Two Approaches To Buffer Management Under Demand Uncertainty: An Analytical Process

by

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B.S. Economics
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Submitted to the Engineering Systems Division
In Partial Fulfillment of the Requirements for the Degree of

Master of Engineering in Logistics

at the

Massachusetts Institute of Technology

June 2004

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ABSTRACT

Based on a particular case study, this paper presents two approaches to buffer management under demand uncertainty, which is characterized by high lumpiness, dispersion and volatility. The common theme of both of the two approaches is not to find an advanced statistical method to improve demand forecast on the basis of historical data. Rather, these approaches provide new business paradigms to deal with demand uncertainty.

The first approach, make-to-anticipated-order (MTAO), takes advantage of the mechanism of make-to-order (MTO) and develops a process that the production is pulled by anticipated orders instead of being pushed by the forecast of unpredictable future demand. The implementation of this method, on one hand, breaks through the precondition of MTO that the total production cycle time should be less than customers' desired lead-time. On the other hand, MTAO enjoys the advantage of arranging production by responding to customer demand to reduce inventory costs and obsolescence risks of MPS level items.

The second approach makes use of postponement and commonality strategy to lower demand uncertainty. The basic principle is that aggregate demand is more stable than disaggregate demand. Thus, if a common module instead of various individual modules in a module family acts as a MPS item, the demand of the common module will represent the aggregate demand of all individual modules in the module family and more accurate forecast can be made. Then by using the forecasted demand distribution of the common module, we can figure out optimized multistage inventory placement to buffer demand uncertainty with the minimum holding cost of total safety stock. In effect, by implementing postponement and commonality strategy, we change the push-pull boundary and leave more demand uncertainty to the pull part of the system.

Thesis Supervisor: Christopher Caplice

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To my dad

Table of Contents

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Acknowledgments

I would like to offer special thanks to my dear wife, Shan, my dad and my mom, for their support and patience during my studies at MIT. Without them I would not be able to accomplish so difficult goal.

I want to thank J.R. Pulido and Ken Xie, who helped me polish the writing of my thesis. I also want to thank Ee Learn Tay who gave me good advices on the thesis project.

I would like to thank my advisor Dr. Caplice for his insightful comments, patience and encouragement.

Finally, I must express my thanks to Ping Wang, who helped me enter into the challenging research field—supply chain management.

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1. Introduction

1.1. Project background

Today's telecommunication equipment market is increasingly dynamic and volatile. Accelerating changes in technology, customer preference and economic cycle are changing the market in two aspects: 1) the straightforward—the effect of product obsolescence, difficulty in meeting customers' personalized requirement in short lead time, shutting down local production and switching to outsourcing; 2) the far-reaching—the effect of regrouping the whole industry that can be caused by profound innovation of information technology or prevailing changes of consumer behavior. These changes challenge traditional operation and control based upon stable supply and demand analysis, whereas nowadays demand is characterized by high uncertainty and volatility. Based on a particular case study of a supplier in the telecommunication equipment market, this paper provides two approaches to buffer management under demand uncertainty and evaluates subsequent improvements in terms of cost effectiveness and service level through a series of analyses on demand characteristics, operation process and buffer policy.

1.2 Environment introduction

1.2.1 Product introduction

WIDGET X, a general name of an optical product line in the telecommunication equipment company (the Telecom), represents various finished products. These products have different features and functions in terms of different combinations and configurations of 305 sub-assembly modules from 6 distinct module families. As to final assemblies or finished products, theoretically, the number of combinations is huge. For example, with 95 choices in the module family of circuit pack and 105 choices in the module family of optics, there can be 9975 (95*105) possible combinations of final assemblies. On the side of demand, the customer requirements from the international market and from domestic market are highly diverse. In 2002, more than 500 final assemblies of WIDGET X were ordered by worldwide customers. WIDGET X falls into the category of mass customization product lines.

1.2.2 Production lead-time and desired delivery time

Typically, after orders are placed, the desired delivery time of finished products range from 10 days to 4 weeks with the average time of 3 weeks. To execute deliveries, the Telecom has three production phases. The first phase produces basic components by appointed tier 2 supplier with lead times from 8 to 12 weeks. The second phase produces the modules of all module families by tier 1 supplier with lead times from 3 to 5 weeks. The final phase involves assembly and testing in the Telecom with lead-time of 1 week. (Figure 1)

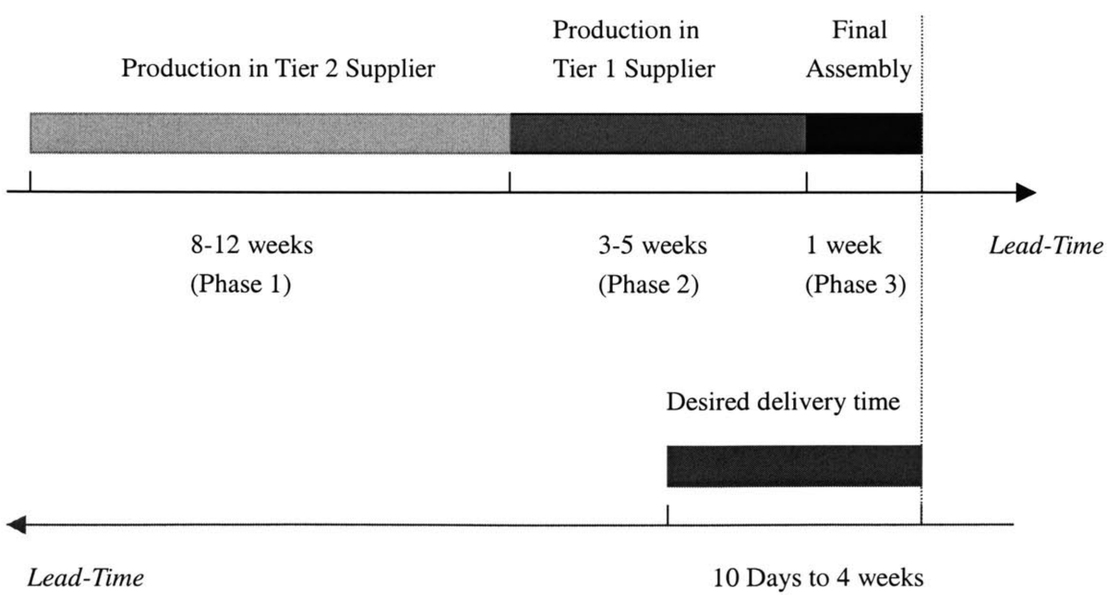

Figure 1: Lead Time Framework

1.2.3. Demand characteristics

In the Telecom, since the lead-time of final assembly and testing is 1 week and falls into the scope of desired delivery time, the final assembly and testing of finished assemblies is triggered by actual orders. The products in the bill of manufacturing (BOM) are therefore modules not finished assemblies. Namely, we can view modules as "final products" in this case. Moreover, suppose demand equals sales (with no lost sales), we can roughly view sales data as demand information. According to statistical analysis, we find that there are two prominent demand characteristics in historical data. First, as shown in Figure 2, the demand of modules is scattered and sporadic. Approximately half of the modules have annual demand less than 10 while only 14% of the modules have annual demand over 65. Furthermore, the dispersion directly results in demand discontinuity. For example, some modules have demand in a time window of few months to one month. Therefore, the demands are not regular. Second, the demand is volatile. In terms of monthly demand (Figure 3), we find that the coefficient of variation (CV) for more than 99% of the individual modules are bigger than 1 and extremely high.

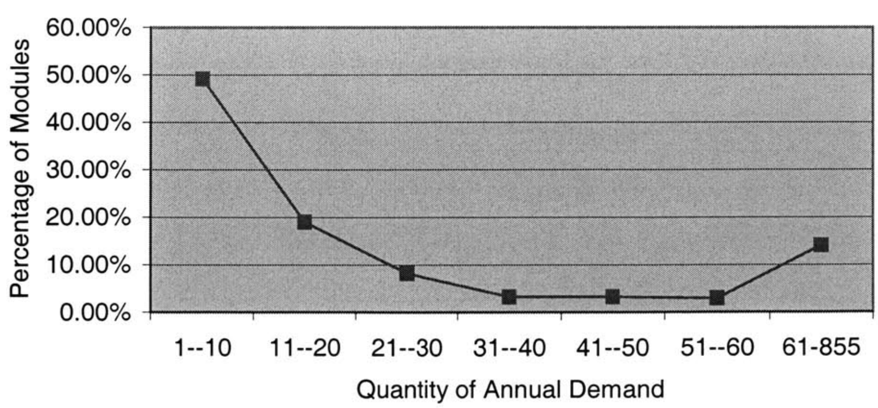

Figure 2: Distribution of Annual Demand

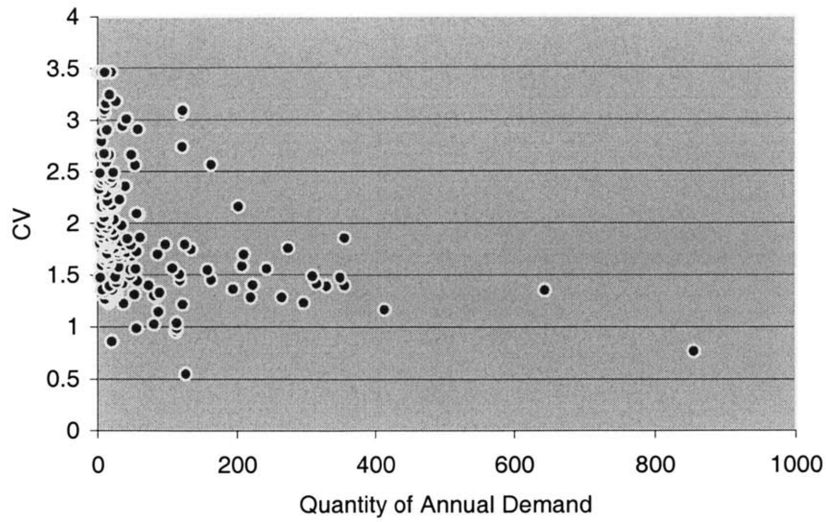

Figure 3: Distribution of CV & Quantity of annual demand of individual modules

1.2.4. Current buffer policy

Currently, the Telecom buffers demand uncertainty by means of safety stock--a mix of modules and basic components in both suppliers' warehouses and the Telecom's assembly plant. Method of equal time supplies is being employed and the safety stocks of all materials are set equal to the same time supply. In other words, all 305 modules have safety stock set to the same number of periods of supply, say, 3 months and the length of the time period is empirically decided. A module is reordered when its inventory position drops to 3 months of supply during a periodic review.

