There was no concise data for these measures at facilities 1 and 2. Moreover these values did not extend from the week that had been committed to the customer to the point of final delivery.

Measure 4: Logistics Costs (Million DM per year / DM per Vehicle)

Location: Yearly output:	Facility 1 193,700 vehicles		Facility 2 178,400 vehicles		Facility 3 191,575 vehicles		Facility 4 308,850 vehicles		Facility 5 107,150 vehicles	
	MDM p.a.	DM / Veh.	MDM p.a.	DM / Veh.	MDM p.a.	DM / Veh.	MDM p.a.	DM / Veh.	MDM p.a.	DM / Veh.
Inbound Transportation:	73.27	378.27	92.77	520.01	56.05	292.57	75.30	243.81	38.80	362.11
Incoming goods dock:	13.78	71.14	10.25	57.46	32.79	171.16	26.40	85.48	12.70	118.53
Warehousing:	53.59	276.66	7.73	43.33	17.04	88.95	42.40	137.28	20.50	191.32
Ensuring material availability for production: (Internal transportation)	61.71	318.59	73.00	409.19	57.40	299.60	60.00	194.27	26.90	251.05
Production steering:	31.53	162.78	19.13	107.23	31.91	166.57	38.80	125.63	18.60	173.59
Inventory holding costs: Raw Mat. + WIP	17.07	88.13	16.10	90.25	9.30	48.54	13.20	42.74	9.10	84.93
Total:	250.95	1,295.57	218.98	1,227.47	204.49	1,067.39	256.10	829.21	126.60	1,181.53

Measure 5: Total Manufacturing Costs (Million DM per year / DM per Vehicle)

Location: Yearly output:	Facility 1: 193,700 vehicles		Facility 2: 178,400 vehicles		Facility 3: 191,575 vehicles		Facility 4: 308,850 vehicles		Facility 5: 107,150 vehicles	
	MDM p.a.	DM / Veh.	MDM p.a.	DM / Veh.	MDM p.a.	DM / Veh.	MDM p.a.	DM / Veh.	MDM p.a.	DM / Veh.
Logistics costs:	250.95	1,295.57	218.98	1,227.47	204.49	1,067.39	256.10	829.21	126.60	1,181.53
Labor costs:	559.79	2,890.00	502.20	2,815.00	519.55	2,712.00				
Total Value Added:	810.74	4,185.57	721.18	4,042.47	724.04	3,779.39	256.10	829.21	126.60	1,181.53
Material costs:	2,219.10	11,456.38	2,093.00	11,732.06	1,209.00	6,310.84	1,716.00	5,556.10	1,183.00	11,040.60
Total Manufacturing:	3,029.84	15,641.95	2,814.18	15,774.53	1,933.04	10,090.23	1,972.10	6,385.31	1,309.60	12,222.13

Process Data:

Case Study
Desktop Five Box Model

Company 1
Benchmarking Project

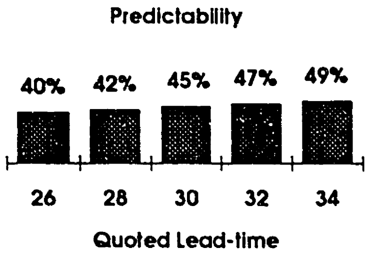
Competitive LT	
# Planned QLT < Com	1
# Planned QLT > Com	0
Planned Quoted LT	30
Response-Time	24.2
Response-T Var	12.1

Responsiveness 72%

0%	Process: Quoted LT > Comp LT
20%	Supply Constraints
10%	Forecast Error Constraints

Product Predictability 44.5%

50%	Inventory Service Level
70%	Process Reliability
60%	"Perfect Product" Percentage
100%	Other



Inventory($000)
$126,414
13.39 Days
23.97 Turns

90% Forecast Error Coverage

0.418

WACT (Days)
75

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- 10% ----------> + 10%

Under	Within	Over
5%	90%	5%

Graph Lead-time Increment
2

Requires	8%	"Upside"
=	5.8	Days Safety Stock

$757,461	Output Forecast ($000/Qtr)
48425	Number of Orders
48425	Units (per Quarter)

(Forcst. error) Sigma	6.0%
Mu	0.00

Assumed SLT (wks)	4.84
ɉma(% wkly demnd)	24%

Standard Costs:

This Stage:	Stage 0	Stage 1	Stage II
Material	$0.00	$0.00	$11,456.38
VA	$0.00	$0.00	$4,185.57
Total	$0.00	$0.00	$15,641.95

Case Study
Pipeline Inventory Distribution

Company 1

45% Product Predictability
50% Inventory Service Level
70% Process Reliability

Ship to Systems Plants from Stage (1 or 2): 1
Pct of Output Forecast to Systems Plants: 0%

Pct of Output Forecast from ALL Dist. Centers: 100%
Weeks on hand if 1 Dist. Ctr.: 6.0
Number of Dist. Centers: 1

	Supplier			Components				Production				Dist.	Product	
	Raw	WIP	F.G.	L.T.	Raw	WIP	F.G.	L.T.	Raw	WIP	F.G.	F.G.	Totals	
Inventory if no Forecast Error:														
Mfg. Inv $K	$0	$0	$0	$0	$0	$0	$0	$8,535	$48,452	$12,315	$6992	$0	$76,294	
Weeks	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1.0	0.2	0.1	0%	1.52	Wks
Days													7.62	Days
Inventory to Cover Forecast Error:														
LLT %:	100%				100%				100%					
% SS Units	0%		0%		0%		0%		70%	20%	10%	0%	100%	
Mfg. Inv $K	$0		$0		$0		$0		$34,455	$9,844	$5,821	$0	$50,120	
Sup Inv $K	$0				$0									
Tot SS Wks	0.00		0.00		0.00		0.00		0.81	0.23	0.12	0.00	1.15	
										Upside Flex (Weeks)	1.15			
Total Inventory:										Upside Flex (Days)	5.77			
Mfg. Inv $K	0.00	0.00	$0	$0	$0	$0	$0	$8535	$82907	$12315	$12813	$0	$126,413.93	
Wks	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.2	1.8	0.5	0.2	0.0	2.68	Wks
Days	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	8.84	2.37	1.18	0.00	13.39	Days

Case Study
Desktop Five Box Model

Company 2
Benchmarking Project

Process Data:

Competitive LT

# Planned QLT < Com	1
# Planned QLT > Com	0
Planned Quoted LT	25
Response-Time	15.5
Response-T Var	7.8

Responsiveness 72%

0%	Process: Quoted LT > Comp LT
20%	Supply Constraints
10%	Forecast Error Constraints

Product Predictability 52.7%

50%	Inventory Service Level
90%	Process Reliability
60%	"Perfect Product" Percentage
100%	Other

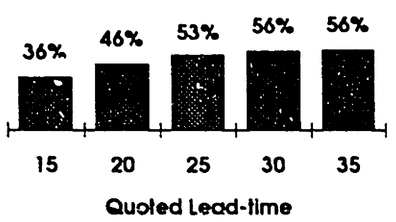
Inventory($000)
$82,877
14.83 Days
21.53 Turns

90% Forecast Error Coverage

WACT (Days)
27.2

Requires 31% "Upside"
= 8.4 Days Safety Stock

Predictability



Graph Lead-time Increment
5

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- 20% ----------> + 20%

Under	Within	Over
20%	60%	20%

$446,000	Output Forecast ($000/Qtr)
44600	Number of Orders
28273	Units (per Quarter)

(Forcst. error) Sigma	24.0%
Mu	0.00

Assumed SLT (wks)	3.1
ɟma(% wkly demnd)	96%

Standard Costs:

This Stage:	Stage 0	Stage 1	Stage II
Material	$0.00	$0.00	$11,732.06
VA	$0.00	$0.00	$4,042.47
Total	$0.00	$0.00	$15,774.53

Case Study
Pipeline Inventory Distribution

Company 2

52.7% Product Predictability
50% Inventory Service Level
90% Process Reliability

Ship to Systems Plants from Stage (1 or 2): 1
Pct of Output Forecast to Systems Plants: 0%

Pct of Output Forecast from ALL Dist. Centers: 100%
Weeks on hand if 1 Dist. Ctr.: 6.0
Number of Dist. Centers: 1

	Supplier			Components				Final Production				Dist.	Product	
	Raw	WIP	F.G.	L.T.	Raw	WIP	F.G.	L.T.	Raw	WIP	F.G.	F.G.	Totals	
Inventory if no Forecast Error:														
Mfg. Inv $K	$0	$0	$0	$0	$0	$0	$0	$6,430	$21,536	$6,581	$3431	$0	$37,978	
Weeks	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.7	0.2	0.1	0.0	1.29	Wks
Days													6.46	Days
Inventory to Cover Forecast Error:														
LLT %:	100%				100%				100%					
% SS Units	0.0		0%		0.0		0.0		70%	20%	10%	0%	100%	
Mfg. Inv $K	$0		$0		$0		$0		$29,885	$10,010	$5,005	$0	$44,899	
Sup Inv $K	$0				$0									
Tot SS Wks	0.00		0.00		0.00		0.00		1.17	0.33	0.17	0.00	1.67	Wks
									Upside Flex (Weeks)		1.67		8.37	Days
									Upside Flex (Days)		8.37			
Total Inventory:														
Mfg. Inv $K	0.00	0.00	$0	$0	$0	$0	$0	$6430	$51421	$6581	$8436	$0	$82,877.24	
Wks	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.3	1.9	0.6	0.3	0.0	2.97	Wks
Days	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.26	9.46	2.77	1.34	0.00	14.83	Days

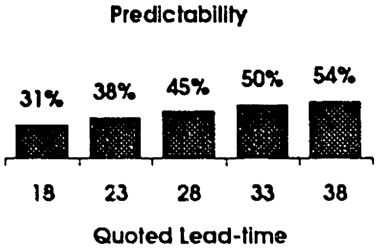
Case Study
Desktop Five Box Model

Company 3
Benchmarking Project

Process Data:

Competitive LT

# Planned QLT < Com	1
# Planned QLT > Com	0
Planned Quoted LT	28
Response-Time	22.5
Response-T Var	11.3



Graph Lead-time Increment 5

Responsiveness 72%

0%	Process: Quoted LT > Comp LT
20%	Supply Constraints
10%	Forecast Error Constraints

Inventory($000)
$109,098
21.01 Days
17.56 Turns

<------------ Bandwidth ----------->
- 20% -----------> + 20%

Under	Within	Over
20%	60%	20%

Product Predictability 44.6%

50%	Inventory Service Level
70%	Process Reliability
60%	"Perfect Product" Percentage
100%	Other

90% Forecast Error Coverage

WACT (Days)
34.5

Requires 31% "Upside"
= 10.6 Days Safety Stock

$478,938	Output Forecast ($000/Qtr)
47894	Number of Orders
47465	Units (per Quarter)

Forcst. error) Sigma 0.240
Mu 0.00

Assumed SLT (wks) 4.5
ma(% wkly demnd) 96%

Standard Costs:

This Stage:	Stage 0	Stage 1	Stage II
Material	$0.00	$0.00	$6,310.84
VA	$0.00	$0.00	$3,779.39
Total	$0.00	$0.00	$10,090.23

Case Study
Pipeline Inventory Distribution

Company 3

45% Product Predictability
50% Inventory Service Level
70% Process Reliability

Ship to Systems Plants from Stage (1 or 2): 1
Pct of Output Forecast to Systems Plants: 0%

Pct of Output Forecast from ALL Dist. Centers: 100%
Weeks on hand if 1 Dist. Ctr.: 6.0
Number of Dist. Centers: 1

	Supplier			Components				Final Production				Dist.	Product	
	Raw	WIP	F.G.	L.T.	Raw	WIP	F.G.	L.T.	Trans.	Raw	WIP	F.G.	Totals	
Inventory if no Forecast Error:														
Mfg. Inv $K	$0	$0	$0	$0	$0	$0	$0	$4,148	$25,450	$25,450	$3684	$0	$58,733	
Weeks	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.9	0.9	0.1	0.1	2.08	Wks
Days													10.40	Days
Inventory to Cover Forecast Error:														
LLT %:	100%				100%				100%					
% SS Units	0%		0%		0%		0%		70%	20%	10%	0%	100%	
Mfg. Inv $K	$0		$0		$0		$0		$34,231	$9,780	$6,354	$0	$50,365	
Sup Inv $K	$0				$0				$0					
Tot SS Wks	0.00		0.00		0.00		0.00		1.49	0.42	0.21	0.00	2.12	
									Upside Flex (Weeks)		2.12			
Total Inventory:									Upside Flex (Days)		10.61			
Mfg. Inv $K	0.00	0.00	$0	$0	$0	$0	$0	$4148	$59681	$25450	$10039	$0	$109,097.89	
Wks	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.2	2.3	1.3	0.3	0.1	4.20	Wks
Days	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	11.68	6.37	1.56	0.50	21.01	Days

Appendix 3.4: Charts outlining results of sensitivity analysis

Charts 1.1.1 -1.1.3: The impact of changes in the demand variance over the forecasting horizon on the level of inventory and supply reliability at each manufacturing facility, without adjusting the finished goods demand variability for changes in the forecast accuracy. *p.140 - 142*

Charts 1.2.1 -1.2.3 The impact of changes in the demand variance over the forecasting horizon on the level of inventory and supply reliability at each manufacturing facility with adjusting the finished goods demand variability for changes in the forecast accuracy. *p.143 - 145*

Charts 2.1 - 2.3: The impact of changes in the fill rate throughout the pipeline on the level of pipeline inventory and thus on the pipeline supply reliability at each manufacturing facility. *p.146 -148*

Charts 3.1 - 3.3: The impact of changes in the average cycle time for material in the pipeline on the level of pipeline inventory and pipeline supply reliability at each manufacturing facility. *p.149 - 151*

Charts 4.1 - 4.3: The impact of changes in the order response time on the order response reliability, and thus on the overall pipeline supply reliability at each manufacturing facility. *p.152 - 154*

Charts 5.1 - 5.3: The impact of changes in the variance of the order response time on the order response relia bility, and thus on the overall pipeline supply reliability at each manufacturing facility. *p.155 - 157*

Charts 6.1 - 6.3: The impact of changes in the lead time quoted to customers on the order response process reliability, and thus on the overall pipeline supply reliability at each manufacturing facility. *p.158 - 160*

Charts 7.1 - 7.3: The impact of a simultaneous change in the order response time and average material cycle time at each manufacturing facility. *p.161 - 163*

Chart 1.1.1: Impact of demand variance on inventory and supply reliability at manufacturing facility 1 without adjusting finished goods demand variabilitiy for changes in forecast accuracy

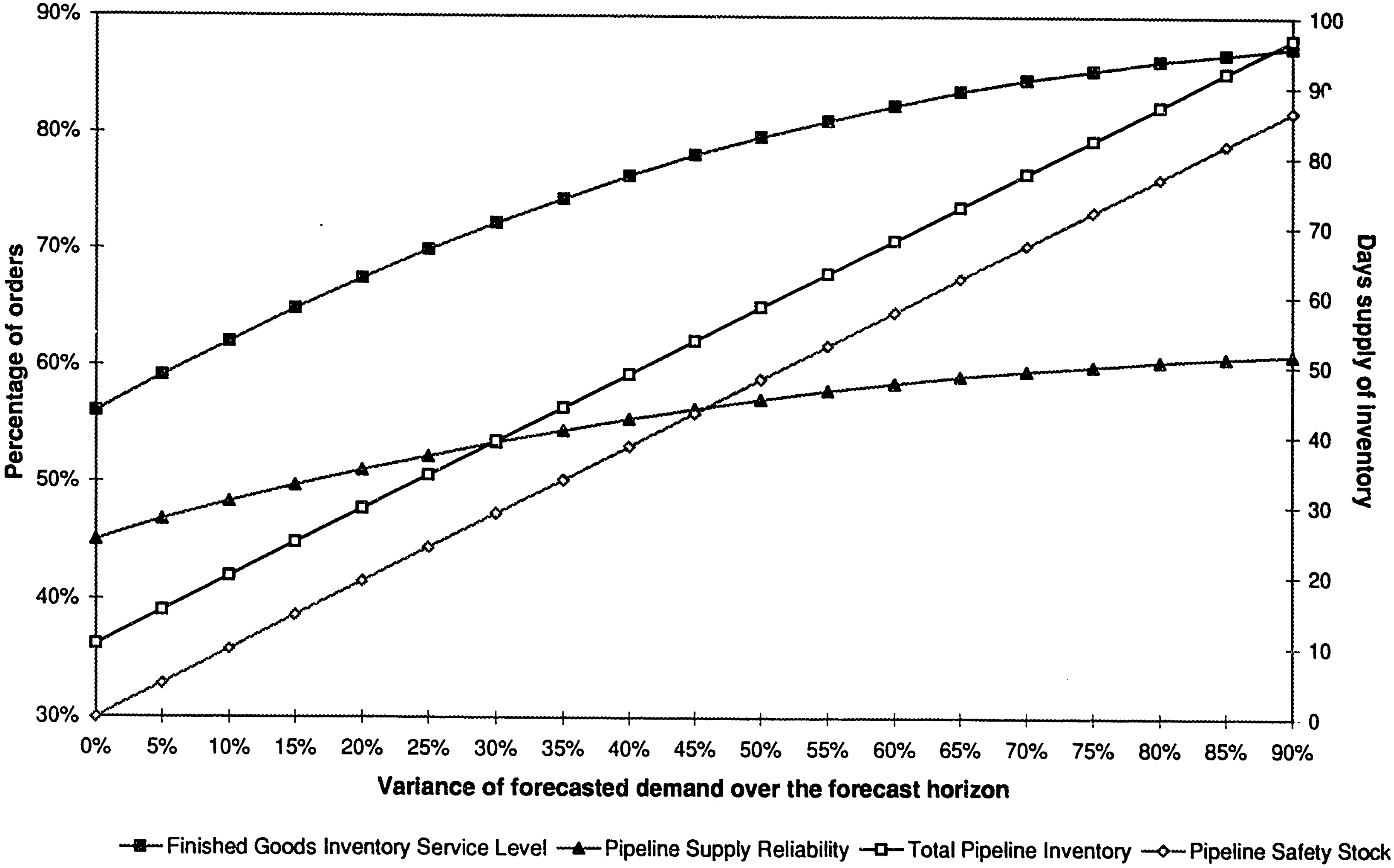


Chart 1.1.2: Impact of demand variance on inventory and supply reliability at manufacturing facility 2 without adjusting finished goods demand variabilitiy for changes in forecast accuracy