Under this buffer management, all too often, the Telecom finds itself in an awkward situation: On the one hand, if it holds too many inventory of some modules without demand or with low demand for a long period, the inventory will lead to high holding cost and high risk of obsolescence. On the other hand, the safety stock of more popular modules is not sufficient to meet customer demands. Insufficient inventory leads to lost sales, penalty costs for backorders and low service levels. With the inherent high cost and time risk of most modules, one must manage demand uncertainty through better buffer management to optimize inventory placement, and to increase service level and customer satisfaction as well.

1.2.5. Framework of production decision making

To illustrate the particular environment of the Telecom, I depict the process of production decision making in the Telecom in Figure 4. Some basic but important stages are introduced and analyzed in details to provide necessary understandings in the case of reengineering the processes under different buffer management schemes. We begin with decision hierarchies first to unfold the analysis of decision making.

Anthony (1965) provides a framework to identify a hierarchy of interconnected decisions. The hierarchy has evolved to become strategic planning, tactical planning and operational control.

Strategic planning, with long-range scope influence, is a key responsibility of senior management. Strategic decisions should be implemented consistently and uniformly in all functional areas of the organization. Except for long-term strategies on network design, product development, technology innovation etc., the Telecom employs postponement as its basic production strategy. By postponing the differentiation and customization of the finished product as long as possible in the manufacturing process, the Telecom can avoid maintaining a full-line inventory of finished assemblies, as well as meet various customer demands. Furthermore, to ensure effectiveness of postponement implementation, the company adopts modularity in the product design. Thus it only takes less than one week to assemble modules into required finished products. As noted earlier, we can treat the modules for final assembly as finished products in this environment. Nevertheless, with 305 different modules and a high variation in demand, the current buffer policies are still hard to manage and to control demand uncertainty effectively. In addition, due to physical differences among individual modules, commonality of basic components is relatively low, therefore upstream manufacturers cannot use risk pooling effect to reduce downstream demand volatility.

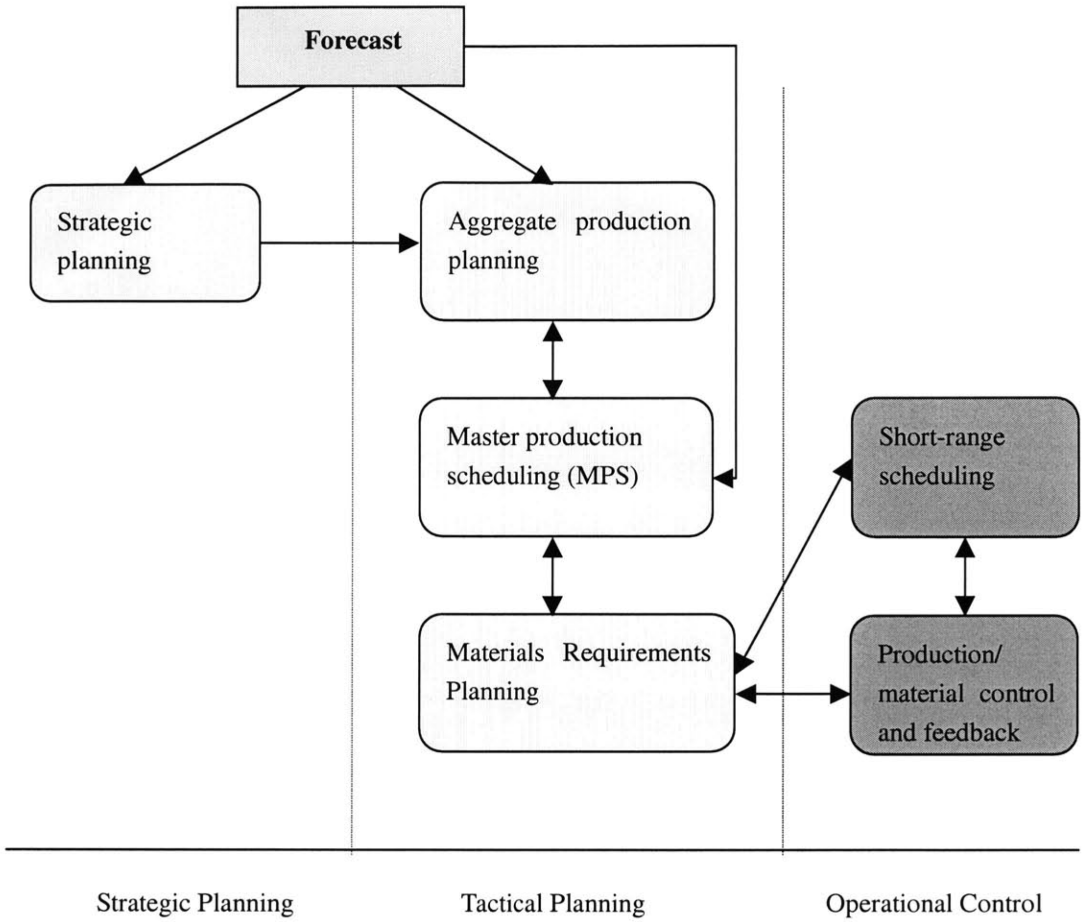

Figure 4: Production Decision Making Framework

Tactical planning that involves both middle and top management is a medium range activity concerned with the proper and effective use of existing resources to add more value within a given market situation. Specifically, with the planning horizon of 12 months in the Telecom, tactical planning decides such problems as the amount of inventory, the size of workforce, transportation mode and so on. Moreover, as shown in Figure 4, there are three blocks: aggregate planning, master production scheduling, and materials requirements planning, in the tactical level and each with different functions and mechanisms in the decision making process.

Aggregate planning is concerned with determining the production rate, workforce size and inventory levels in such way that fluctuations in demand are economically satisfied. With its planning horizon of 12 months into the future, the time block is one month, and the planning is done on an aggregate basis for product families—that is, not on an individual module basis but on a module family basis in this case. Compared to irregular and lumpy demand of individual modules, the six module families have more stable demand trajectory. For example (Figure 5), the module family of optics has 105 different individual modules and each of them has a CV from 1.3 to 3.5 while the CV of the optics family is only 0.75, much lower than that of any individual modules. Consequently, it is easier and more accurate to forecast demand in terms of module family than individual modules. This observation coincides with the principle that aggregate forecasts are more accurate.

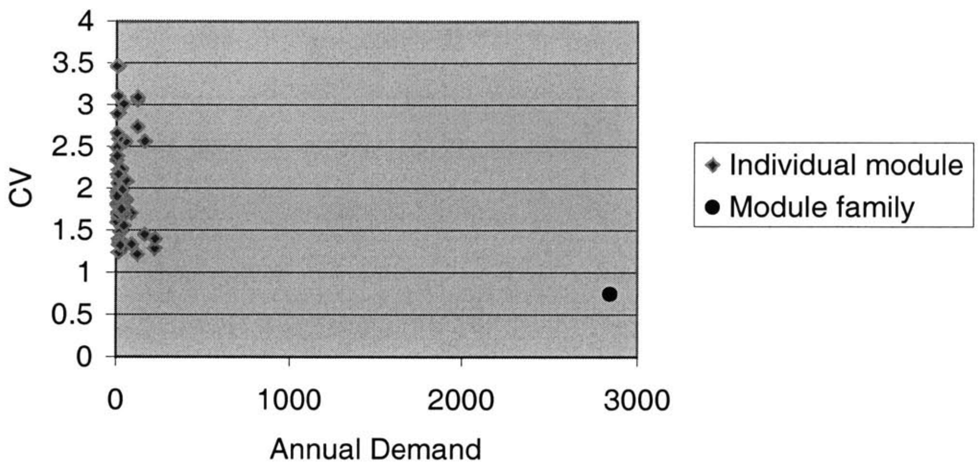

Figure 5: Distribution of
CV & Annual Demand of individual modules and module family

In the introduction of aggregate planning, we mentioned an important time concept- planning horizon, which directly decides the scope of planning in terms of time. More specifically, planning horizon is the time period on how far into the future to use demand forecast or some other information in making the current decisions. Suppose the future demand can be forecast accurately or the demand is constant, it makes no difference between the long horizon and the short horizon. However, real demand is stochastic and is hard to predict accurately, so the planning time period cannot be too long because a forecast is always wrong and the longer the forecast horizon the worse the forecast. Nevertheless, as a rule of thumb, the planning horizon should be at least longer than the total production cycle of planning products. Next, to control future uncertainties, a mechanism of rolling horizons is implemented at the Telecom. Namely, with the planning horizon of 12 months, only the results of aggregate production plan of the first month are actually implemented. Then, at the end of the month, a new rolling horizon for the next month is used to establish new results, and so on. This arrangement is critical to keep production flexible and adaptive to the constant change of real demand, and as a result it reduces forecast errors.