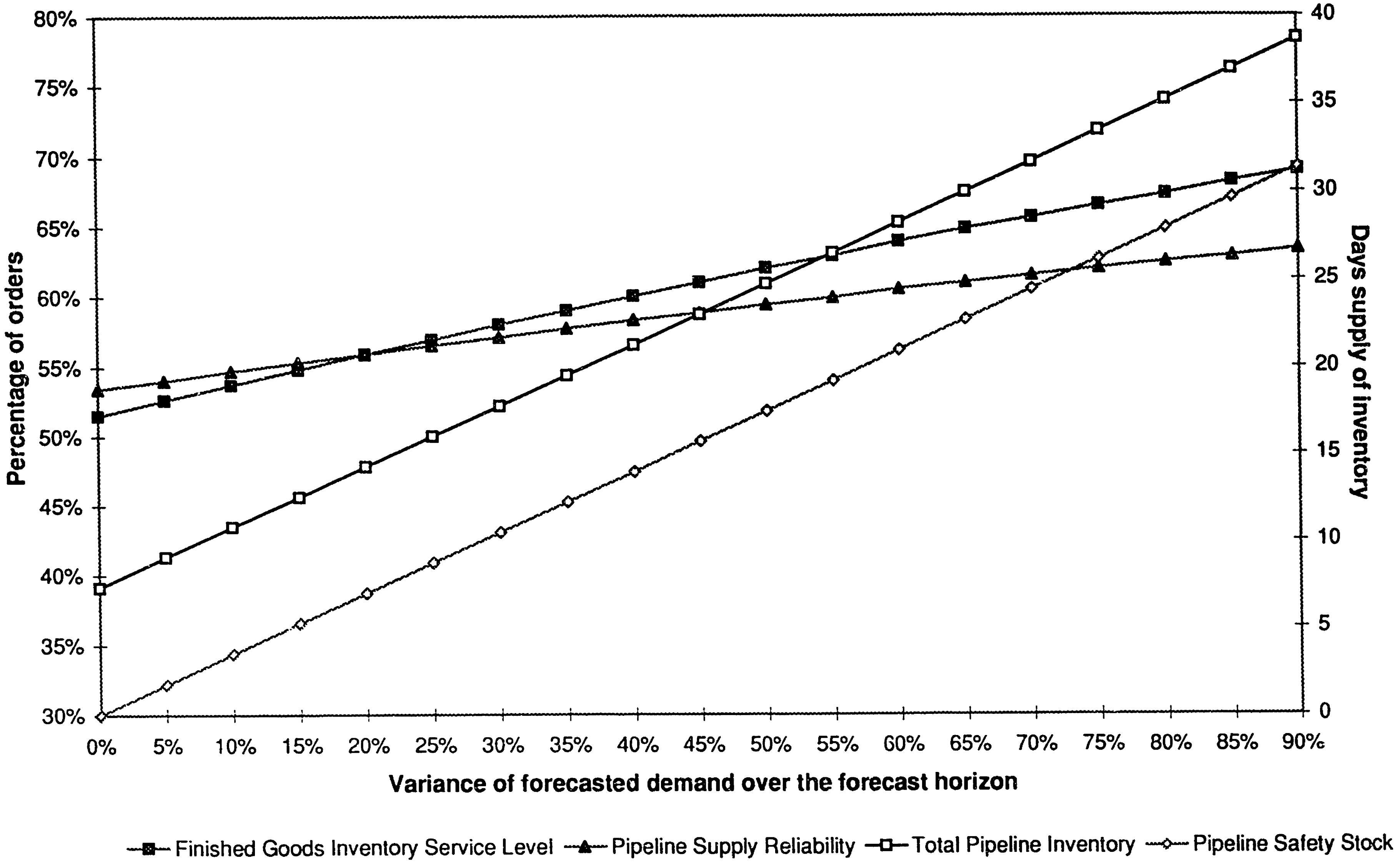


Chart 1.1.3: Impact of demand variance on inventory and supply reliability at manufacturing facility 3 without adjusting finished goods demand variabilitiy for changes in forecast accuracy

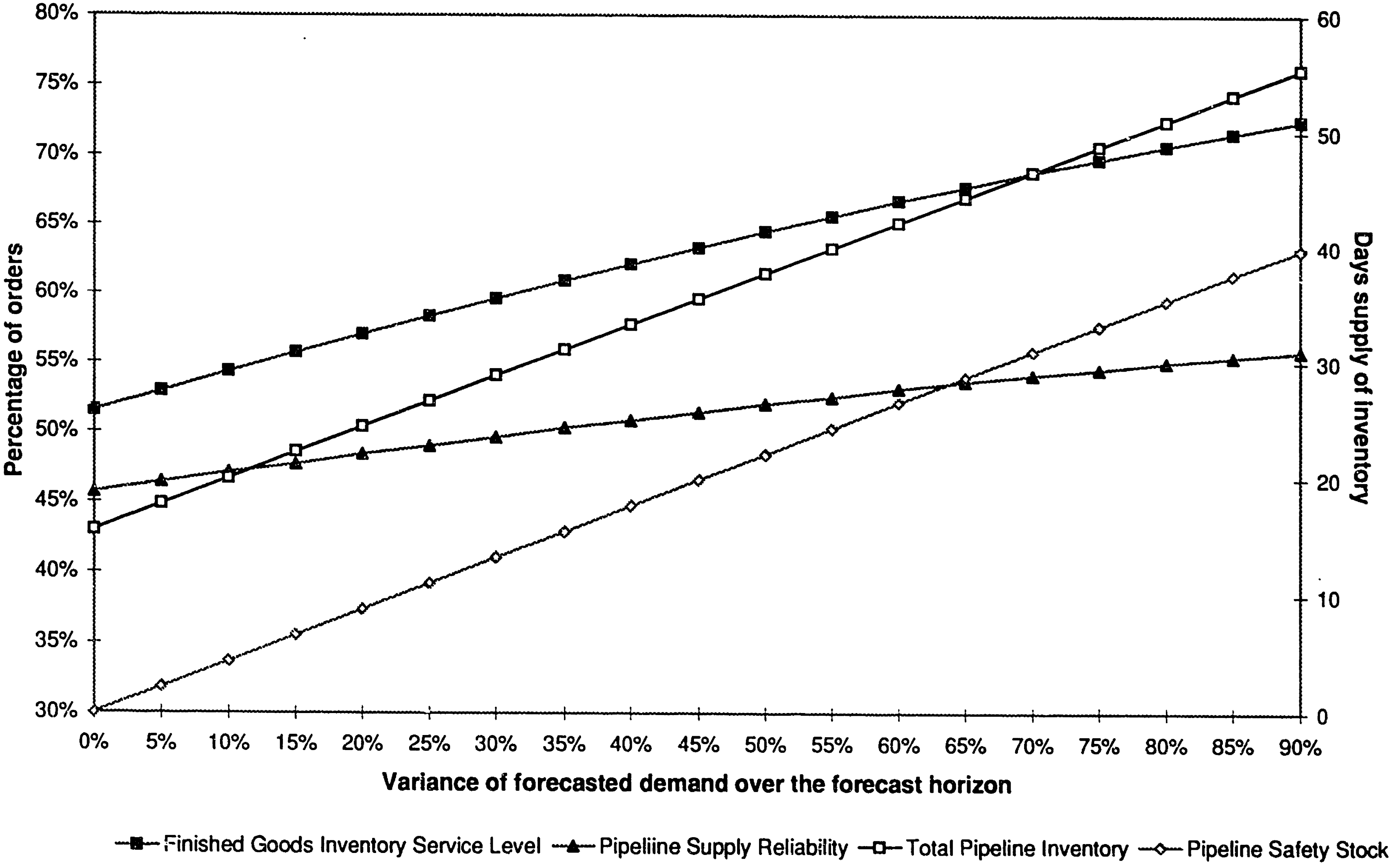


Chart 1.2.1: Impact of demand variance on inventory and supply reliability at manufacturing facility 1 after adjusting finished goods demand variabilitiy for changes in forecast accuracy

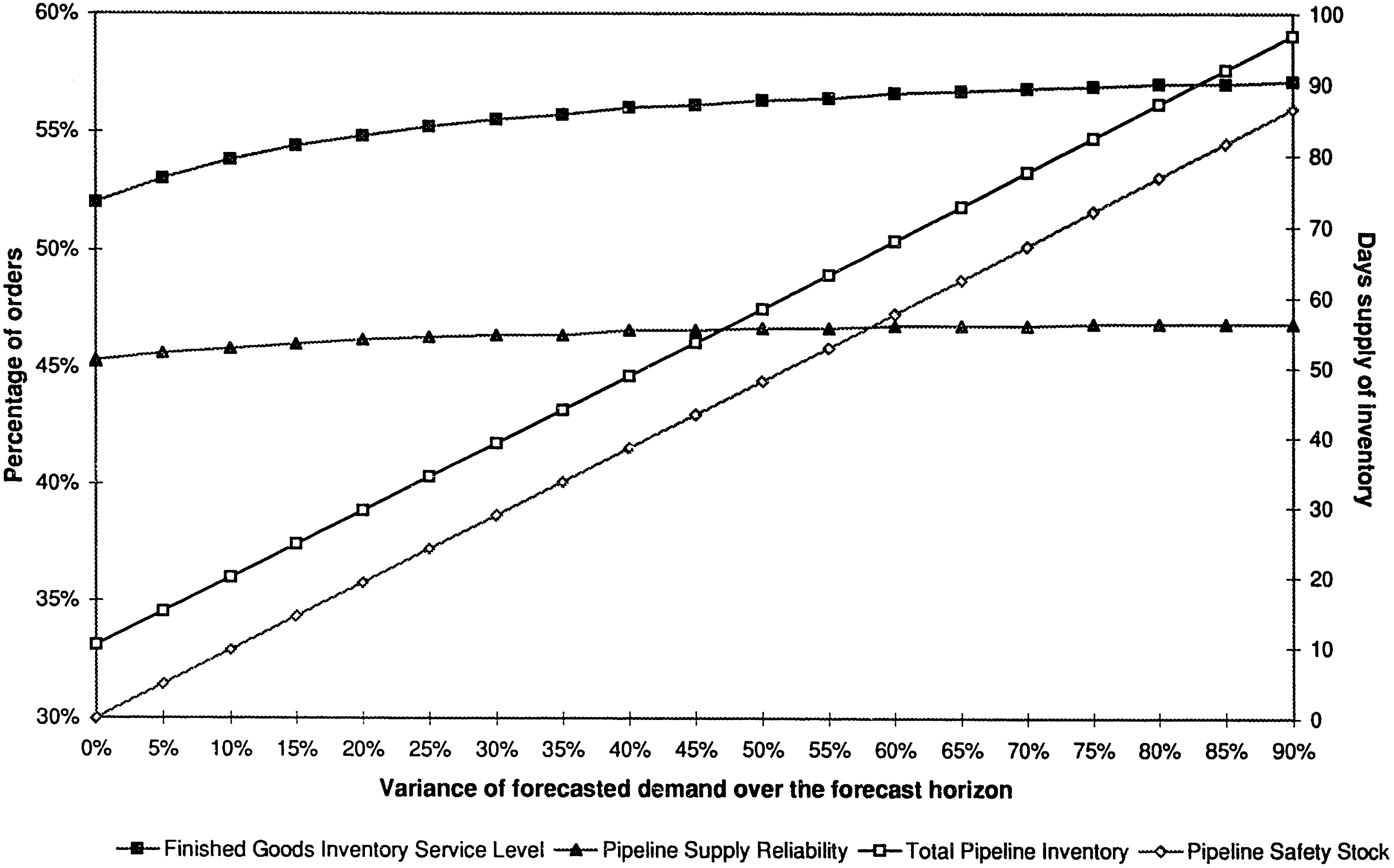


Chart 1.2.2: Impact of demand variance on inventory and supply reliability at manufacturing facility 2 after adjusting finished goods demand variabilitiy for changes in forecast accuracy

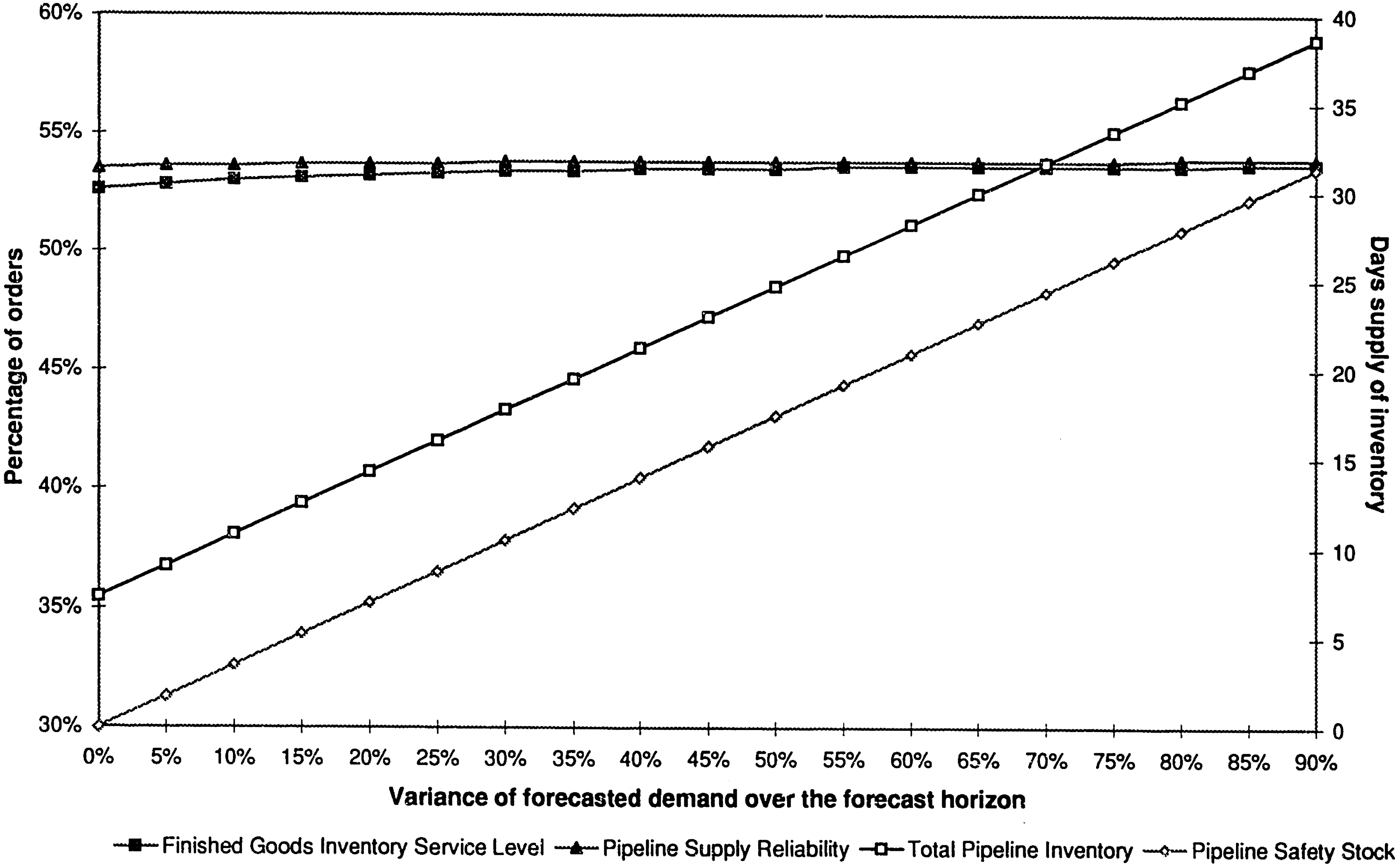


Chart 1.2.3: Impact of demand variance on inventory and supply reliability at manufacturing facility 3 after adjusting finished goods demand variabilitiy for changes in forecast accuracy