MPS, master production scheduling, is derived from demand forecast and aggregate production plan. It disaggregates the aggregate production plan into a production schedule of individual modules, and determines how many and when to produce or outsource. It acts as a primary interface between forecast and production, and drives the consequent operations, such as production, assembly, etc.. At the Telecom, the actual production or outsourcing of final modules are based on MPS, so we also call these modules MPS level items.

Since the other blocks in Figure 4, including materials requirements, short-range scheduling and production/ material control and feedback, are beyond the discussion scope of this paper, the mechanisms of these controls won't be discussed in the context.

2. Approaches to buffer demand uncertainty

Numerous authors have argued that the use of inventory (safety stock), lead time (safety time), excess capacity or other leverages can be used to buffer a process from external uncertainty. The appropriate method depends on the specific characteristics of demand itself.

2.1. Analysis of demand uncertainty

2.1.1. Demand attributes

We conclude that the demand for WIGET X in terms of individual modules has 3 outstanding attributes: lumpiness, dispersion and volatility.

1. Lumpiness: 28 of total 305 modules only have one order within a year and the average annual demand is 40. The coefficient of variations (CV) of almost all modules range from 1.3-3.5 and, the bigger the CV, the greater the differences between each period's demand and the greater the number of periods with zero demand (Figure 5).

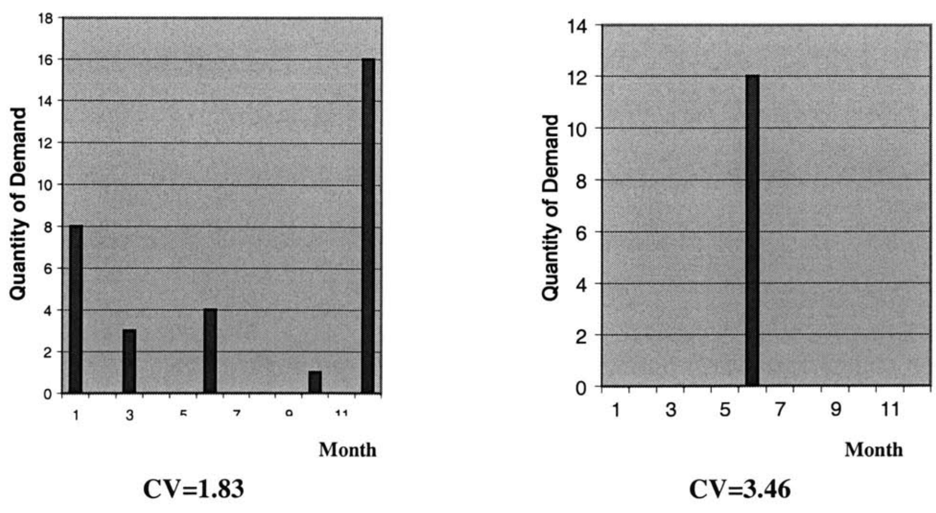

Figure 5: CV & Quantity of demand

2. Dispersion: The demand for most modules is dispersed and displays no obvious correlation between different modules. Rather, a surge of demand for a particular module seems to be singular with no relation to others.
3. Volatility: It is frequent to find in the sales data for a certain material that a period of high demand was followed by a quite long period of zero demand or low demand. As shown in Figure 6, an increase tendency of a certain demand could end at anytime and change to zero demand in the next period, or persistent low demand can quickly switch to extremely high demand. In other words, customer interests seem to change quickly and cannot be predicted with accuracy according to historical analysis.

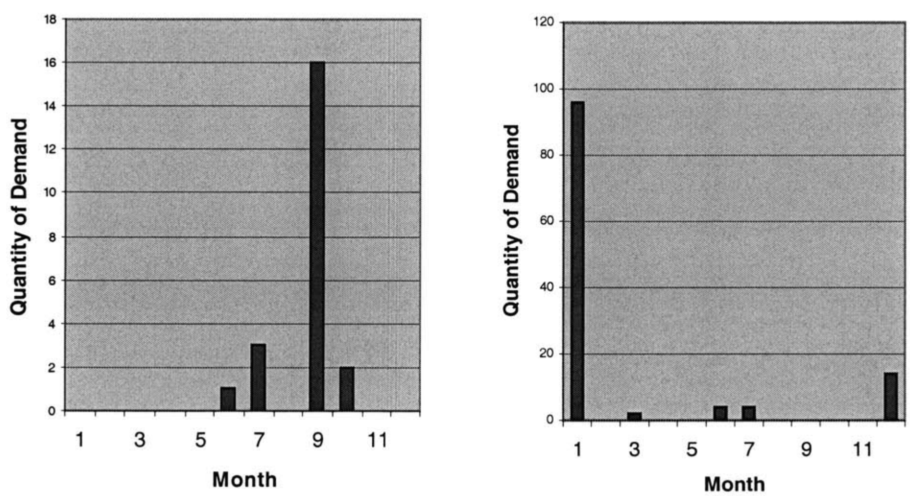

Figure 6: Discreteness of Demand

2.1.2. Main reasons to demand uncertainty

As far as the aforementioned attributes are concerned, the demand is extremely unstable. This is due to personalization, complex purchasing decision processes and other miscellaneous factors. These analyses can help to find the proper buffer management to cope with such demand uncertainties.

1. Personalization: Since the telecommunication equipment market has evolved

to mass customization stage, vendors not only need to meet their customers' basic demand in terms of functions and features, but also offer personalized service to meet customers' preference in order to improve market competence. However, personalization is closely related to diversity, dynamics, and low demand density. Therefore existing discrepancies of personalized demand among different customers and transformation of personalization itself make the demand more random and unpredictable than ever.

2. Complex purchasing decision processes: Many reasons, such as system expansion, system updating, adding service functions and so on, may lead to actual purchase of WIDGET X. Moreover, some other indirect and non-technological factors sometimes play important roles in deciding orders. For example, customers may order more products when they have abundant budget on hand or order a zero or fewer products when their budget is tight. These various complex causes during the purchasing decision process worsen the demand uncertainties both in quantity and in time.
3. Miscellaneous factors: The Telecom has various customers in different industries and with different system standards. These different customers may bring multiform uncertainties to orders. For example, if old customers want to add more functions and features in their purchased systems, they often ask for a short delivery and skip many technical negotiations. The new customers, especially in foreign market, might go through a complex decision making and negotiation process before placing orders so, the desired lead-time is relatively long. However, it might remain shorter than the total production cycle time. Almost all the MPS level items and modules have different demand requirements when they are supplied to different types of customers. The complexity of demand requirement and market diversity therefore contributes to the uncertainty of demand.

2.2. Literature review

2.2.1. Buffer policy based on forecasted demand distribution

There is a large literature dealing the demand uncertainty. C.J. Ho (1995) and Bobko and Whybark (1985) suggest CV as a robust measurement of demand variations and examine the impact of various degrees of demand lumpiness on the system performance of MRP systems. However, they focus on the optimization of lot-sizing on the MRP level based on the premise that the quantity of MPS level items have been decided, and do not concern themselves with the aspect on how to determine the size of MPS level items in the case of stochastic demand. Some operation researchers, by using dynamic equilibrium models or case studies, have combined flexibility and buffer management to cope with uncertainty. Specifically, Newman et al. (1993) argue that companies might be using buffers such as inventory (safety stock), lead time (safety time), and excess capacity to compensate for an imbalance between flexibility and the level of uncertainty in the environment. In addition, Buzacott and Shanthikumar (1994) compare the performance of all the leverages and suggest that safety time is preferable to safety stock if there is a good forecast of future required shipments, or either safety stock or safety time could be used if all that can be predicted is the mean demand. Regarding the viewpoint that safety stock acts as a buffer for uncertainty in the MPS level, Metters (1998) gives three different strategies. First, a new order is triggered only when there is a real stock-out. Second, an implicit approach triggers a new order whenever an inventory falls down to the safety stock level. The third approach is to use stable safety policy. Furthermore, Tang and Grubbström (2002) provide a quantitative analysis on planning and re-planning MPS under stochastic demand to achieve high service level and favorable inventory situation. In addition to buffer policies in terms of inventory, lead-time and capacity, Kneppelt (1984) proposes another method, option overplanning, which creates buffer by increasing the safety factor of sub-assemblies and components in the planning bill of materials.

Nevertheless, the above-mentioned buffer methods are based on a basic assumption that demand uncertainty can be scoped in a forecasted demand distribution. For example, several authors assume that the future demand is normally distributed and the demand boundary is bounded by mean and standard deviation derived from historical data. In other words, it's assumed that future demand can be deducted through historical data such as via time series methods, or by taking account of some other factors such as seasonality and product life cycle. The predetermined future demand will be input to models to get final solutions.

From another point of view, some authors view the demand uncertainty as chaotic, stochastic and disorderly behavior. Proposed by Kaplan and Glass (1995) and Abarbanel (1996), chaos is termed as aperiodic, bounded dynamics in a deterministic system with sensitivity dependence on initial conditions, and has structure in phase space. Generated by fixed rules that in themselves involve no element of chance, chaos is deterministic. This statement can be easily understood, for example, we always make sense of the reasons and correlations of an accident after it happened. So, although a chaotic behavior can be predicable theoretically, the non-linear relations of many causes make the behavior less predictable or unpredictable in reality. Furthermore, because of the unknown non-linear relationship of internal and external variables, historical data shows very weak ability to predict the future change, and demand patterns cannot be easily observed. The forecast error therefore is always huge. The lumpy demand in terms of individual modules is exactly the case that forecast cannot rely on historical data. Consequently, methodologies based on such historical data analysis will not be a good choice.

2.2.2. Two thoughts on buffer management

Two thoughts are derived from the arguments for buffer management. First, to deal with irregular, chaotic and unpredictable demand, solutions, which can make the production planning respond to customers' real demand, are more advisable, such as make to order (MTO). Second, from another point of view, we can use buffer policies that utilize forecasted demand distribution to buffer uncertainty if the demand of the MPS level item is relatively stable and predictable. This goal can be achieved if we turn to forecasting the demand of module families and view module families as MPS level items to arrange production plans, because the aggregate demand of a module family is stable and has lower CV (Figure 5). Hence, it can be forecasted more accurately. Therefore, based on the two thoughts, I provide two strategic approaches to deal with the demand uncertainty under the specific environment: one is to use responsive strategy to trace demand rather than to forecast demand to arrange production planning when MPS level items are individual modules. The other method is to use postponement strategy to turn module families into MPS level items by postponing the customization of individual modules in the same family until the point the actual order is received. Meanwhile, this method can also be understood as shifting the pull-push boundary in the Telecom from the assembly level to the module family level. In the following chapters, the two approaches are discussed in depth separately.

3. Managing demand uncertainty through make-to-anticipated-order (MTAO)

3.1. Buffer policy aimed at being responsive to uncertain demand

Lee (2002) argues that to be responsive, companies use make-to-order and mass customization processes as means to meet the specific requirements of customers. In the make-to-order system (MTO), production is demand driven so that it is coordinated with actual demand rather than forecasted demand. Moreover, under no production constraints and no lot-sizing requirements, a company needs no buffers, such as inventory or excess capacity, to cope with uncertainty, and just responds to acquired orders and arranges production plan as per the fluctuation of real demand. The variance of production level is the same as the variance of total demands. On the other side, make-to-stock (MTS), which utilizes the forecasts of demand, becomes less effective both in buffer cost and service level for forecast errors.

Much literature has introduced popular management systems on the basis of MTO, such as quick-response programs, just-in-time (JIT) production systems, kanban related inventory management, lean manufacturing and so on. In particular, Fisher et al (1994) provide "accurate response" as a meaningful control method to those companies whose demand is highly volatile and has high seasonality, such as fashion apparel companies, to improve forecasts and redesign planning process by taking account of lost sales and distinguishing predictable and unpredictable demand. It is an advisable method to manage seasonal demand and capacity restriction in some industries, however it's difficult to manage lumpy demand because the reasons that cause the lumpiness are obscure.

Although to manage demand uncertainty of lumpy products, the MTO method is better than MTS, the premise of execution of MTO strategy is that customers are willing to wait for a delivery lead-time that exceeds the manufacturer's total production cycle time, or the total lead time (TLT). The TLT in Telecom (Figure 1), however, is much longer than customers' desired lead-time, which theoretically impedes the application of MTO at the Telecom. An alternative method is to get familiar with the customers' purchasing procedures, to take advantage of customers' early purchasing information and signals to anticipate potential orders. Production decision can be made according to the anticipated orders TLT+1 time in advance of the expected due date. This uncertainty management method is called make-to-anticipated-order (MTAO) or order overplanning, which was proposed and studied by Bartezzaghi and Verganti (1995), Verganti (1997) and Zotteri and Verganti (2001).

Compared to actual orders in MTO, the orders in MTAO are estimated and forecasted by customer service unit (the service unit), which could be sales department, marketing department or a combined trans-functional unit in a manufacturer. The service unit should actively contact their customers to get early purchasing information, collect announcements and estimate the possibility of actual orders based on the information. Accordingly, more attention will be focused on orders from each individual customer and then decouple the orders into MPS level modules to organize production. Since in MTAO, anticipated orders, other than actual orders, are managed, a coherent set of operation processes has to be established to reduce inner uncertainties and improve implementation effectiveness.

3.2. Technique and control of make-to-anticipated-order (MTAO)

MTAO contains a coherent and specialized set of techniques and organizational collaborations. Based on a case study of an Italian telecommunication vendor proposed by Bartezzaghi and Verganti (1995), we can divide the analysis of MTAO into 3 main parts by referring to the process of production decision making (Figure 4). The first part, forecast and planning management, illustrates how to forecast and control orders; the second part, MPS control under uncertainty, deals with MPS changes on rolling horizon basis; the third part, redundant orders and unexpected orders management, focuses on slack and unexpected demand control.

Moreover, causal loops in terms of systems dynamics are presented to help illustrate the process and logic of the three parts in MTAO.

3.2.1. Forecast and planning management

In the forecast procedure, the service unit has to collect as many purchasing signals or information as early as possible from its customers. Unlike other forecast technologies that focus on consolidating demands of all customers in a certain time period, forecasts in MTAO pay attention to those customers who have expressed their purchasing interests or whose purchasing intents have been detected. If we count the processing time that customers prepare for their final decisions into the purchasing process, the new situation can be described as per Figure 8, where the total time of placing an order always be longer than TLT and make MTAO possible. Regarding the Telecom, since WIDGET X is technology intensive and relatively expensive as well, customers often need a long time period for inquiry, consultation, comparison and discussion before confirming orders. In general, early purchasing information may directly come from the customer side, such as inquiry calls, while sometimes the information can be collected by the service unit, perhaps during the regular visits to customers or through analyzing public news. After getting early purchasing signals, the service unit should make closer connections with potential buyers and try to learn more customer about intentions to answer the following questions:

- What product does the customer want to order?
- Shall the anticipated orders turn into actual orders eventually?
- When is the due date?
- What's the final configuration of the order?

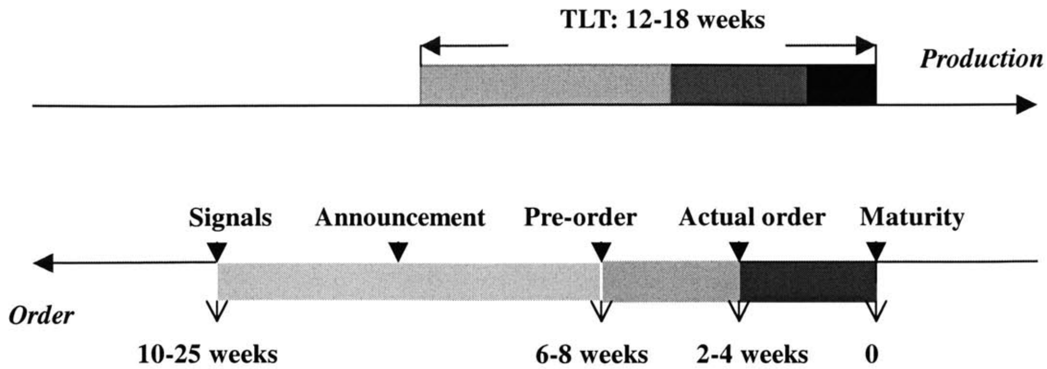

Figure 8: Lead time comparison between production and order

Also, these four questions are the main uncertainties of anticipated orders. The service unit, therefore, should make use of various opportunities to gather customers' purchasing information to reduce the uncertainties and to increase accuracy of anticipated orders. There are four steps to deal with these uncertainties:

In the first step, based on preliminary purchasing signals and interactive communication, the service unit decides whether WIDGET X can meet the customers' demand, and figures out the customers' fundamental requirements in terms of features and functions. If the demand is beyond the scope of the functionality of WIDGET X, the service unit may switch emphasis of information collection from the customer.

In the second step, the service unit analyzes the Telecom's competitiveness in the market, as well as customers' attitudes and preferences to its products to perceive whether the Telecom can get the order. This procedure, however, is extremely complex for final decision for an order is not simply made by one or two apparent reasons. Rather than use the objective analysis, the service unit should get familiar with the customers' purchasing customs and understand their corporate culture to enhance the acuteness of perception. All too often, many seemingly irrational or uncorrelated matters will eventually lead to actual purchasing decisions, such as budget issues noted earlier. On the other hand, announcement of biding or shortlists, and pre-order declarations released by customers in the early and middle stages of the purchasing process can help the service unit to further evaluate the opportunity and probability of acquisitions. Therefore, the service unit should combine the information of objective analysis and announcements to improve its anticipated forecast.

Next, to forecast expected due date of an anticipated order more precisely, the service unit needs more communication with customers. The tactics of how to get useful information are the same as in the second step.