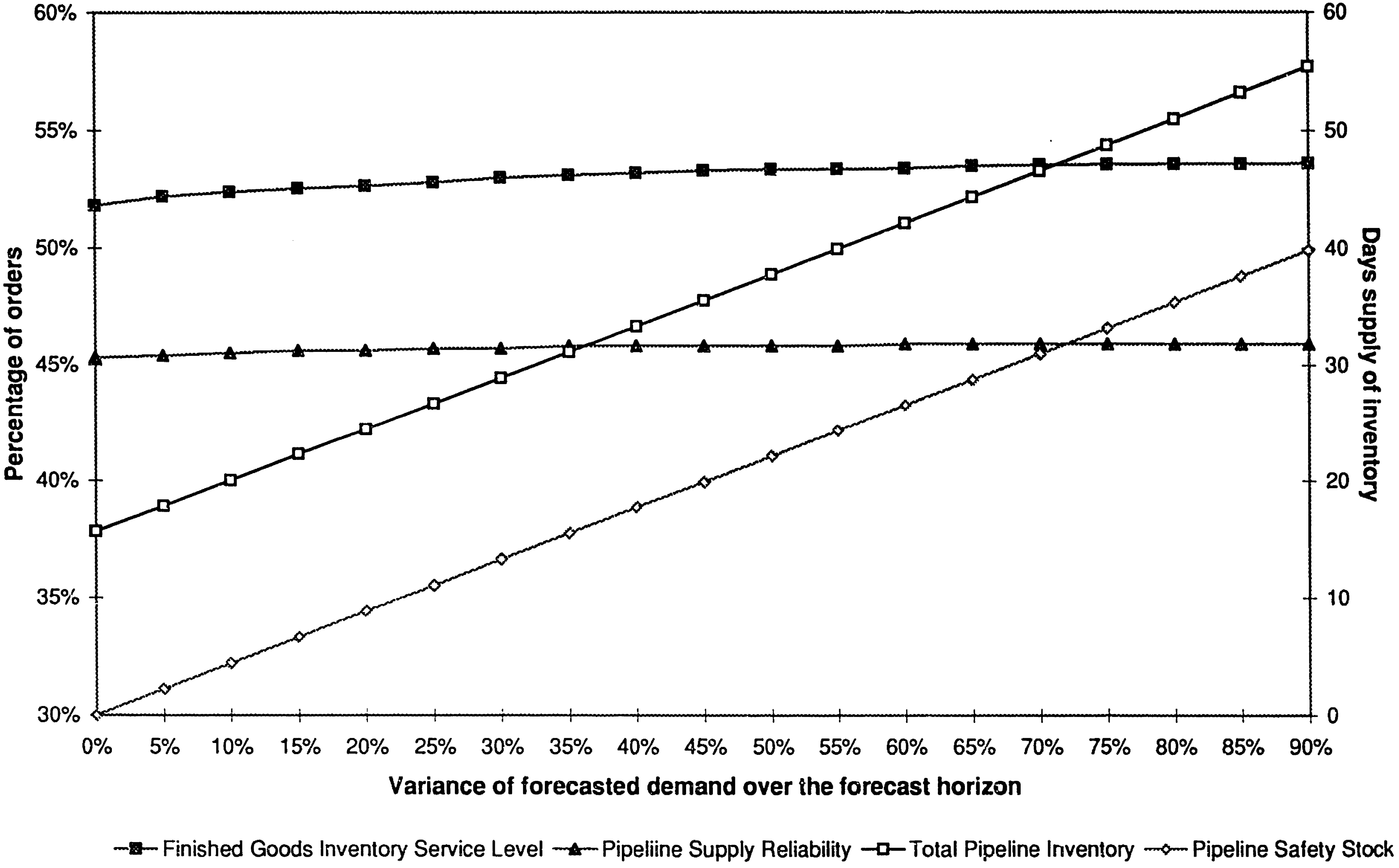


Chart 2.1: Impact of fill rate on inventory and supply reliability at manufacturing facility 1

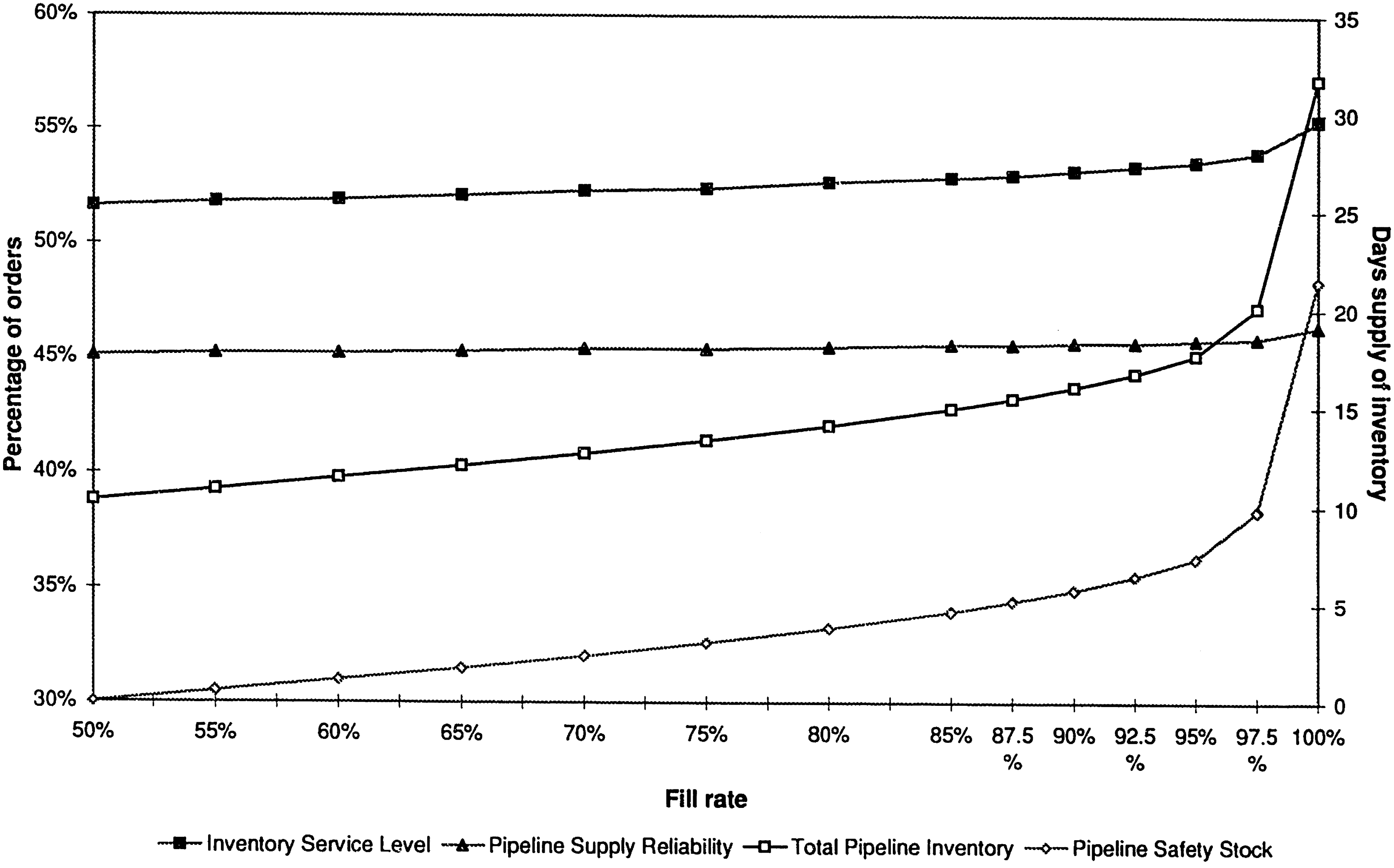


Chart 2.2: Impact of fill rate on inventory and supply reliability at manufacturing facility 2

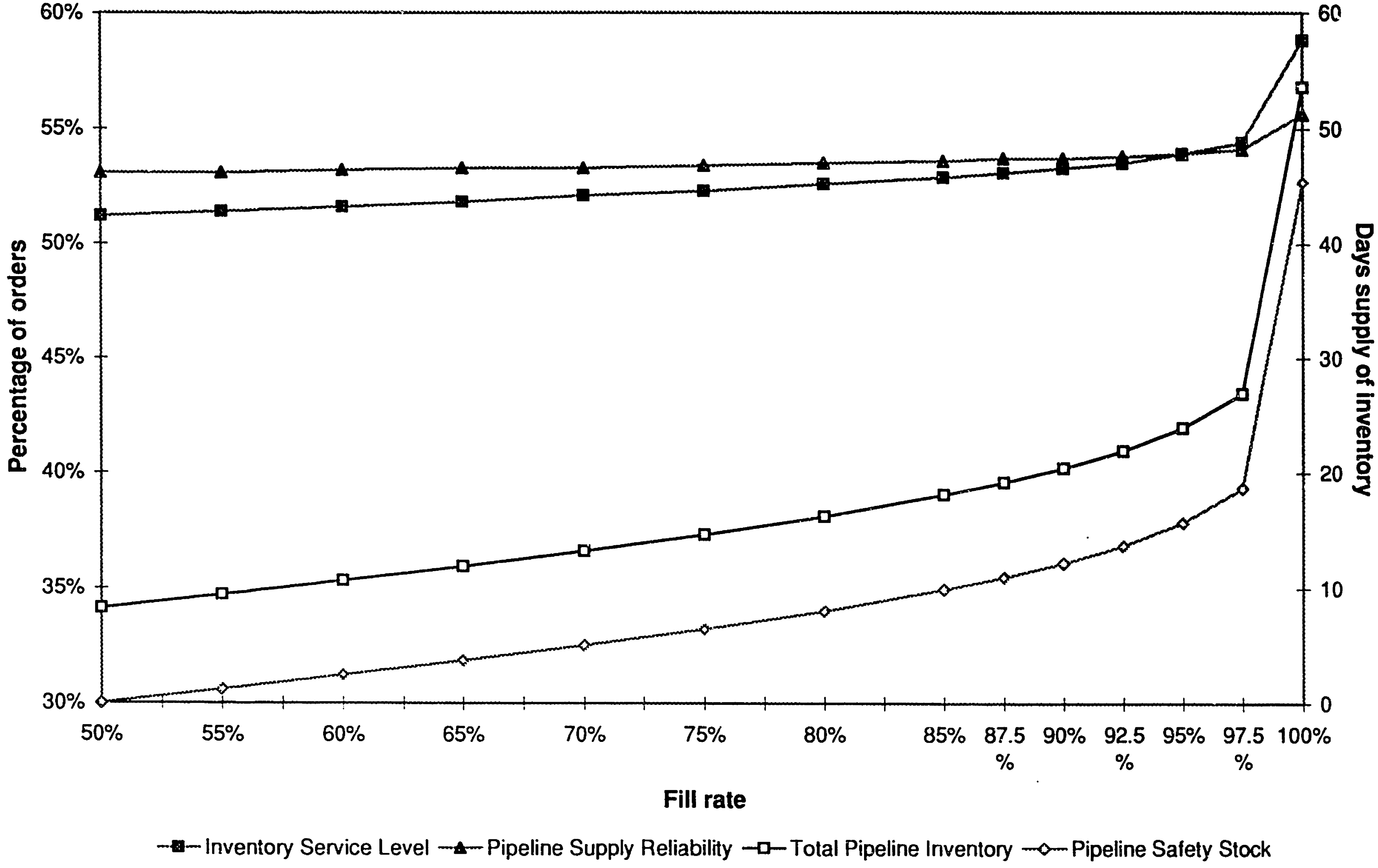


Chart 2.3: Impact of fill rate on pipeline inventory and supply reliability at manufacturing facility 3

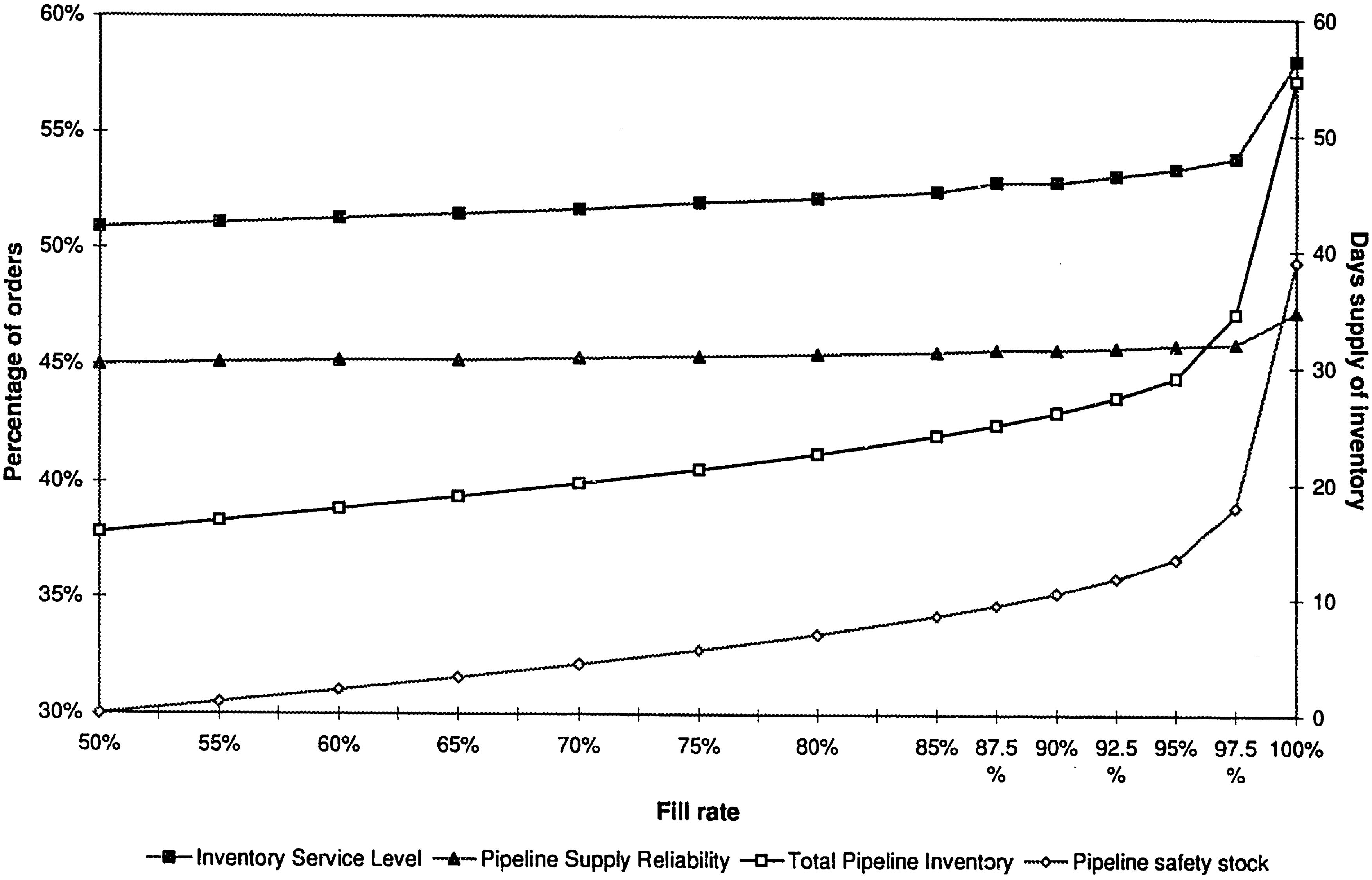


Chart 3.1: Impact of average cycle time on inventory and supply reliability at manufacturing facility 1