In the fourth step, for various reasons, such as installation requirement or geographic differences, the finalized configuration cannot be known exactly until the actual order is received. The uncertainty of different configurations can be handled by adding more possible configurations into the anticipated order, so as to satisfy multiple orders that may be actually received. Usually, the service unit can take advantage of the demand continuity and repetitiveness of a certain customer to decide planned configurations. Moreover, with updated information, those configurations proved to be redundant will become buffers in the system.

Besides dealing with uncertainties in forecast, another important issue in the procedure is to decide how to use the forecast information to make a final decision on anticipated orders. Zotteri and Verganti (2001) provide two methods for choice. One is a decentralized approach, in which the information of anticipated orders by each service unit will be incorporated into production planning. The other is a centralized approach, in which the planning unit will aggregate the information supplied by each service unit and decide the final anticipated orders. The authors also propose that in the centralized approach, due to the split of forecasting and planning responsibility, the service units provide probabilistic estimate of future orders from individual customers, while the planning unit integrates these forecasts at the group level to determine which orders to produce. To give a generic comparison of the two approaches, the authors develope a Bayesian-Markovian model to evaluate their performances. They find that the centralized approach exceeds the decentralized approach in terms of service level and redundant inventory level. However, the advantage of the decentralized method comes from organizational management, because this method is based on clear, specific forecasting and planning of each single customer.

With respect to the Telecom, a centralized approach is recommended for two reasons. First, since trans-functional collaboration in the Telecom as a new corporation paradigm is ongoing, the organizational impediments among different units are reduced. Second, the service unit forecasts orders on an individual customer basis which lacks a comprehensive vision of the overall market requirements. The planning unit can consolidate the probabilistic anticipation from each service unit and make an aggregate forecast to improve the accuracy of anticipated orders.

Finally, to better understand the causal relationship in the forecast and planning procedure, we make use of causal loop, B1, (Figure9) in terms of system dynamics to demonstrate the logic of the process. The service unit is encouraged to contact customers, especially those who are planning to place orders. However, the less the service unit contacts these customers, the less early purchasing information and signals it can get and make use of, thus the accuracy of anticipated orders decreases and the forecast errors increase. The uncertainty of anticipated orders therefore increases and operation performance becomes worse. Bad operation performance, on the other hand, can stimulate and motivate the service unit to get closer with its customers to collect more useful information and do further communication in order to improve forecast quality and reduce forecast errors, thus to improve the operation performance. This structure is a balancing loop, which means the system can reach to an equilibrium condition finally if all the causal relationship works. Moreover, there are two key nodes in the process: one is getting information to make forecast; the other is getting more information to improve forecast. Both concern the operation of the service unit. Therefore, the role of the service unit should be clearly positioned and new managerial rules, such as compensation and promotion related to performance, are to be built accordingly to leverage the service unit's operation under the new environment. Apparently, forecast in MTAO is not a result of computation based on historical data, but it is instead a new managerial process. In addition, since the service unit only takes measures against uncertainties of order acquisition and configuration within a single anticipated order, the buffer to the uncertainty of the whole demand is not explicitly known. The Telecom needs to adjust redundant modules orders in the MPS procedure.

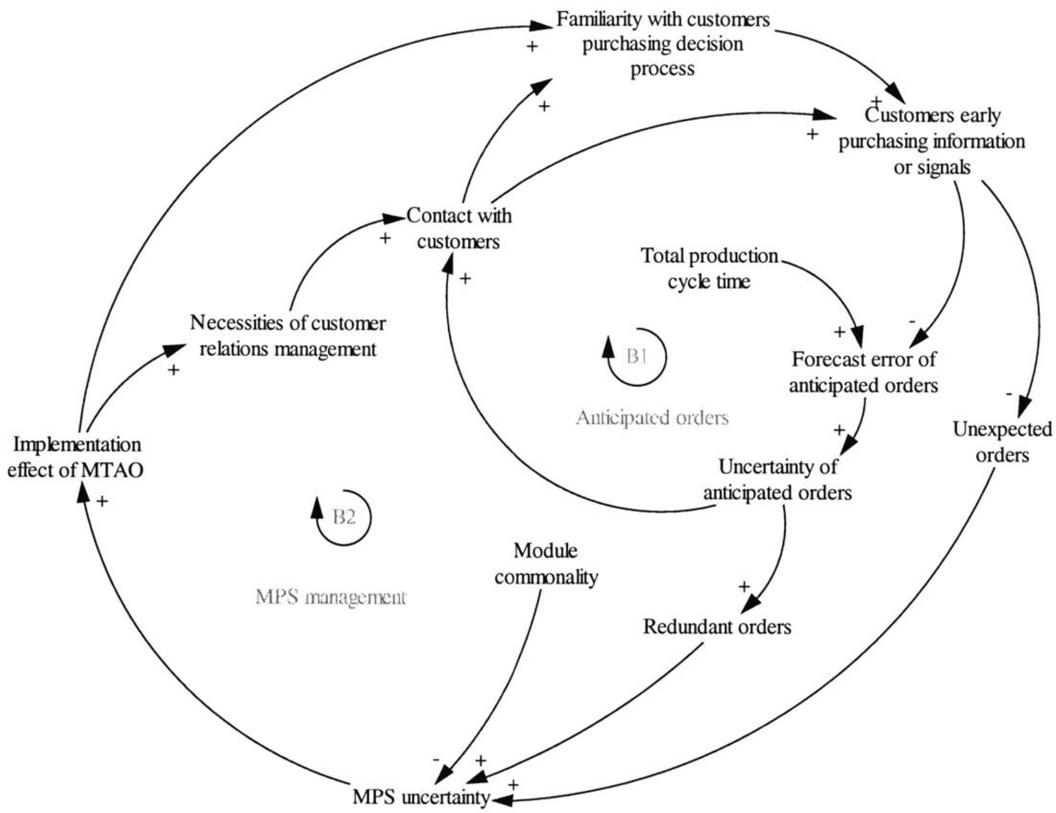

Figure 9: Logic and process of MTAO in terms of System Dynamics

3.2.2. Strategic master production scheduling (MPS) management

Since anticipated orders are not real, they have many uncertainties before turning into actual orders, such as order acquisition, due date, configuration and so on. On the other hand, to match the demand of anticipated orders, production according to anticipated orders will be started TLT+1 time periods in advance of the expected due date. As time approaches the due date, various uncertainties will be eliminated progressively by more explicit purchasing information announced by customers (Figure 8) or collected by the service unit. With the elimination of order uncertainties, the master production scheduling (MPS) is to be adjusted according to requirement of actual orders. There are two steps to illustrate the mechanism of the procedure.

1. If anticipated orders and over planned configurations are confirmed to produce, they will be decoupled to MPS level items, such as individual modules, and the production plan of these items will be shown in the MPS. When these orders and configurations are eliminated for some reasons, the production plan of these modules will be removed from the row of production in the MPS and transferred to the row of inventory in the MPS.
2. The inventory of these modules becomes slack or redundant modules in the system and has two consequences. First, the redundant modules can be reabsorbed by latter anticipated orders and configurations, which can use these modules. Second, the redundant modules can act as safety stock to buffer unexpected demand, such as unexpected configurations.

In addition, a causal loop of MPS Management in Figure 9 is provided to analyze the logic of the procedure and explain the process of MPS management. The more redundant modules from over planned orders and configurations, the more inventory will be shown in MPS, while the more unexpected demand, the more inventory can be offset. Moreover, since high commonality of redundant modules can increase the probability of modules being consumed, the higher commonality the redundant modules have, the sooner they can be reabsorbed with less inventory left in MPS. The less inventory, the less holding cost and the lower the obsolescence risk, the better effectiveness can be achieved from MTAO implementation. Nevertheless, more unexpected demand increases the probability of backlog or lost sales, thus decreases service level accordingly and decreases the effectiveness of MTAO implementation. Effectiveness of MTAO implementation can stimulate the service unit to put more effort on customer relationship management to achieve more accurate forecast, and therefore leads to less redundant modules and less unexpected orders. In summary, to maintain a stable MPS and to keep a high service level, the Telecom needs to reinforce its customer relationship management, as well as to improve redundant orders and unexpected orders control.

3.2.3. Redundant orders and unexpected orders control

Since anticipated orders cannot avoid demand uncertainties of acquisition, configuration and so on, overestimation has to be considered in the process of deciding anticipated orders to meet actual demand. As time goes by, demand uncertainties are gradually eliminated by more deterministic demand information. Subsequently, overestimated modules are adjusted from production to inventory in low product level and become slacks or buffers in the system. However, unlike other buffer methods, such as safety stock, the quantity and specification of these buffers in MTAO cannot be known explicitly at the point of planning, because these buffers or slacks are identified by the subsequent purchasing information and actual orders. Therefore, theoretically, if there is no objective control at the beginning of planning anticipated orders, the possible slack or buffers in the subsequent production pipeline can be too high to be effectively managed. The concerned holding costs and obsolescence risks increase. Based on the observations, Bartezzaghi and Verganti (1995) summed up two managerial tools to manage the buffers in over planning system or MTAO system. One is aggregate control and the other is detailed control.