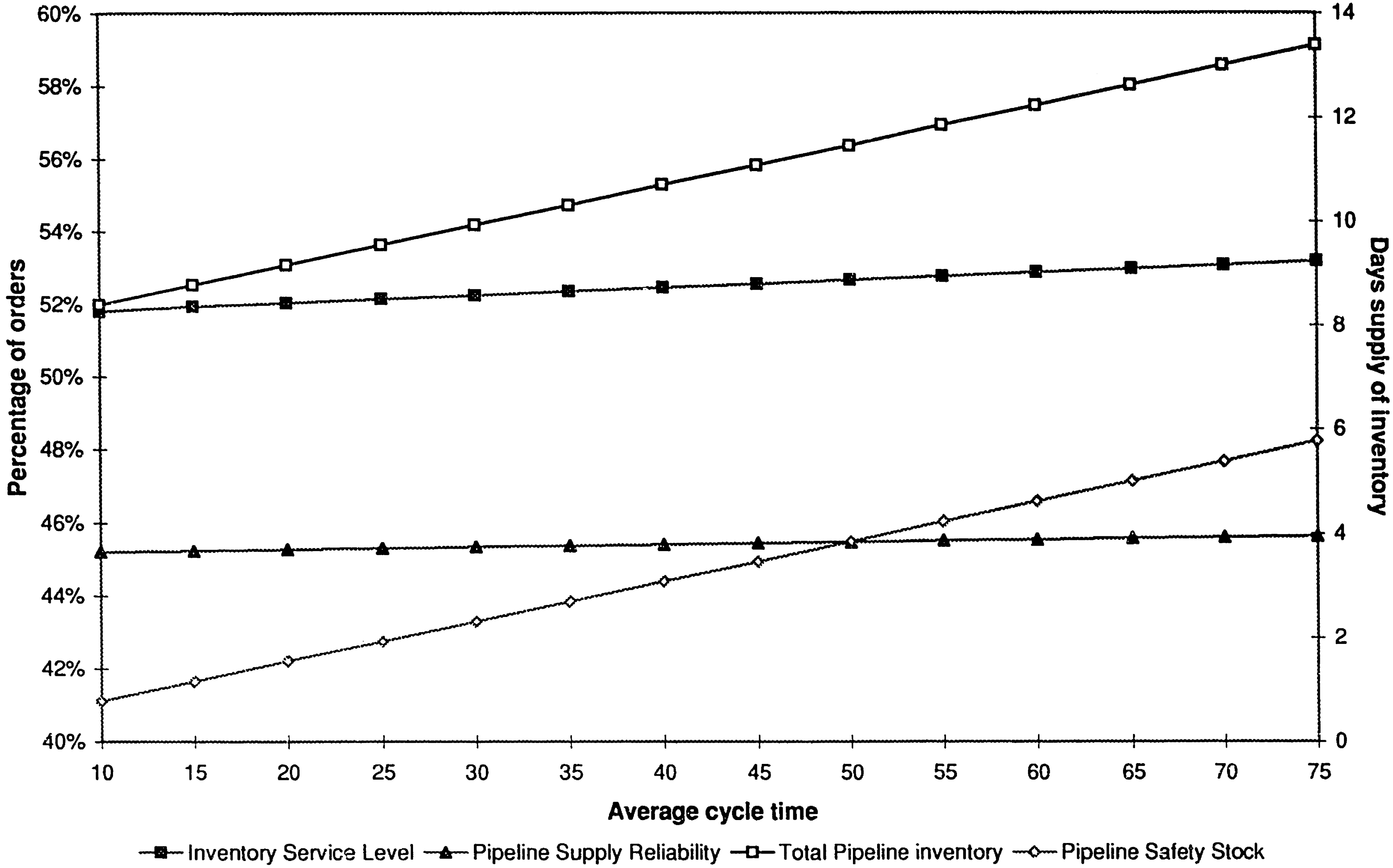


Chart 3.2: Impact of average cycle time on inventory and supply reliability at manufacturing facility 2

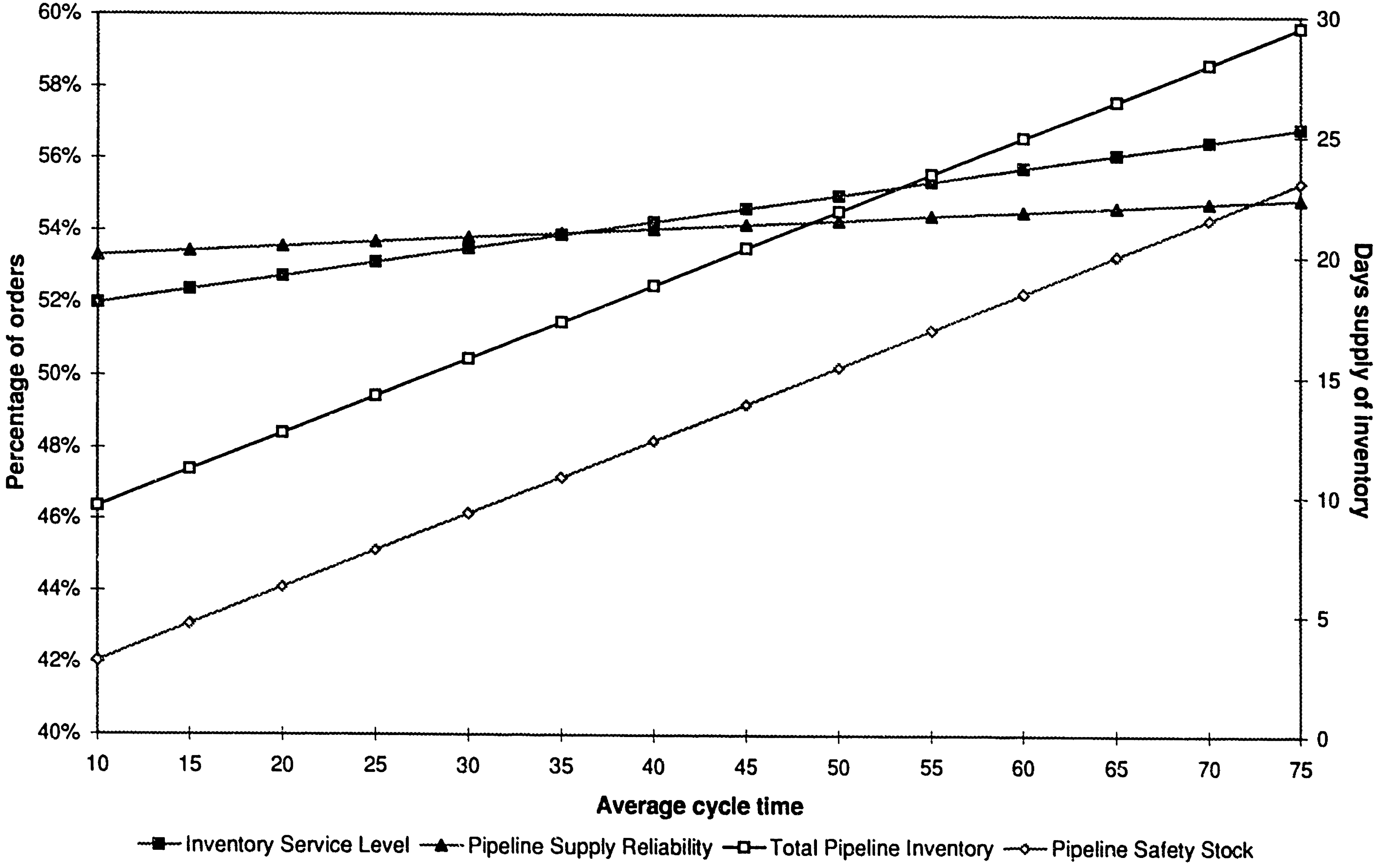


Chart 3.3: Impact of average cycle time on inventory and supply reliability at manufacturing facility 3

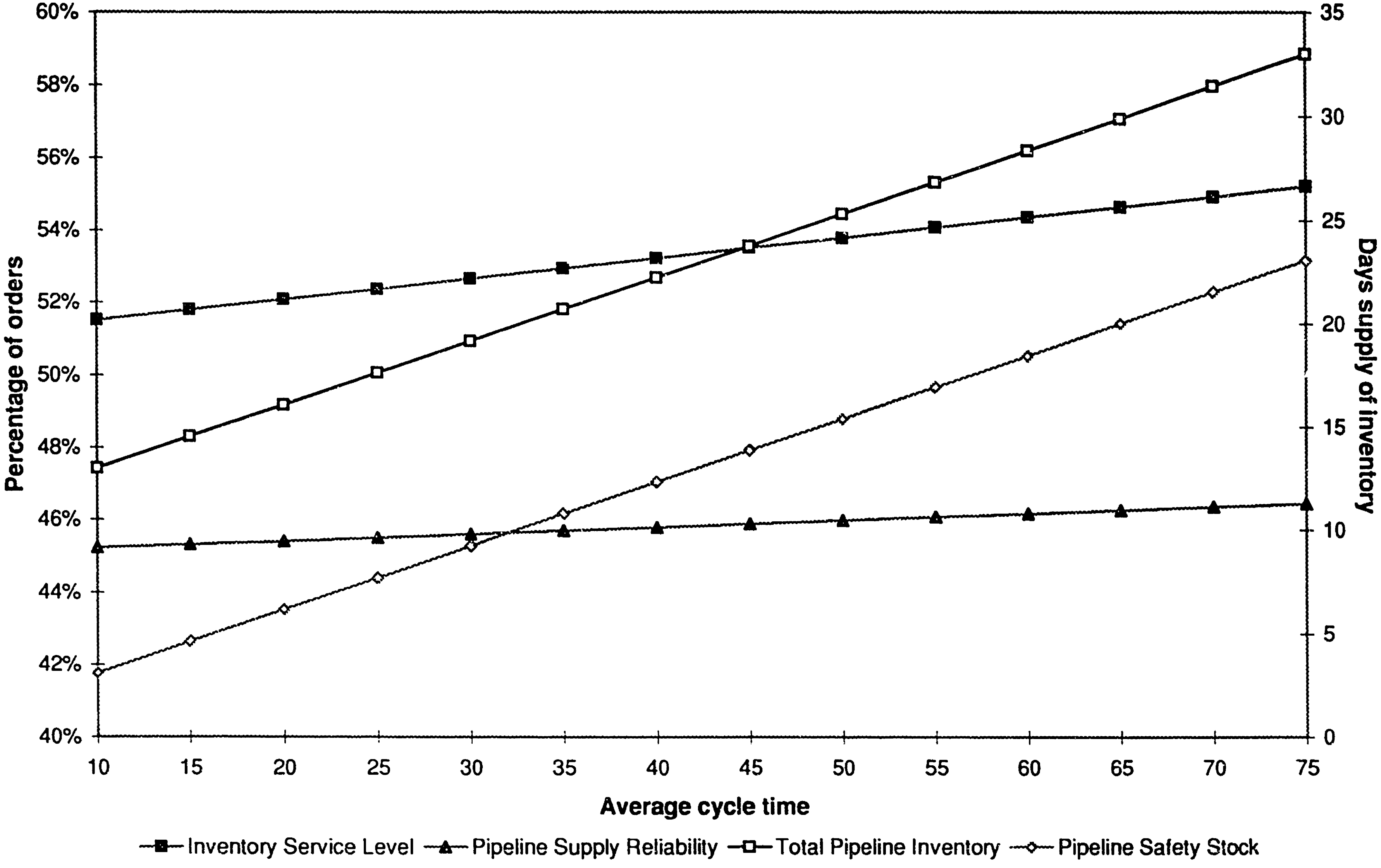


Chart 4.1: Impact of response time on process and overall pipeline supply reliability at manufacturing facility 1 [Quoted lead time: 30 days]

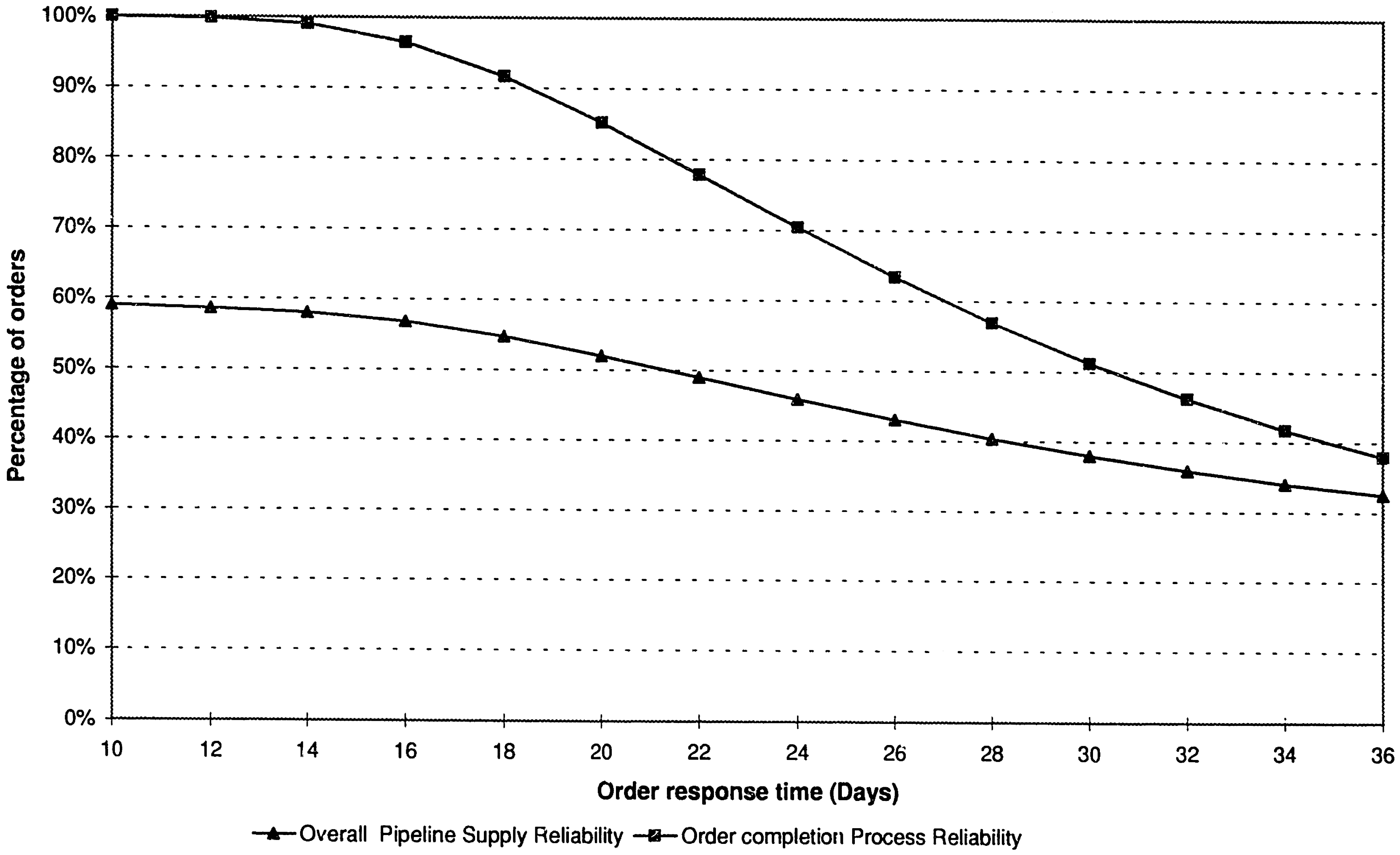


Chart 4.2: Impact of response time on process and overall pipeline supply reliability at manufacturing facility 2 [Quoted lead time: 25 days]

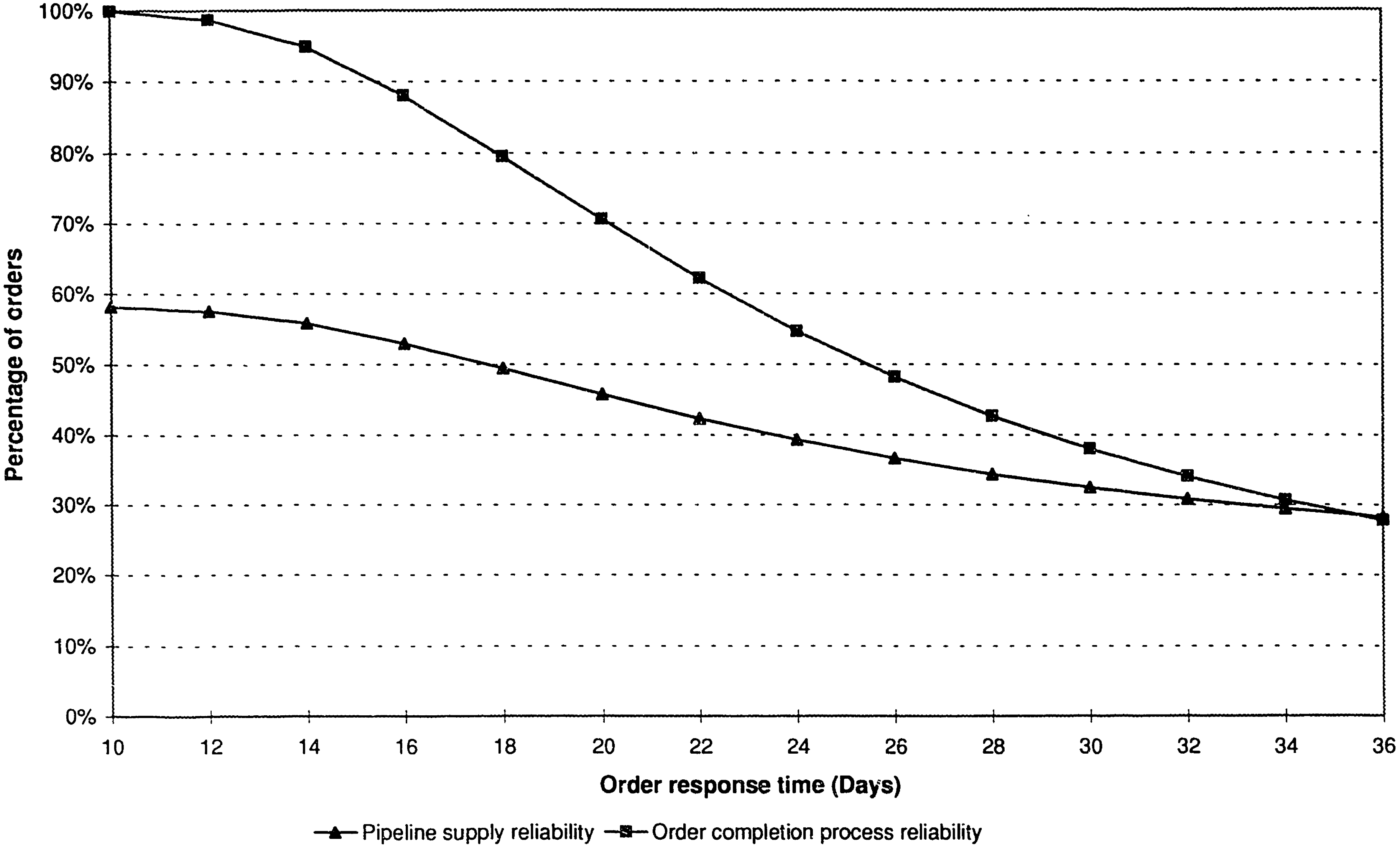


Chart 4.3: Impact of response time on process and overall pipeline supply reliability at manufacturing facility 3 [Quoted lead time: 28 days]

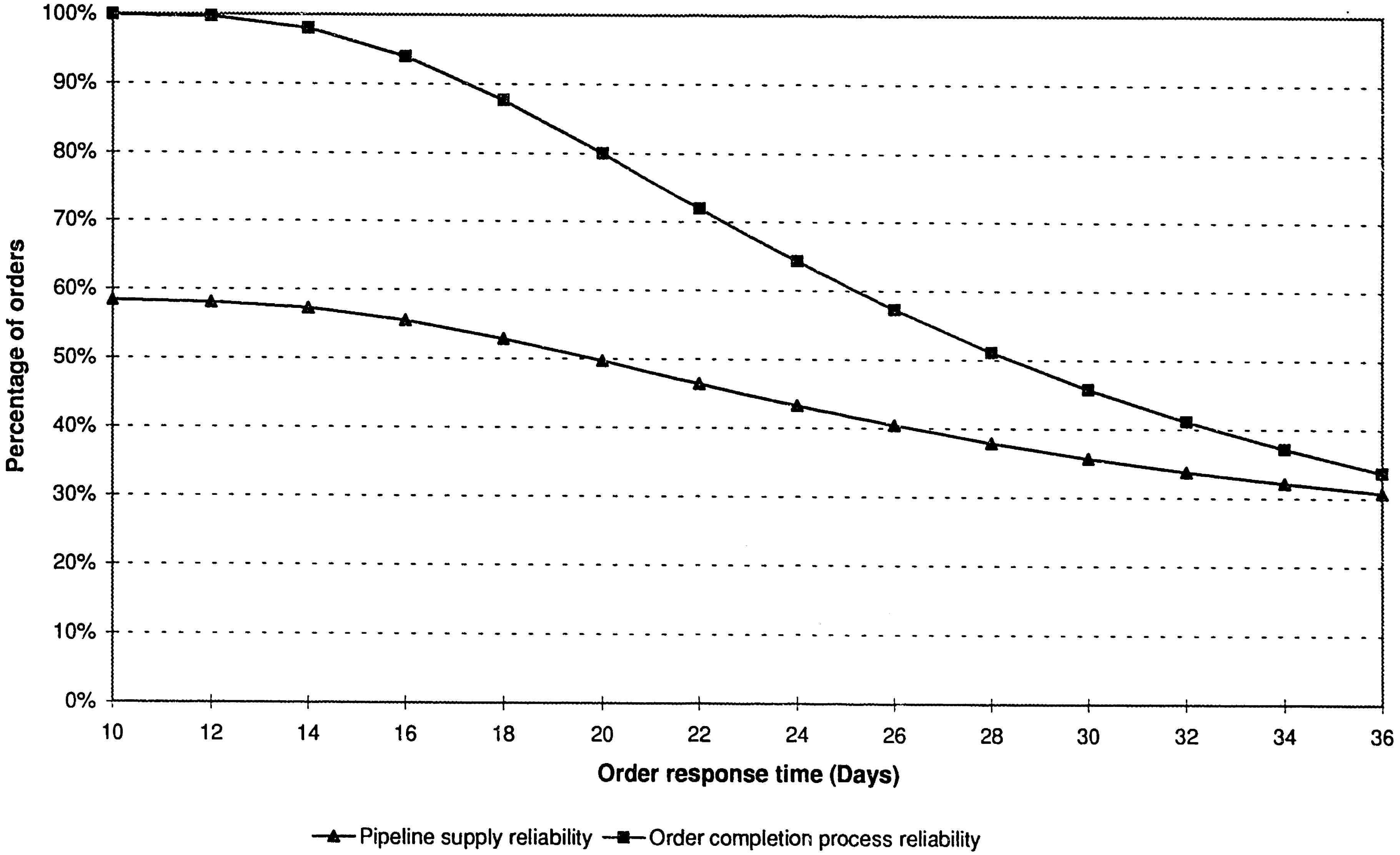


Chart 5.1: Impact of response time variance on process and overall pipeline supply reliability at manufacturing facility 1 [Quoted lead time: 30 days / Average response time: 24.2 days]

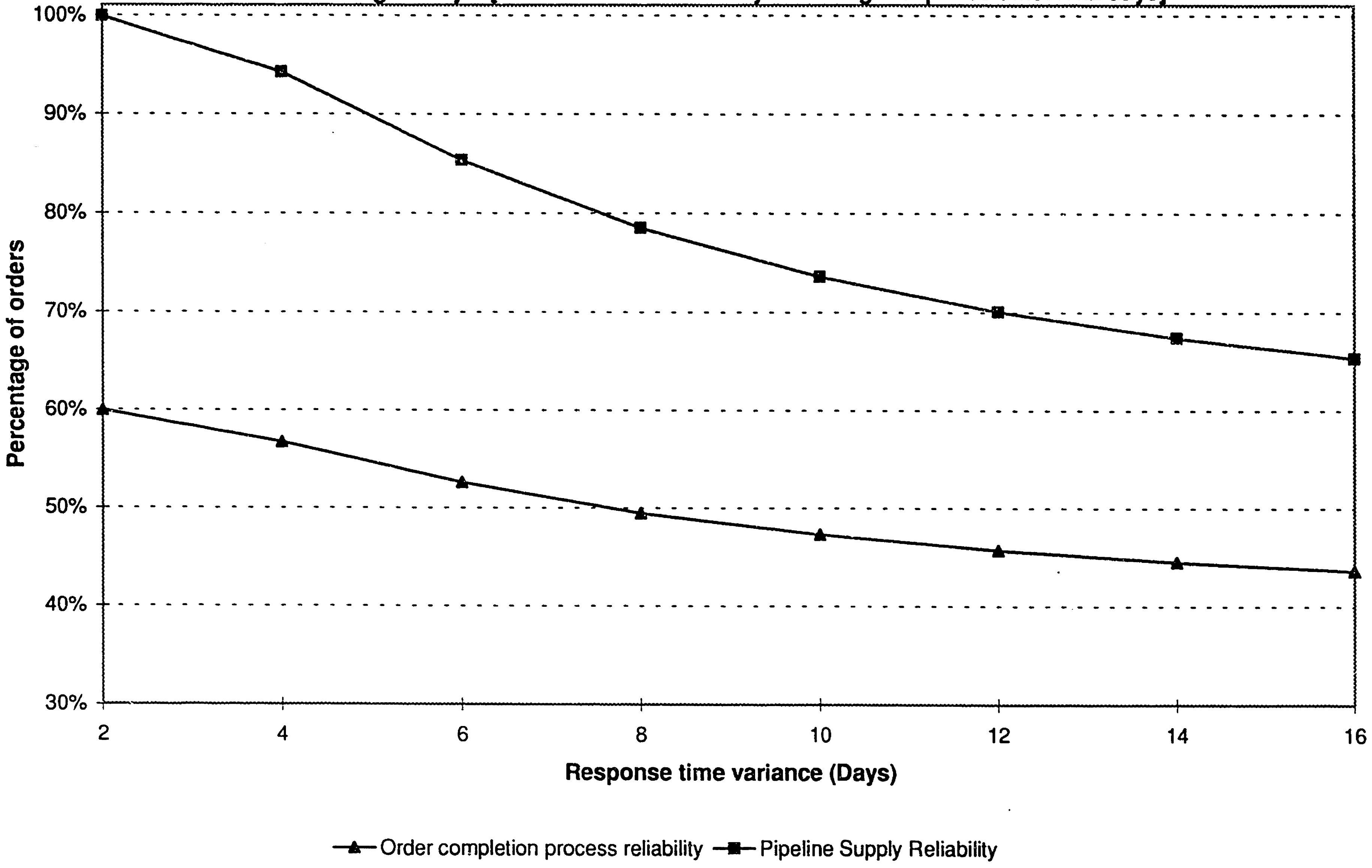


Chart 5.2: Impact of response time variance on process and overall pipeline supply reliability at manufacturing facility 2 [Quoted lead time: 25 days / Average response time: 15.5 days]

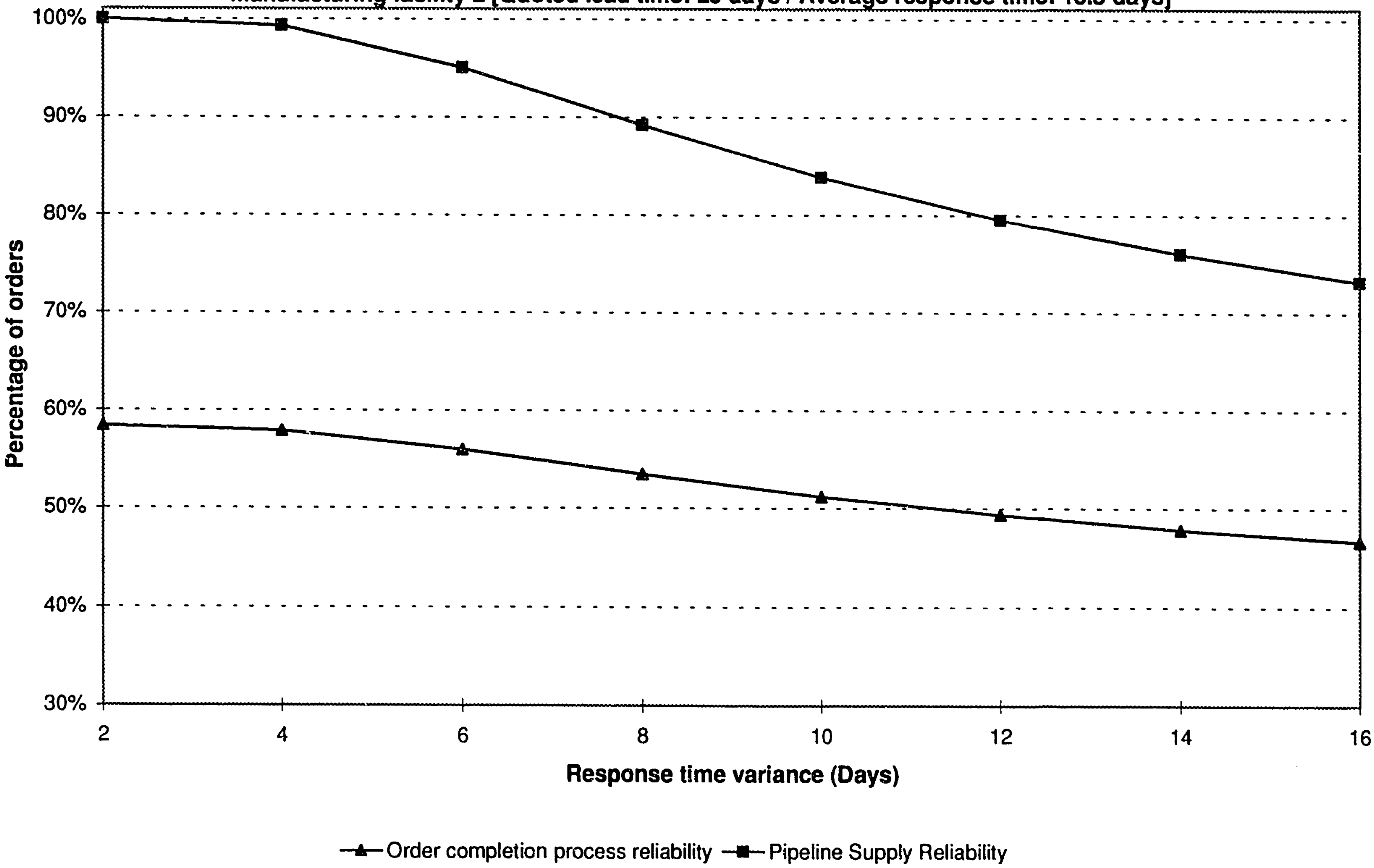


Chart 5.3: Impact of response time variance on process and overall pipeline supply reliability at manufacturing facility 3 [Quoted lead time: 28 days / Average response time: 22.5 days]

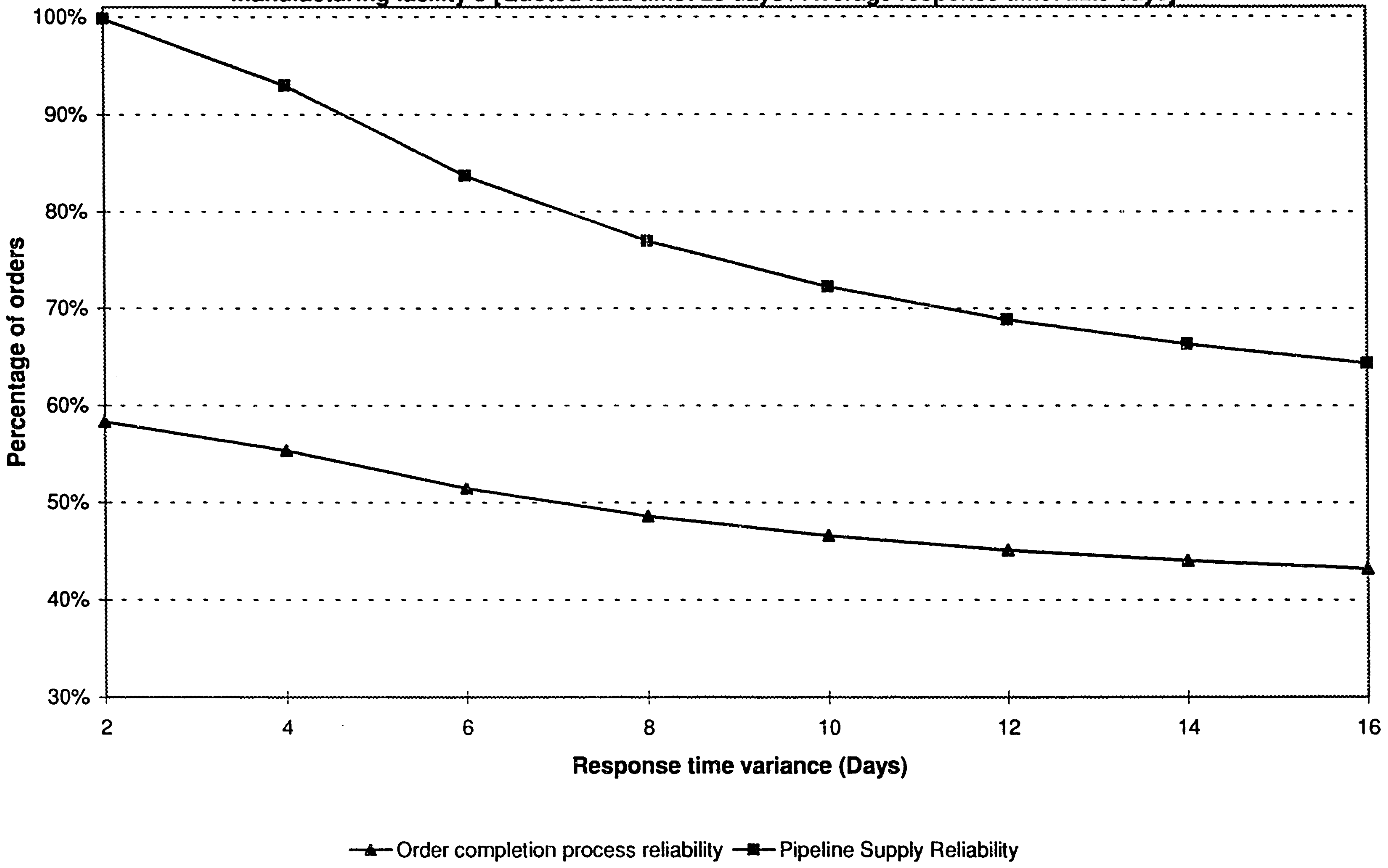


Chart 6.1: Impact of quoted lead time on process and overall pipeline supply reliability at manufacturing facility 1 [Avg. response time: 24.2 days]