Aggregate control is to set an upper boundary of anticipated orders in terms of MPS level modules by referring to aggregate planning in terms of module family . The mechanism of this method is based on the principle that the aggregate demand of a module family is more stable and predicable than the demand of individual. Overestimation ratio, OR%, is introduced to represent the boundary of anticipated orders and can be formulated as:

$$OR\% = \frac{Q(f,r) - A(f,r)}{A(f,r)} \qquad (1)$$

In the equation, Q(f,r) is the overall dollar value of MPS level modules decoupled from anticipated orders launched within the time horizon TLT +1 for the market, r, and module family, f. A(f, r) refers to the value of forecasted demand of module family over the TLT +1 period. The OR% in each TLT +1 period cannot exceed managerial overestimation ratio, OR*%, which is determined by the planning unit by taking the annual budget into consideration. Nevertheless, in the case of the telecom, the managerial ratio, OR*%, is hard to implement on the basis of short period, TLT +1, because the lumpy demand of individual modules varies intensively between different periods of TLT +1, say 3 months. For example, no demand occurs in the first 3 months while high demand surges in the second period and again, no demand occurs afterwards. Alternatively, to make the ratio more applicable, it's better to use a longer time horizon, such as 12 months, instead of the production cycle time, TLL +1, in modeling overestimation ratio.

The new ratio called the cumulative overestimation ratio can be formulated as,

$$\text{COR}\% = \frac{\text{CQ}(f,r) - \text{TA}(f,r)}{\text{TA}(f,r)} \qquad (2)$$

where TA (f, r) represents the annual forecasted value of module family, which will be updated every month based on a rolling horizon basis. CQ(f, r) is cumulative value of anticipated orders (including those that have been changed to actual orders) within the planning horizon of 12 months. Top management decides the managerial ratio, COR*%, as the maximum COR%, by considering their management goals. Essentially, by setting cumulative overestimation ratio, the quantity of redundant modules can be managed in a controlled scope. The risk of holding too much slack and the volatility of production/inventory adjustment in MPS therefore decrease.

Detailed control concerns individual anticipated order management. In practice, time fence and simulation of MPS are two powerful methods. Time fence keeps the physical production of anticipated orders in low product level to reduce risk of uncertainty. For example, in the telecom, all anticipated orders are only allowed to produce in the plants of tier 2 suppliers in terms of basic components unless the orders have turned into actual orders. The other method, simulation of MPS or simulation of MPS and MRP, is to detect deficiency of production capacity or shortage of materials when MPS is scheduled or rescheduled, and to remind the planning unit to arrange supplementary in advance, especially when several large anticipated orders concentrate in the same time period. Since detailed control may concern many functions in a company, from forecasters in the service unit to the planners in the planning unit to the manufacturing/outsourcing department and so on, the mechanism of trans-functional collaboration, such as to make final decision through inter-functional meeting, is important to successful implementation of the these methods.

Unexpected orders can be buffered either by inventory of redundant items in the production pipeline due to elimination of anticipated orders if the inventory can meet the requirements of the unexpected orders, or by safety stock which is set according to a combined analysis. To illustrate the mechanism of the buffer control, and to figure out a optimal safety stock, a simplified model under the environment of MTAO in terms of a binomial tree, is provided as follows:

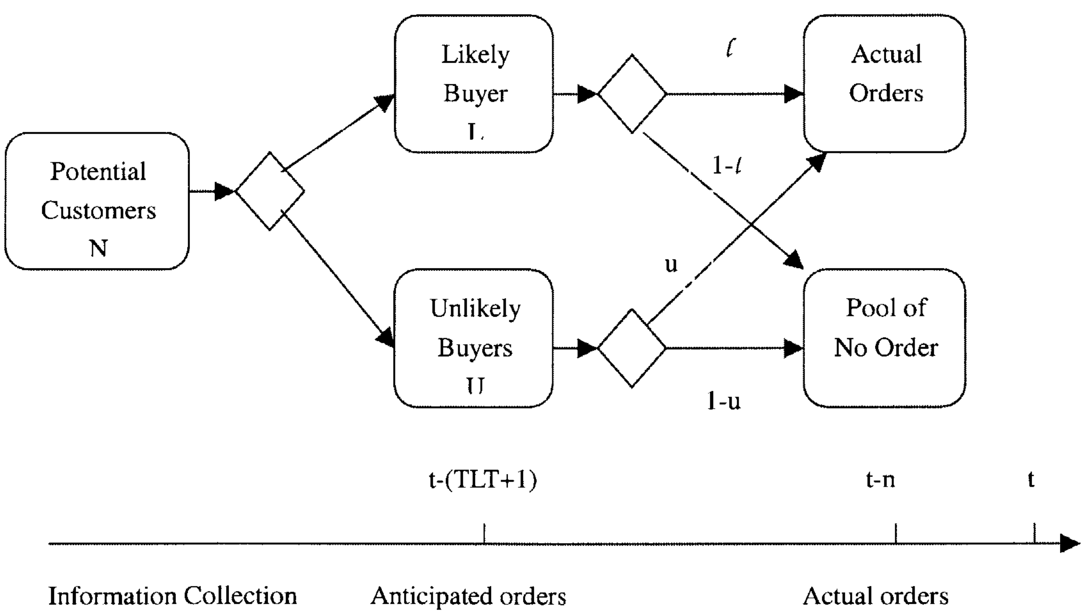

Figure 10 Binomial Tree for Demand in MTAO

In a specific market, for a certain final product, WIDGET X-1, the number of total potential customers is N. According to the forecast of the service unit, the total customers can be divided into likely buyers, L, and unlikely buyers, U.

Assuming each buyer only places one order at a time, in the time period of TLT+1 ahead of due date, t, anticipated orders, L, are put into MPS for real production while the probability that an anticipated order eventually turns into actual orders is ℓ and the number of actual orders is Al. On the other hand, the probability that an unlikely buyer places an unexpected order is u and the total number of unexpected orders is Au. Therefore, if no further information is collected between t-(TLT+1) to t-n (the time that actual orders are declared), the total number of unexpected orders, Au, is a random variable. In terms of a binomial distribution, the density function of Au can be formulated as:

$$f(Au) = C_{N-L}^{Au} u^{Au} (1-u)^{N-L-Au} \qquad (3)$$

The mean, m, and standard deviation, σ, unexpected order, Au, are respectively:

$$m_{Au} = (N-L)u \qquad (4)$$

$$\sigma_{Au} = \sqrt{(N-L)(1-u)u} \qquad (5)$$

Thus, the concerned stock to buffer unexpected orders, B, can be represented as:

$$B = m + k\sigma = (N-L)u + k\sqrt{(N-L)(1-u)u} \qquad (6)$$

where k is a safety factor. Since the mean of redundant orders (L-Al) is L(1- ℓ), the unexpected orders can be buffered by the sum of redundant orders and safety stock, SS, as :

$$B = SS + \text{is } L(1-\ell) = (N-L)u + k\sqrt{(N-L)(1-u)u} \qquad (7)$$

Therefore,

$$SS = (N-L)u + k\sqrt{(N-L)(1-u)u} - L(1-\ell)$$

$$= Nu - L(u+\ell-1) + k\sqrt{(N-L)(1-u)u} \qquad (8)$$

From expression (8), we find that the high value of ℓ and small value of u can significantly decrease the quantity of SS. In other words, a strong forecasting capacity of anticipated orders with low forecast errors can mitigate the burden of safety stock and achieve high service level. To buffer the unexpected orders, the decision of the final amount of safety stock therefore comes mainly from forecasters' subjective estimation of N, L, u and ℓ by early purchasing information of individual customers in each time period rather than historical data analysis. The system is a more pull-oriented than push-oriented method and the adjustment of safety stock may respond to demand fluctuations to deal with lumpiness. For example, if no anticipated orders expected, no safety stock is required.

3.2.4. Service Level analysis

Based on the simplified model as shown in Figure 10, Verganti (1997) proposes a quantitative method to calculate service level under MTAO system. As service level is a critical factor to evaluate the effectiveness of a buffer policy, we provide a sensitivity analysis of service level with some important variables in the buffer management. Next, domain of applicability of various buffer methods is introduced to identify suitable methods under specific demand environment.

In terms of binomial distribution, the density function of the actual orders, Al, is:

$$f(Al) = C_L^{Al} l^{Al} (1-l)^{L-Al} \qquad (9)$$

If the number L of likely buyers is constant, the expected probability of satisfying the total demand of MPS level items in a given period is:

$$S(L) = \sum_{Au=0}^{\min(N-L,L)} \left(f(Au) \sum_{Al=0}^{L-Au} f(Al) \right) \qquad (10)$$

However, since the number L of likely buyers is a random variable rather than fixed one, the probability of L should be taken into consideration in calculating service level. Assuming p is the probability of an individual customer that is expected to place an order, we can formulate the density function of L as:

$$f(L) = C_N^L p^L (1-p)^{N-L} \qquad (11)$$

Thus, considering dynamics of likely buyers, the service level in the system is:

$$\text{Service Level} = \sum_{L=0}^{N} f(L) * S(L)$$

$$=\sum_{L=0}^{N}\left[C_{N}^{L}p^{L}(1-p)^{N-L}*\sum_{Au=0}^{\min(N-L,L)}\left(f(Au)\sum_{Al=0}^{L-Au}f(Al)\right)\right] \quad (12)$$

3.3. Domain of applicability of make-to anticipated-order (MTAO)

The domain of applicability of MTAO depends on two major factors:

1. The amount of early customers' purchasing information and signals is considerable higher than the information that can be gained by analyzing the historical data and forecasting future demand. For example, if the probability that an anticipated order eventually turns into actual orders is 100% and the probability that an unlikely buyer places an unexpected order is 0%, MTAO can achieve a high effectiveness with no inventory and 100% service level, whereas other buffer managements that depend on forecasted demand distribution on the basis of historical data need inventory or other buffers to guarantee service level. In this case, MTAO is obviously suitable.
2. The second major factor that decides the domain of applicability of MTAO is the number N of potential customers in the market. Assuming that
   - (a) ℓ, the probability that an anticipated order eventually turns into actual orders, is 65%,
   - (b) u, the probability that an unlikely buyer places an unexpected order, is 2%,
   - (c) p, the probability of an individual customer that is expected to place an order, is 10%,

we input different numbers of potential customers (Table 1) in the market and get different service level respectively by using equation (12). Figure 11 illustrates the correlation between the two variables. As N increases, the service level decreases and effectiveness of MTAO decreases accordingly. In other words, MTAO is more suitable for the market that has small number of potential customers.