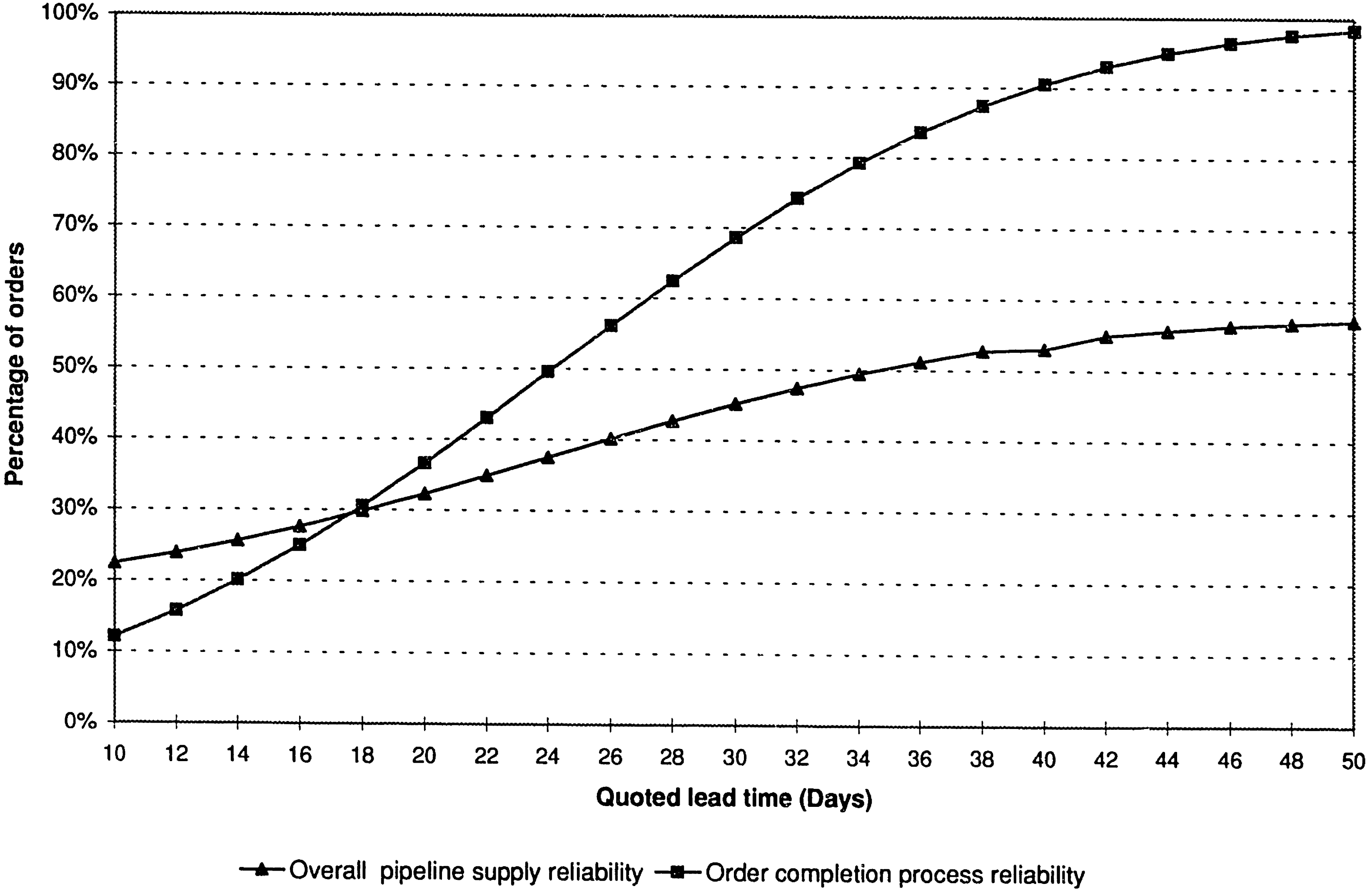


Chart 6.2: Impact of quoted lead time on process and overall pipeline supply reliability at manufacturing facility 2 [Avg. response time: 15.5 days]

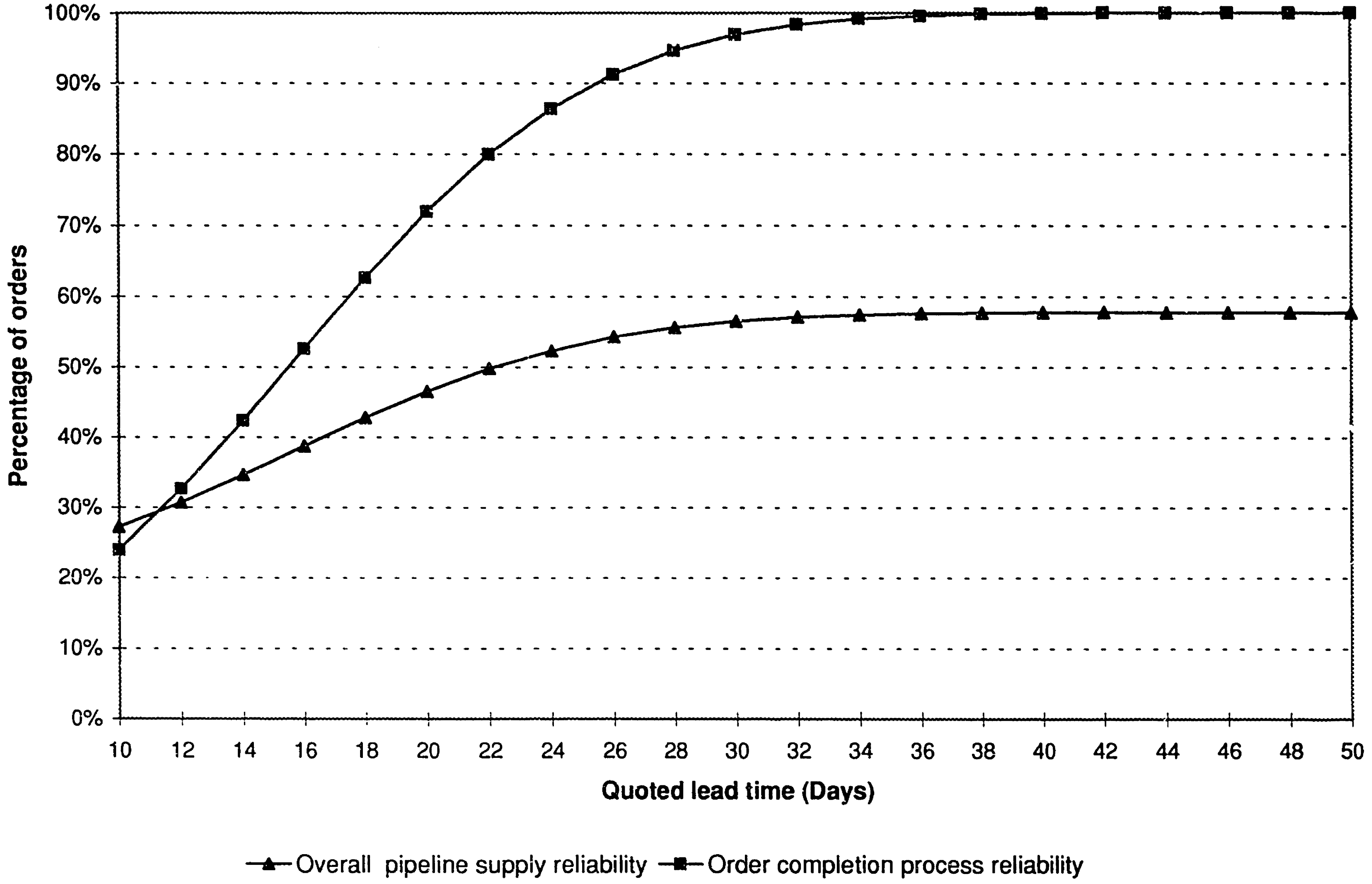


Chart 6.3: Impact of quoted lead time on process and overall pipeline supply reliability at manufacturing facility 3 [Avg. response time: 28 days]

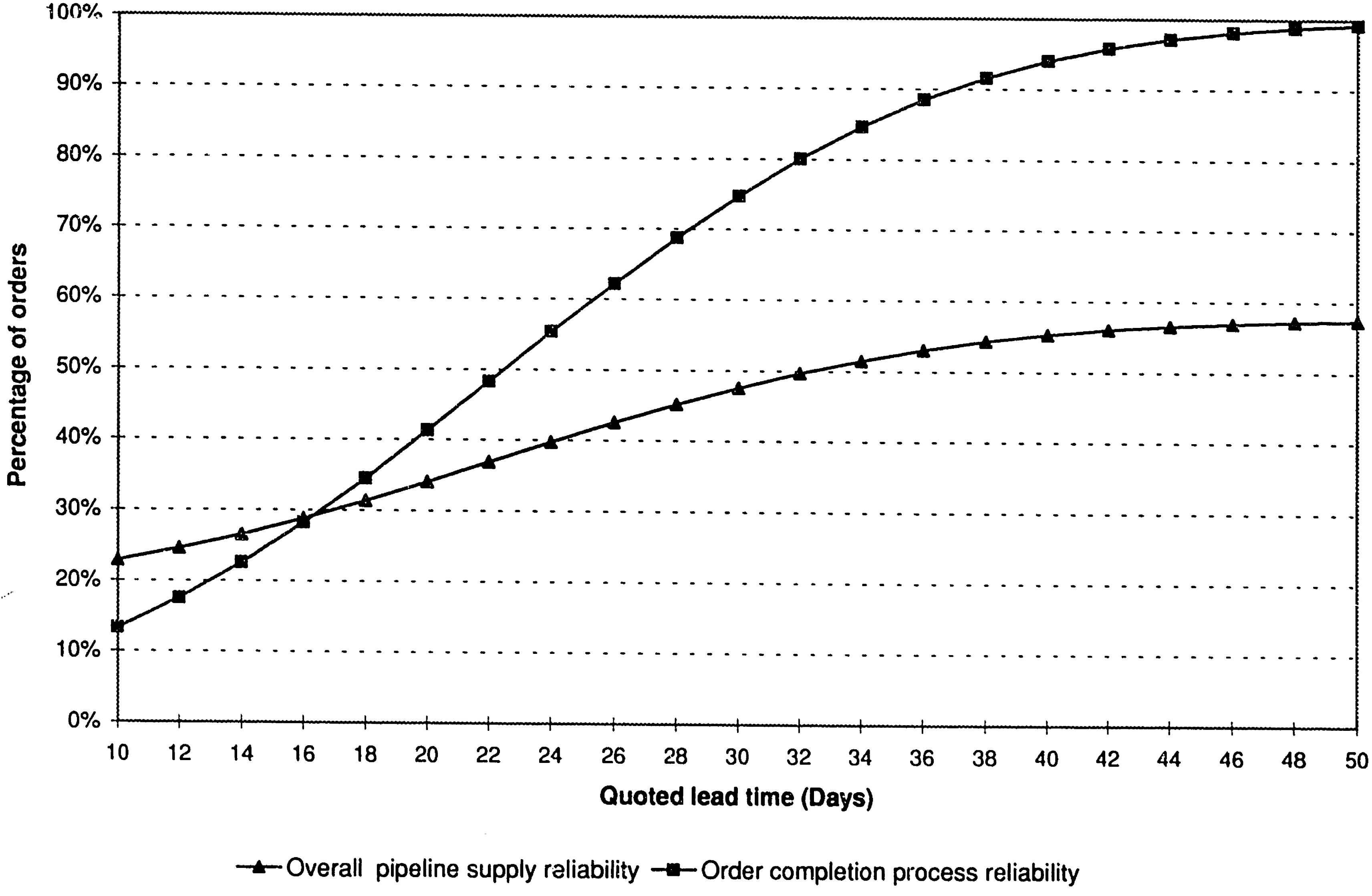


Chart 7.1: Impact of simultaneous increase in response time and cycle time on supply reliability at manufacturing facility 1 [Quoted lead time: 30 days / Demand variance: 6%]

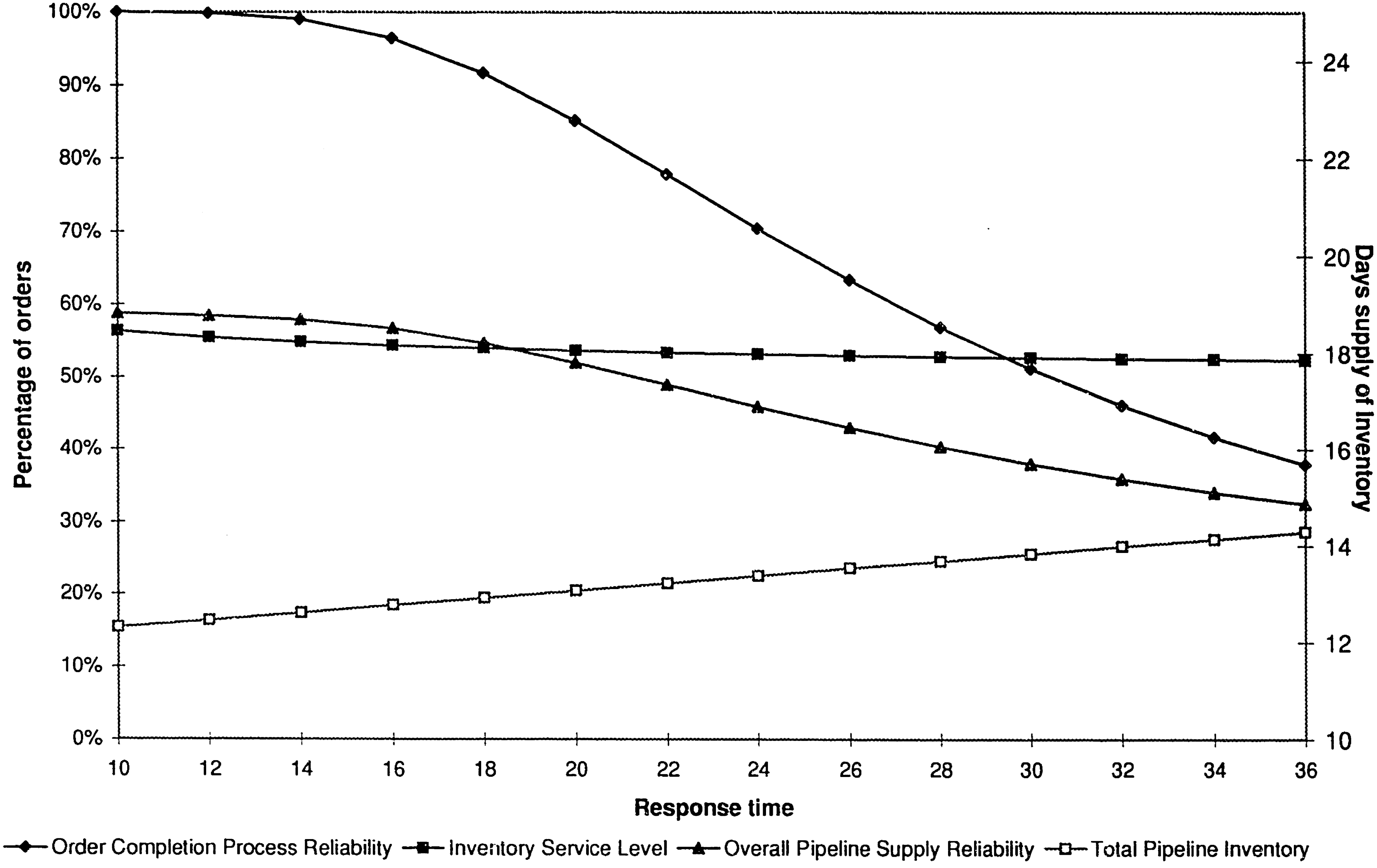


Chart 7.2: Impact of simultaneous increase in response time and cycle time on supply reliability at manufacturing facility 2 [Quoted lead time: 25 days / Demand variance: 24%]

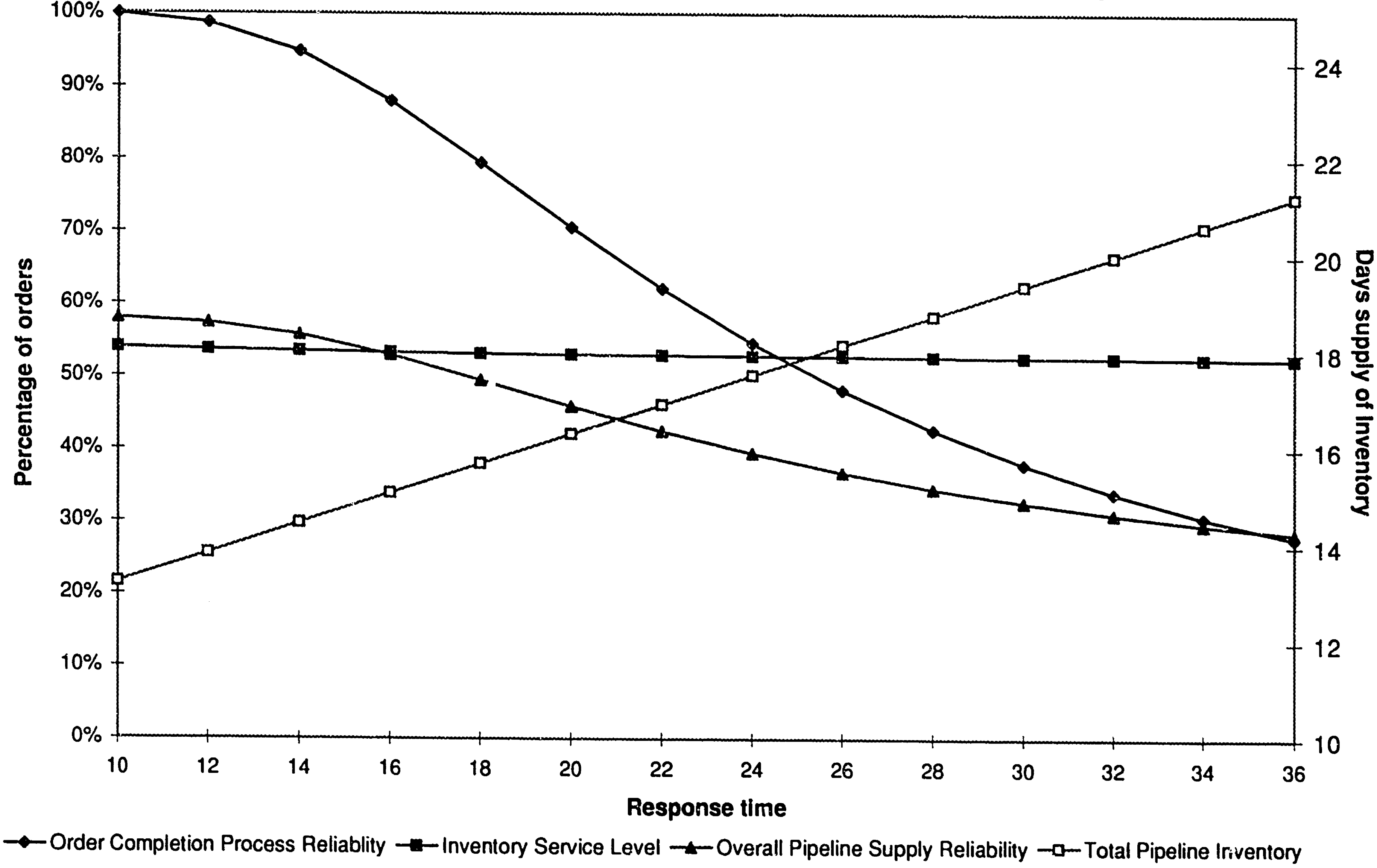
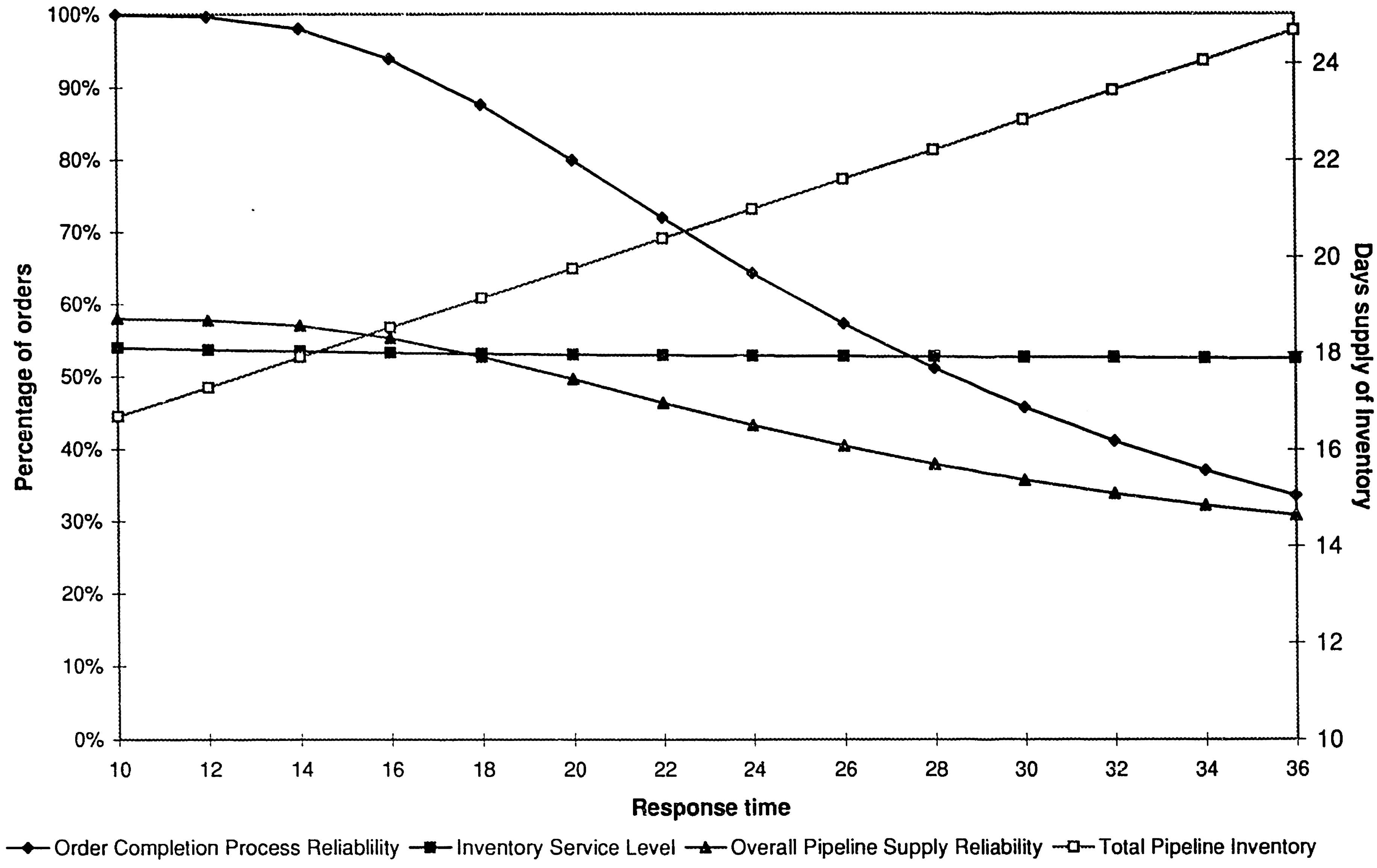


Chart 7.3: Impact of simultaneous increase in response time and cycle time on supply reliability at manufacturing facility 3 [Quoted lead time: 28 days / Demand variance: 24%]



Appendix 4.1: Mathematical programming formulation to determine an optimal tradeoff between finished goods inventory and manufacturing capacity investments

This formulation attempts to find an optimal production schedule along with optimal quarterly production line purchasing decisions such that a deterministic weekly demand is met. In the situation where production capacity decisions do not consider a possible tradeoff between inventory and production capacity and a cyclical demand exists, this program could lead to a more efficient allocation of capital expenditures.

Three indices will be used throughout this model: production stage, product type and week number:

1. The product pipeline is composed of a total of k stages. (i.e. s = 1,...k)
2. A total of n specific products can be produced. (i.e. p = 1,...,n)
3. A quarter with thirteen weeks is observed. (i.e. w = 1,..,13). Depending on actual purchasing and demand patterns, this period can be extended or reduced.

The following *exogenous variables* can be defined:

- $dem_{s,p,w}$ ≡ The customer demand for finished goods of product p in week *w* at stage *s*. [Units]
- $fr_{s,p,w}$ ≡ The maximum permissible percentage of demand for good p that can remain unfulfilled at the end of week w at stage *s*. It is also known as the fill rate for good *p*. [%]

- $dso_{s,p,w}$ ≡ The number of days sales outstanding for product *p* in week *w*. [Days]
- $\mathrm{adv}_{s,p}$ ≡ The number of weeks that product *p* will need to be ordered and booked as purchased in advance from downstream suppliers [integer]

- $\mathrm{ss}_{s,p}$ ≡ The minimum level of safety stock required at stage *s* for product *p* [Units]
- $\mathrm{os}_{s,p}$ ≡ The maximum possible inventory level of product *p* at stage *s*. [Units]

- $\mathrm{rm}_{s,w}$ ≡ The maximum available regular hours of labor at stage *s* in week *w*. [Hours]
- $\mathrm{om}_{s,w}$ ≡ The maximum available overtime hours of labor at stage *s* in week *w* [Hours]

- $\mathrm{m}_{s,p}$ ≡ Units of product *p* produced by one worker in one hour at stage *s*. [Units/Hour]
- $h_{p,r}$ ≡ Average number of input parts *r* required to produce product *p*. [Integer]

- $product_{p,s}$ ≡ The production time for product p at stage s [Hours]
- $start_s$ ≡ The time required to start up a production line at stage *s* [Hours]

- $matl_{s,p,w}$ ≡ The material cost of inventory of a product *p* in week w at stage *s*. Note: for simplicity the model assumes that the value added is incurred when the product leaves one stage and moves to the next downstream stage.

- cap_s ≡ The capital expenditure associated with adding a production line at stage *s*. [$]
- $life_s$ ≡ The useful life of a production line at stage *s* in terms of units produced. [Units]

Moreover, the following *environmental parameters* can be listed:

- *r* refers to the yearly carrying cost of holding goods [%]
- *lr* refers to the hourly wage cost of direct labor. [$/hr]
- *lo* refers to the hourly cost of overtime labor [$/hr]

From the discussion in section 4.1.2, the following five *decision variables* can be defined:

- $X_{s,p,w}$: The number of units of product p to be produced at stage *s* in week *w*. This variable could take on any positive real value, however should be preferably specified as an integer value.
- $P_{s,w}$: The number of production lines to be purchase at stage *s* at the beginning of week *w*. This variable can have any positive integer value.
- $I_{s,p,w}$: The number of units of product *p* retained in finished goods inventory at stage s in week w. This variable could take on any positive real value, however should be preferably specified as an integer value to reduce the solution procedure complexity.
- $L_{s,p,w}$: The number of production lines *p* to start-up at stage *s*, in week w in order to meet the requested shipments. This variable will have positive integer numbers.
- $RT_{s,p,w}$ / $OT_{s,p,w}$: The amount of overtime that must be spent to accommodate demand for product p at stage s in week *w*.

All decision variables are assumed to be greater or equal to zero.

The objective function of this model maximizes the residual income from manufacturing capacity investments as defined in section 4.1.2 and can be stated as:

$$\max z(\bar{x}) = P(\bar{x}) - [\text{Capital charge} * A(\bar{x})] \qquad [7.1]$$

$$\text{s.t. } \bar{x} \geq 0$$

where the vector $\vec{x}$ is a vector of the five decision variables listed above. $P(\vec{x})$ is the net profit resulting from the set of decisions in $\vec{x}$ and $A(\vec{x})$ is the asset base generated by the inventory and capacity levels chosen in $\vec{x}$. As mentioned the approach to find a maximal profit from operations does not maximize revenues but rather minimizes costs at a constant revenue level. The revenue is assumed to remain constant if the demand constraints are met.

With these definitions, the mixed integer program can be formulated as follows:

Objective: Minimize the total net quarterly cost of operations in a *k* stage product pipeline associated with the smallest possible asset base. These costs also go over all periods and products:

$$\text{Min } z = \sum_{s=1}^{k} [\text{Costs of labor, materials, holding inventory, and depreciation}] \qquad [7.2]$$

$$- \text{Weighted average cost of capital} * \sum_{s=1}^{k} [\text{Inventory asset value + Capacity investment}]$$

Brealey and Meyers[i] provide a detailed description of the weighted average cost of capital, the weighted average capital cost of raising funds by means of equity and debt, and methods to determine it. All costs included in equation 7.2, that are incurred at a production stage *s* are outlined in the terms 7.3 through 7.8. All assets are expressed in 7.2 are outlined in the terms 7.9 through 7.10.

1.) The costs of labor at stage *s* are incurred in form of fixed salaries for regular work hours and as overtime payments for overtime hours worked. i.e.:

$$\sum_{w=1}^{13} \sum_{p=1}^{P} \{lr * RT_{s,p,w} + lo * OT_{s,p,w}\} \qquad [7.3]$$

2.) Material costs at stage *s* are incurred for all input materials required for production of finished goods throughout the quarter: i.e.:

$$\left[\sum_{w=1}^{13} \sum_{p=1}^{P} X_{s,p,w,} * matl_{s-1,p,w}\right] \qquad [7.4]$$

3.) The costs of holding inventory include the costs of holding raw material inventory, work-in-process inventory, and finished goods inventory in the pipeline. i.e.:

Raw materials inventory holding costs at stage *s* are incurred as soon as a purchase has been booked $adv_{s,p}$ days in advance:

$$\left[\frac{r}{52\text{ weeks}}\right] * \left\{\sum_{w=1}^{13}\sum_{p=1}^{P} matl_{s-1,p,w} * X_{s,p,w} * adv_{s,p}\right\} \qquad [7.5]$$

Work-in-process inventory holding costs at stage *s* are assumed to be incurred throughout production and while waiting for production to start. At the start of production, the material value is assumed to increase from matl_{s-1} to matl_s :

$$\left[\frac{r}{52\text{ weeks}}\right] * \left\{\sum_{w=1}^{13}\sum_{p=1}^{P}\left[matl_{s,p,w} * X_{s,p,w} * \left(\text{prod}_{s,p} + \text{start}_s * \text{L}_{s,p}\right)\right]\right\} \qquad [7.6]$$

Finished Goods inventory holding costs at stage *s* are incurred only on a weekly basis, as finished can be maintained for one week based on the constraints:

$$\left[\frac{r}{52\text{ weeks}}\right] * \left\{\sum_{w=1}^{13}\sum_{p=1}^{P} matl_{s,p,w} * I_{s,p,w}\right\} \qquad [7.7]$$

4.) The computation of the depreciation costs for the manufacturing machines assumes a straight line depreciation over 10 years with 0 scrap value and a steady state cost rate for each machine:

$$\frac{1}{40\text{ Quarters}} * \left[\sum_{w=1}^{13} P_{s,w} * \text{cap}_s\right] \qquad [7.8]$$

4a.) Alternatively, the depreciation expenses can be determined based on usage:

$$\frac{\left[\sum_{w=1}^{13} P_{s,w} * \text{cap}_s\right]}{\text{life}_s} * \left[\sum_{p=1}^{P}\sum_{w=1}^{13} X_{s,p,w}\right] \qquad [7.9]$$

5.) The asset values of [7.2] are reflected in the capital expenditures for each period w and in the asset value of the average amount of finished goods and raw materials inventory present at the production stage:

$$\left[\sum_{w=1}^{13} P_{s,w} * cap_{s,w}\right] + \left[\frac{1}{13\text{ (Weeks)}} * \left\{\sum_{w=1}^{13}\sum_{p=1}^{P} I_{s,p,w} * matl_{s-1,p,w} + X_{s,p,w} * matl_{s,p,w}\right\}\right] \qquad [7.10]$$

Subject to: Connectivity constraints for each stage and general shop floor and budget constraints for all stages:

A general set of aggregate production planning constraints for one production stage is listed in Bitran and Hax.[ii] In addition to these constraints, this formulation introduces connectivity constraints for serially connected production stages. Finally, this formulation considers the fact that a production line purchasing budget might not be permitted to exceed some maximal level. The following constraints can therefore be listed:

Constraints [7.11] and [7.12] are connectivity constraints for serially connected production stages whereas constraints [7.13] through [7.16] are shop-floor constraints pertaining to each individual stage. Finally constraint [7.17] is a budget constraint that applies to all stages.