N	2	5	7	10	20	30	40	50
Service Level	96.56%	92.45%	90.28%	87.69%	82.81%	78.86%	55.97%	44.12%

Table 1: Number of potential customers and corresponding service level

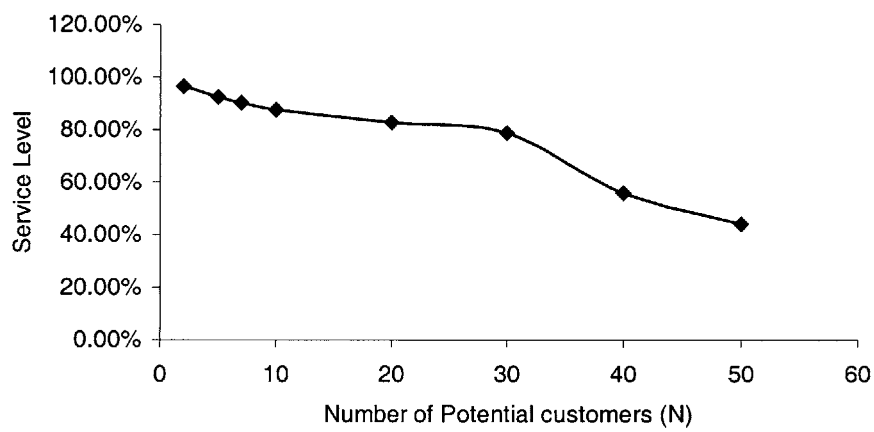

Figure 11: Relationship between N and service level

3.4. Conclusion

MTAO is an approach to buffer management under chaotic and lumpy demand, which is not well predicted through historical data. The mechanism of MTAO is to make use of early purchasing information and signals from potential customers and organize production according to anticipated orders TLT+1 time periods in advance of the expected due date. The implementation of this method, on one hand, breaks through the precondition of MTO that the total production cycle time should be less than customer desired lead time by making use of an extra time that customers think over purchasing plans before they place actual orders. On the other hand, MTAO enjoys the advantage of arranging production by responding to customers demand to reduce inventory costs and obsolescence risks of MPS level items. MTAO is also called order overplanning for its unique process of buffer control compared to other buffer approaches, such as safety stock, safety lead-time or option overplanning. Although MTAO is not yet a perfect solution and depends more on subjective decision-makings, it is an innovative idea and contributes many insights on management of demand uncertainty.

1. MTAO is a new paradigm on operations. Under demand uncertainty, it focuses on looking into future of customer purchasing process to direct production by responding to anticipated demands rather than looking behind to arrange buffers by figuring out demand patterns to buffer uncertainty. Thus, when it is hard to forecast according to historical data and customers' desired lead-time is too short to implement MTO, MTAO brings new opportunities. A case study by Bartezzaghi and Verganti (1995) on a European telecommunication supplier has revealed the advantages and perspectives of this method.
2. MTAO can enhance trans-functional collaboration within a company. Many decisions, such as aggregate forecast, cumulative overestimation rate, will rely on organizational efforts while more communication and collaboration among different departments will improve utilization of corporation resources and achieve higher efficiency.
3. The implementation of MTAO stimulates the suppliers to develop closer intercompany operating ties with their customers or to reinforce their customer relationship management, because, as we discussed in the previous subsections, close customer relationship tremendously contribute to accuracy of anticipated orders and therefore improve implementation of MTAO. Furthermore, harmonized vertical collaboration with customers provides extraordinary opportunities to streamline the supply chain of the suppliers and benefit from global optimization. Actually, many innovative solutions have emerged in this field to coordinate vertical supply chains, such as VMI, CPFR and more specific approaches are expecting to be generated under particular industries. For example, as WIDGET X is a technology intensive product, the

Telecom can collaborate its customers by providing a long-term technological consulting service.

4. According to the process analysis, we find that the forecast and planning of anticipated orders are empirically and subjectively decided, therefore the eliminated orders or slacks cannot be controlled explicitly in the system and it's hard to use these implicit slacks to buffer unexpected demand. Moreover, since anticipated orders are made in terms of each single customer, the uncertainties of independent demand are not combined.
5. MTAO lacks a mechanism to deal with demand from new markets and unfamiliar markets. As a potential solution, price can be leveraged to get more early purchasing information from new customers.
6. As proposed by Zotteri and Verganti (1995) based on a case study, MTAO entails high organizational costs to collect information from customers and change information within company. It increases costs of implementation of MTAO.

4. Managing demand uncertainty by postponement and commonality strategy

4.1. Postponement and commonality

Since the demand of MPS level items or individual modules in the Telecom is extremely lumpy, irregular and volatile, a responsive buffer method, MTAO, is introduced to deal with the demand uncertainty. However, if the demand of MPS level items become more stable and predictable, MTAO may not be a good choice because buffers in MTAO cannot be implicitly managed and controlled. Alternatively, buffer policy of safety stock is recommended, and buffers can be explicitly managed and controlled in the whole operation process. To reduce the volatility of demand, MPS level items can be alternated from individual modules to module families through postponement.

In detail, the differentiation of each module in a module family is postponed to the point when the actual order is received. Then a common module instead of various individual modules in a module family acts as the MPS level item, and the aggregate demand of the common module is expected to be more stable than disaggregated demand because of the risk pooling effect. This postponement strategy to aggregate demand therefore can be achieved by module commonality.

Module commonality reduces the total number of distinct modules and can bring about benefits in many occasions throughout a firm. In addition to reducing forecast errors from a risk pooling perspective, commonality also leads to improving the economy of scale through larger order size, reducing lead-time uncertainty, and simplifying planning and control. Baker et al. (1986) establish a model with two end items with independent and uniformly distributed demands to evaluate commonality quantitatively. They provide three insights from their research. First, the total inventory in number of units decreases with commonality. Second, the inventory level of the common component is smaller than the combined inventory levels of the components it replaces. Third, the inventory levels of non-common components increase with commonality. In addition to the benefits of commonality, Howard (1994) and Lee and Billington (1994) argue that postponement can shorten the configuration and customization lead-time, improve forecast accuracy by shortening the forecast time horizon, and enhance a firm's flexibility and responsiveness in an uncertain and changing market. In the Telecom, commonality and postponement can be achieved by innovative production design.

Brown et al (2000) give an example of Xilinx, Inc. that uses innovative product design to implement postponement. The common products in Xilinx are designed so that the product's specific functionality can be set after the customer receives it. Xilinx designs its products to be programmable, allowing customers to fully configure the function of the integrated circuit using software. In the operation, a generic part is created in the initial stages of the manufacturing process. In the later stages, this generic part is customized to create the finished product. Xilinx manufactures a small number of generic parts and holds them as inventory. The use of these generic parts and common products allow Xilinx to hold less inventory in those finished products.

From the example, we find that one should integrate product design and process reengineering to take full advantage of commonality and postponement. This is because the execution effectiveness of commonality or postponement strategy, such as inventory cost savings, depends on the interactions of component cost structure, replenishment lead-times, production times and desired delivery times. This viewpoint is critical to multistage inventory placement, which will be discussed later.

Implementation of postponement and commonality strategy in terms of individual modules will change the push-pull boundary of the production system in the Telecom. Currently, the Telecom locates the push-pull boundary at the stage of assembly and testing, while individual modules are MPS level items (Figure.1). If differentiation of individual modules is postponed to the point that actual orders are received, the push-pull boundary will be relocated at the stage of common module production, while common modules become MPS level items. As shown in Figure 12, in the upstream stages of push-pull boundary, production is pushed by utilizing past information to forecast the future customer demands, such as MRP system. Since aggregate demand information is more accurate than disaggregate data, the forecast in terms of common module is more accurate. In the downstream stages of push-pull boundary, configuration of common module and assembly and testing are triggered by actual orders. If the processing time of configuration of common modules is half week, the minimum delivery time can be reduced to one and half week by the Telecom to increase customer satisfaction and improve competitiveness.