1. The percentage of demand for each product at the downstream stage that needs to be met in the current period can come from output manufactured by regularly scheduled and overtime labor and from inventory that was retained from the previous period less the inventory that is intended to be maintained in the current period:

$$\mathrm{m}_{s,p}\left[\mathrm{RT}_{s,p,w}+\mathrm{OT}_{s,p,w}\right]+\left[I_{s,p,w-1}-I_{s,p,w}\right]\geq fr_{s,p,w}\ *dem_{s,p,w}\quad \forall \text{ all s, p, w} \qquad [7.11]$$

2. The production of product *p* requires the upstream production of input part *r* at the supplier stage *s-1* in week *w-L*, where *L* is the lead time, in weeks, required by the supplier to produce part *r*.

$$\mathrm{m}_{s\text{-}1,r}\left[(\mathrm{RT}_{s\text{-}1,r,w\text{-}L}+\mathrm{OT}_{s\text{-}1,r,w\text{-}L}\right]+\left[I_{s-1,r,w}-I_{s-1,r,w-1}\right]\ =\ fr_{s-1,p,w}\ *\sum\nolimits_{p=1}^{P}h_{p\ r}\ \mathrm{m}_{s,p}\left[\mathrm{RT}_{p,w}+\ \mathrm{OT}_{p,w}\right]$$

$$\forall \text{ all s,w,p} \qquad [7.12]$$

3. At each stage and in each period, the total number of hours required by operations to start up production lines and to manufacture products cannot exceed the combination of regular work hours and overtime:

$$\sum\nolimits_{p=1}^{P}\left\{\left[\mathrm{start}_{w}*\mathrm{L}_{p,w}\right]+\left[\frac{\mathrm{X}_{p,w}}{\mathrm{m}_{p,w}}\right]\right\}\leq\sum\nolimits_{p=1}^{P}[\mathrm{RT}_{s,p,w}+\mathrm{OT}_{s,p,w}]\quad \forall \text{ all s,w} \qquad [7.13]$$

4. At each stage and in each period, the total amount of regularly scheduled labor hours cannot exceed the maximum available hours of regular labor at that stage in that period:

$$\sum\nolimits_{p=1}^{P}RT_{s,p,w}\ \leq\ \mathrm{rm}_{s,w}\quad \forall \text{ all s, w} \qquad [7.14]$$

5. At each stage and in each period, the total amount of labor hours scheduled for overtime cannot exceed the maximum available hours of overtime labor at that stage in that period:

$$\sum_{p=1}^{P} OT_{s,p,w} \leq \mathrm{om}_{s,w} \quad \forall \text{ all s, w} \qquad [7.15]$$

6. The inventory level of all products at each stage will be constrained by the storage capacity at that stage and by a minimal amount of safety stock that is maintained based long run operational policies.

$$\sum_{p=1}^{P} \mathrm{ss}_{s,p} \leq \sum_{p=1}^{P} \mathrm{I}_{s,p,w} \leq \sum_{p=1}^{P} \mathrm{os}_{s,p} \quad \forall \text{ all s, w} \qquad [7.16]$$

7. Finally, the total amount of capital expenditures for all production stages within a quarter of 13 weeks can be constrained to a specific quarterly budget *N*.

$$\sum_{s=1}^{k} \sum_{w=1}^{13} P_{s,w} \leq N \qquad [7.17]$$

The feasibility of an optimal residual income for a multiple stage system is based on the ability to find continuous and convex objective functions and constraints at each stage, if the objective function is separable at each production stage. Billington[iii] shows that a separable objective function is appropriate for multi product systems, when the set of all products within the pipeline are all part of the same material requirements planning system, but do not share the same pipeline production equipment.

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Appendix 4.2: Iterative procedure[i] to determine a near optimal reorder point and reorder quantity for equation 4.4 under a continuous review policy:

This procedure assumes a strictly convex total cost function and a normally distributed demand over the lead time.

Step 1: Determine the reorder quantity Q^* that minimizes the total logistics cost function in equation 4.4 by means of equation 4.5, assuming that there will be no shortage during the replenishment lead time, or: $\bar{a}(s) = 0$

Step 2: Determine the inverse cumulative probability of stocking out during the replenishment lead time given a reorder level s, $1\text{-}F(s)$, by means of

$$1 - F(s^*) = \frac{V\,W\,Q^*}{K\,\bar{D}} \qquad [8.1]$$

where:

V : per unit value of the commodity (\$/unit)	$\bar{D}$: expected annual demand rate (units/year)
K : per unit stock out cost (\$/unit)	W: per unit annual inventory carrying cost at the storage location (%)

with the shipment size Q from step 1. Next, derive s from $F(s)$.

Step 3: Calculate the expected shortage per cycle, $\bar{a}(s)$, for the reorder level s using a normal approximation of the demand:

$$\bar{a}(s) = \sigma_x\, L'\!\left(\frac{s - \bar{x}}{\sigma_x}\right) \qquad [8.2]$$

where:

$L'(u)$ is the unit normal linear loss integral and $\bar{x}$ is the average demand over the lead time

σ_x is the standard deviation of total demand over the (variable) lead time from equation 3.5:

$$\sigma_x = \sqrt{\bar{L}\,\mathrm{Var}(d) + \bar{d}^2\,\mathrm{Var}(L)} \qquad [8.3]$$

where L is the lead time (in terms of periods) and d is the demand rate, as defined in section 4.2.1.1.

$\bar{a}(s)$ can thus be determined from equations 8.1 and 8.2:

$$\bar{a}(s) = \sqrt{\bar{L}\,\mathrm{Var}(d) + \overline{d^2}\,\mathrm{Var}(L)} * L^{\cdot}\left(\frac{s - \overline{Ld}}{\sqrt{\bar{L}\,\mathrm{Var}(d) + \overline{d^2}\,\mathrm{Var}(L)}}\right) \qquad [8.4]$$

Step 4: Solve for Q given $\bar{a}(s)$ in equation 4.5.

Step 5: Test for convergence: if (Q, s) converge, go to step 6, else: go to step 2

Step 6: Obtain the optimal values (Q^*, s^*)

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Appendix 4.3: Heuristic to determine near optimal levels of inventory at an integrated manufacturing-inventory storage stage within the 5-Box model (Based on Cohen, Lee[i])

The following subscripts will be used throughout the model:

$j \equiv$ location of stage
$r \equiv$ raw material required to produce product
$m \equiv$ production line
$i \equiv$ finished goods
$k \equiv$ location of following production stage or distribution center

The two *demand distributions*, determined by the product pipeline interactions, are:

- $p_{rj}(n)$ = Pr(demand of material r at stage j over material lead time = n);
- $p_{ij}(n)$ = Pr(demand requests for finished good i at stage j from distribution centers during the average production lead time = n);

The "local" service requirements that need to be met are:

* $\overline{\beta_{rj}}$ = minimum fill rate for raw material r at stage j
* $\overline{\beta_{ij}}$ = minimum fill rate for finished good i at stage j
* $\overline{\beta_{ik}}$ = minimum fill rate for finished good i at distribution location k

DESCRIPTION OF INVENTORY STORAGE POINTS

A description of the equations used to determine the service levels, lead-times, and costs at each point within a manufacturing stage follows:

1. <u>Incoming goods dock</u>

At the incoming goods dock of each stage, the material used as production inputs is ordered by means of a continuous review (nQ, R) inventory control policy. This implies that when the inventory position of input part r at stage j drops to the reorder point R_{rj}, an order of nQ_{rj}, where n is a positive integer, will be placed. This ordering policy can be used to set a specific material availability, or service level, for each of the input materials. The incoming goods dock can therefore coincide with a point storing "raw material" within the 5-Box model

Key assumptions for incoming goods dock:

* For a given demand distribution for finished goods and bill of materials, it is possible to generate the input material requirements for production input r.
* A certain level of safety stock of input material is necessary to minimize production delays that are caused by random shortages.

- Both the demand for input materials and the time required to obtain input material from suppliers and sub-suppliers is random.
- The total manufacturing time at this stage is determined by the time required for set-up, material delay, and processing.
- A set of *I* finished goods require production input *r*

As mentioned the total costs of the raw material point will consist of ordering costs, inventory holding costs and the cost of material shortages:

$$TC^{M}_{rj} = \left[\frac{\sum_{i=1}^{I} u_{ri} X_{ij}}{Q_j}\right] C^{K}_{rj} + E(I_{rj}) C^{H}_{r} + E(B_{rj}) C^{B}_{rj} \qquad [9.1]$$

where:

X_{ij} = the mean production requirement of product *i* at stage *j* per period

$E(I_{rj})$ = Expected inventory levels of input material *r* for stage *j*

C_{rj}^{K} = Fixed cost of ordering material

C_{rj}^{B} = Backorder penalty cost

u_{ri} = Amount of input *r* consumed by finished good i

$E(B_{rj})$ = Expected backorder levels of input material *r* for stage *j*

C_{rj}^{H} = Unit holding cost per period

Q_j = Production batch size at stage *j*

The average time spent waiting for input material at each stage is determined by Little's formula:

$$T^{R}_{rj} = \frac{\text{Expected backorder level for material r at stage j}}{\text{Expected usage rate for material r at stage j}} = \frac{E(B_{rj})}{\sum_{i=1}^{I} u_{ri} X_{ij}} \qquad [9.2]$$

The total material delay time T^R for stage *j* producing the product with *r* input materials can be written as: $T_j^R = \sum_{r=1}^{R} T_{rj}^R$, where *R* is the set of input materials required for finished good *i*.

Based the ordering policy described above, the probability of stocking out of input *r* at stage *j* is given by:

$$(1 - \beta_{rj}) = \frac{\sum_{m=R_{rj}+1}^{R_{rj}+Q_{rj}} \sum_{n=m}^{\infty} p_{rj}(n)}{Q_{rj}} \qquad [9.3]$$

where the initial reorder level of input r at stage j is at R_{rj} and the optimal shipment quantity is Q_{rj}.

The service level for each input *r* at this point is therefore given by:

$$\beta_{rj} \geq \overline{\beta_{rj}} \qquad [9.4]$$

2. Production line

The production is scheduled as efficiently as possible by means of the optimal production lot size for the manufacturing of all finished products and for each production line. The production lot size is based on the trade-off between the cost of holding work-in-process inventory and the cost of production processing. This part is assumed to coincide with point storing "Work in Process" inventory.

Key assumptions for production lines:

- A parallel line batch manufacturing process.
- The lot size impacts the queuing time for each job

For each batch of good *i* processed at stage *j* with *M* production lines, the total production lead time T_{ij}^{L} is given by the weighted sum of setup times, processing times, and material delay times.

$$T_{ij}^{L} = \sum_{m=1}^{M} a_{ijm}\left(T_{ijm}^{K} + T_{jm}^{Q} + \frac{Q_{ij}}{P_{ijm}}\right) + T_{ij}^{R} \qquad [9.5]$$

where:

T_{ijm}^{K} = Set-up time for product *i* on line *m* at stage *j*
T_{ij}^{R} = Waiting time for inputs for *i* at stage *j*
P_{jm} = The work rate for the processing on line *m* at stage *j*

Q_{ij} = The production batch size for good *i* at stage *j*
T_{jm}^{Q} = Queuing time at line *m* at stage *j*
a_{ijm} = Amount of production of good *i* at stage *j* assigned to line *m*

The total costs of production of product *i* at stage *j*, TC_{ij}^{P}, are determined by the set-up costs, the product processing costs, and the inventory holding costs:

$$TC_{ij}^{P} = C_{ij}^{K}\frac{X_{ij}}{Q_{ij}} + C_{ij}^{P}X_{ij} + C_{ij}^{H}X_{ij}T_{ij}^{L} \qquad [9.6]$$

where:
C_{ij}^{P} = Processing costs for i at stage j per period
C_{ij}^{H} = Work-in-process holding costs for i at stage j per period

C_{ij}^{K} = Set-up costs for i at stage j per period

3. <u>Finished goods inventory</u>

After production, finished goods may be stored in a finished goods stockpile at each stage. These stockpiles can act as central distribution points and will be depleted as orders are received from the downstream stage or the distribution network. This part is assumed to contain all finished goods inventory of a production stage within the 5-box model.

Key assumptions for the finished goods inventory point:

- Replenishment is triggered by a (*Q*,*R*) inventory control system, where the order size *Q* and order trigger point *R* is equal to a production lot size. This means that the replenishment of the stockpile constitutes an order for production of a fixed batch size *Q*.
- The finished goods stock pile will be filled after the production lead time has elapsed.
- The lead time for the delivery of stock to the next downstream stage, a distribution point, or the final customer, depends on the transportation time from that production stage to the incoming goods dock of the downstream stage, of the distribution point, or of the customer. It also depends on the availability of inventory at the finished goods stock-pile, and on the production lead time.
- The amount of downstream demand for finished goods held at the stockpile that is not fulfilled, E_{ij}, will be produced and shipped out within the regular production and transportation lead times of that product.
- The lead-time provided at each stage *j* for product *i* to the next stage or distribution point *k*, T_{ijk}^{L}, is a Bernoulli random variable that depends on whether the stock pile for *i* is depleted or not.

The fill-rate that is maintained at the inventory stock pile of finished good *i* in stage *j* is β_{ij}. Given a continuous inventory review policy, the fill rate is determined from the quotient of the replenishment batch size and total orders for *i* at *j*:

$$\beta_{ij} = \frac{Q_{ij}}{Q_{ij} + E_{ij}} \qquad [9.7]$$

If the average replenishment transportation lead time T^{T}_{ijk} for finished goods of product *i* between stage *j* and a downstream stage incoming goods dock or distribution point *k* is measured in distribution review periods, then the expected replenishment lead time for *i* from *k* to *k* can be written as:

$$T^{L}_{ijk} = T^{T}_{ijk}\beta_{ij} + (T^{L}_{ij} + T^{T}_{ijk})(1-\beta_{ij}) \qquad [9.8]$$

where T^{L}_{ij} is the production lead time for each product at each production stage.

The total costs of the finished goods stock pile at stage *j* are determined by the holding costs incurred while warehousing the finished goods and shipping them to *K* downstream stages or distribution points. Thus, the average finished goods holding cost of product *i* tied up in transportation is given by Little's formula and the total finished goods stock pile costs TC^{FG} of product *i* at stage *j* can be written as:

$$TC^{FG}_{ij} = C^{H}_{ij}\left[I_{ij} + \frac{Q_{ij}}{2}\right] + \left[\sum_{k} C^{H}_{ijk}\,\mu_{ik}(B * T^{T}_{jk})\right] \qquad [9.9]$$

where:

μ_{ik} = The mean order quantity of product *i* per distribution review period from the distribution

B = The amount of distribution review periods contained in one production planning period.

center k.

C_{ij}^{H} = The unit holding cost per production planning period for finished goods of product i at stage j waiting at the finished goods stock pile

I_{ij} = The expected inventory level just before an order arrives

C_{ijk}^{H} = The unit holding cost per production planning period for finished goods of product i at stage j en route to distribution center k

Q_{ij} = The reorder amount of good i at stage j from the finished goods stock pile

The service constraint for the finished goods stockpile is:

$$\beta_{ij} \geq \overline{\beta_{ij}} \qquad [9.10]$$

4. Distribution Network

The distribution system generates stochastic demand for finished goods. This part of the model has been omitted as it is not required in order to determine inventory levels within a production stage of the 5-Box model. The key restriction that this stage imposes on the model is that the distribution point fill rates for each product $\overline{\beta_{ik}}$ are maintained: $\beta_{ik} \geq \overline{\beta_{ik}}$. These fill rates will translate into the demand that the finished goods assembly stage closest to the distribution network faces. A detailed description of a fitting distribution model along with the corresponding formulations for the cost is given in Cohen, Kleindorfer, and Lee[ii] and in Cohen et al[iii]. The paper of Cohen, Kleindorfer, and Lee also offers a comprehensive review of further literature on stochastic, multi-echelon distribution systems.

DETERMINATION OF OPERATING POLICIES:

Once the lead times and costs at all points have been determined, they can be entered into a heuristic to determine reasonably good operating policies for the various production stages. The heuristic finds approximately optimal lot sizes for both production and material re-supply such that the overall cost objective is optimized given the required fill rates.

Approximately optimal lot sizes can be found by searching for the economic production lot size. This done by finding the Q^{*} that minimizes the total production cost TC^{P}.

$$TC_{ij}^{P} = \frac{A_{ij}}{Q_{ij}} + B_{ij}Q_{ij} + C_{ij} \qquad [9.11]$$

where:

$$A_{ij} = C_{ij}^{K} X_{ij} \qquad [9.12]$$

$$B_{ij} = C_{ij}^{H} A_{ij} \sum_{m} \frac{a_{ijm}}{P_{ijm}} \qquad [9.13]$$

and

$$C_{ij} = \sum_m a_{ijm}(T^K_{iijm} + T^Q_{ijm}) + T^R_j + C^P_{ij} X_{ij} \qquad [9.14]$$

Differentiating with respect to Q_{ij} and setting the result equal to zero. Leads to a solution Q^* that minimizes TC^P for each i at each j. It is defined by:

$$Q^*_{ij} = \sqrt{\frac{A_{ij}}{B_{ij}}} \qquad [9.16]$$

Using the optimal value for the production point problem, it is possible to find a nearly optimal solution to the incoming goods dock subproblem by determining the EOQ at each stage for each input part *r:*

$$EOQ_{rj} = \sqrt{\frac{2\lambda_{rj} m_{rj}\left(C^K_{rj} + C^B_{rj}\right)}{C^H_{rj}}} \qquad [9.17]$$

where λ_{rj} is the mean rate of usage of input material r at stage j and m_{rj} is the mean quantity demanded with each request for r at j.

Next, the EOQ values for each input part r are multiplied by some positive integer n such that they approximate the value of Q_{ij}^* as close as possible, (i.e. $n * \mathrm{EOQ}_{rj} \approx Q_{ij}^*$). Using this EOQ value, the minimal reorder point for the incoming goods, R_{rj}, is set such that it still satisfies the service constraint $\overline{\beta_{rj}}$. This value is then increased iteratively up to the point at which the total incoming goods dock costs TC_{rj}^M are minimized.

Finally, the reorder point for the finished goods stockpile, i.e. the trigger point for production, R_{ij} needs to be determined. This can done by means of results from Cohen et al.[iv] who prove that the service level β_{ij} is increasing in R_{ij}. Thus an approximate solution can simply be found in the smallest possible value R_{rj} that satisfies the fill rate constraint $\overline{\beta_{ij}}$.

As mentioned, the costs of the distribution network can be determined and optimized independently subject to the finished goods stock pile file rate constraint.

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