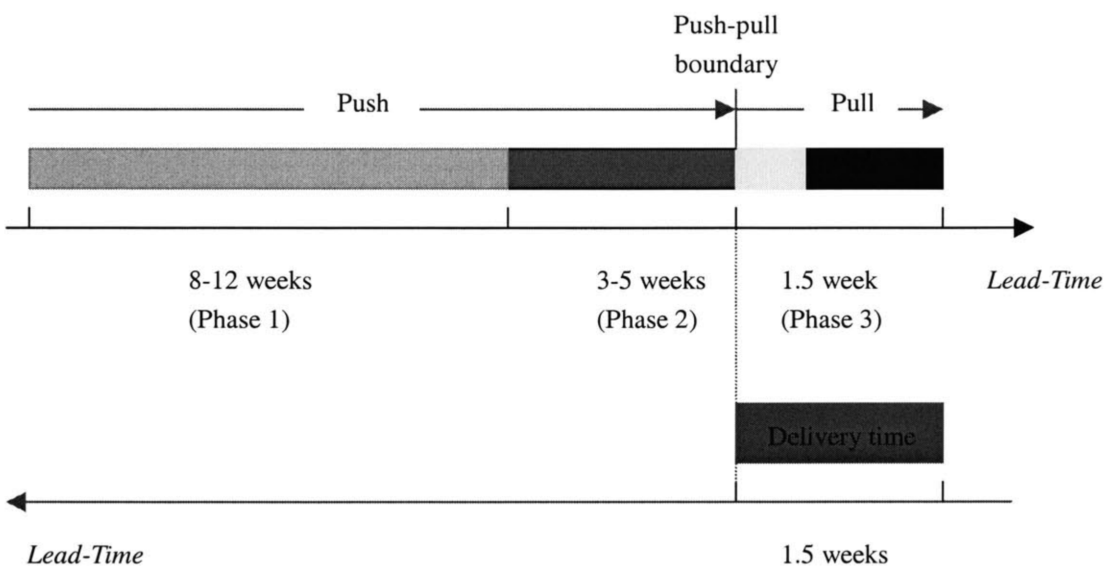

Figure 12: New push-pull boundary

As discussed, using common components and implementing postponement strategy seem to be appealing ideas. However, if a common component is more expensive than the unique components that it replaces, then it will require careful analysis to decide whether it is beneficial to employ the common component. Fong et al (2002) consider the contribution of a more expensive common component in minimizing the expected units shortage for meeting demands of two end products, subject to a budget constraint. They get the result that, assuming Erlang demand distributions, a more expensive common component can be beneficial when the inventory budget is large, but commonality will not be helpful if the budget is small. We select the most important and expensive module family of the six module families to analyze the impact of commonality. To simplify the analytical process, module families are segmented into categories of A, B, and C to classify their importance.

4.2. Segmentation analysis

To tradeoff the cost of implementing an inventory control system and potential benefits of the control system, it is important to differentiate various items in terms of profit contribution, value or revenue. As a rule of thumb, a large portion of the total dollar volume of sales is often accounted for by a small number of inventory items. Typically, the top 20 percent of the items account for about 80 percent of the annual dollar volume of sales. The next 30 percent of the items roughly represent 15 percent of the dollar value. The remaining 50 percent account for 5 percent of dollar sales. These empirical figures are only approximate and vary slightly from one system to another. The three groups are labeled A, B and C respectively. Firms often include slow-moving and inexpensive items in the A category if these items are critical to the whole business. Because A items account for the lion's share of revenue, these items should receive the most personalized attention from management. Inventory levels for A items should be monitored most closely and commonality of A items should be implemented most preferentially. In addition, more care would be taken in the estimation of the various cost parameters required in calculating operating policies. B items are of secondary importance in the category. They deserve a moderate but significant amount of attention, and somewhat less sophisticated inventory methods could be used. For very inexpensive C items with moderate levels of demand, decision systems must be kept as simple as possible. Generally, large lot sizes are recommended by considering more economy of scales than inventory cost.

Table 2 and Figure 13 demonstrate the distribution by value and number of all the module families in the Telecom. Module family 1 (MF.1), optics family, makes up 23 percent of the total number of items, but represents 72 percent of the dollar sales volume. Module family 2 and 3 (MF.2, 3) comprise roughly 41 percent of the modules, but represent 23 percent of the dollar value. Module family 4, 5, and 6 (MF.4, 5, 6) together with other sporadic modules comprise 36 percent of the modules, and represent only 4 percent of the dollar volume.

Category	Module Family	Percent of Value	Cumulative Percent of Value	Percent of Number	Cumulative Percent of Number
A	MF.1	73.0%	73.0%	23.0%	23.0%
B	MF.2	18.0%	91.0%	39.2%	62.2%
	MF.3	5.0%	96.0%	2.0%	64.2%
C	MF.4	2.0%	98.0%	12.0%	76.2%
	MF.5	1.0%	99.0%	5.0%	81.2%
	MF.6	0.5%	99.5%	13.1%	94.4%
	Others	0.5%	100.0%	5.6%	100.0%

Table 2: Distribution by value and number of modules

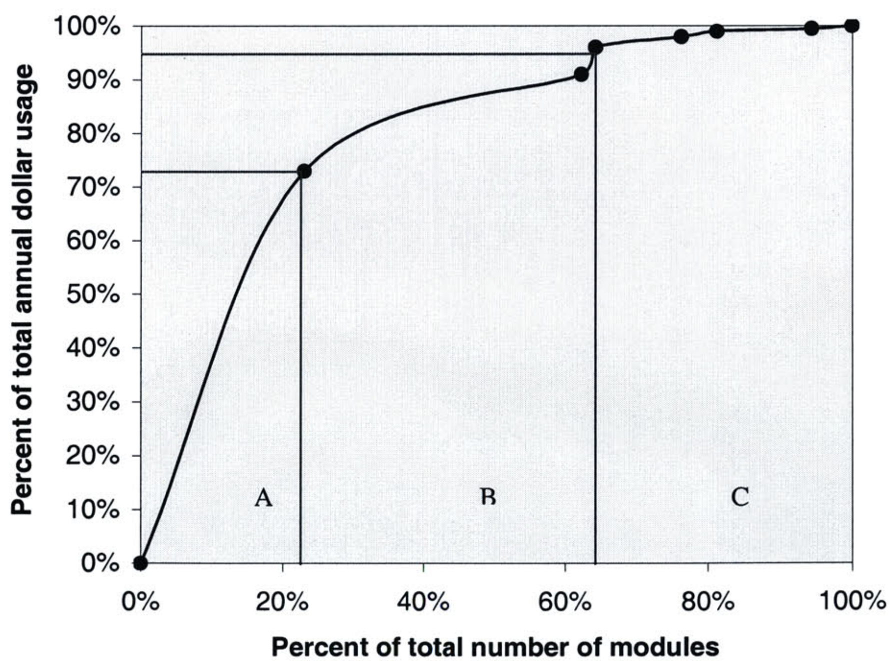

Figure 13: Distribution by value of modules

Module family 1, optics family, falls into the category of A and has the most priority to implement commonality strategy. In light of the experience of Xilinx, commonality can be achieved by innovative production design and can be executed efficiently by process reengineering. The telecom therefore needs to analyze both of the two aspects.

First, based on the characteristics of optics itself, a general idea is to design the common module of the optics family first. Then based on the common module, customized optics can be configured after actual orders are received. In other words, customization of particular optics is postponed and the customers' demand can be met by make-to-order. Thus the push-pull boundary is switched to the stage of common optics modules. The Telecom can take advantage of stability of aggregate demand to produce common modules, and deal with uncertainty of specific demand by subsequent customization according to actual orders as well. Since product design is more technical and beyond the scope of buffer management, we will skip the part of product design and focus on the inventory management to hedge demand uncertainty in the case of the common module of optics family has been available. In particular, optimal multistage inventory placement of the common module of optics family is studied.

4.3. Multistage inventory placement

4.3.1. Equal time supplies

Currently, the inventory policy employed by the Telecom, as stated earlier, is equal time supplies. This is a simple, commonly used approach. In detail, the safety stocks of a broad group of items in an inventory are set equal to the same time supply, for example, an item is reordered when its inventory position minus the forecasted lead time demand drops to a three months supply or lower. This approach is flawed because it fails to take account of the difference in the uncertainty of forecasts from item to item. In applying this policy to a number of items, the policy variable is the common number of time periods of supply. In other words, all items in the group have safety stock set to the same number of periods of supply. It did not prevent stock-out of items with highly variable demand, and it certainly did not optimize inventory costs. A simple periodic review base stock model can further reveal the logic of equal time supply.

In a periodic review base stock, the reorder point, B, is the sum of estimated demand over the lead-time and safety stock. Assuming R refers to review period and replenishment transportation time, μ to mean of demand, σ to standard deviation of demand, and k to safety factor, the reorder point can be formulated as:

$$M_j = B = \mu R + k\sigma\sqrt{R} \tag{13}$$

If we use equal time supply, the reorder point is the M time period supply, then B is:

$$B = \mu M \tag{14}$$

Therefore,

$$k\sigma\sqrt{R} = \mu(M - R) \tag{15}$$

$$k = \frac{\mu(M-R)}{\sigma\sqrt{R}} = \left(\frac{M-R}{\sqrt{R}}\right) * \frac{\mu}{\sigma} = \left(\frac{M-R}{\sqrt{R}}\right) * \frac{1}{CV} \tag{16}$$

From expression (16), if M and R are fixed, the safety factor will be decided by CV and the bigger the CV, the smaller the k or the smaller the CV, the bigger the k. Since high safety factor results in high service level, under equal time supply, the service level of some items with high demand volatility (big CV) is low and the lost sales is high, while the service level of some other items with stable demand (low CV) is too high, thus high redundant inventory is always hold. A scientific way to deal with safety stock is to decide safety factor, k, based on expected service level rather than the time of supply.

Basically, production life cycle is an important criterion to decide safety factor, k. For example, if the products are in the mature phase of the product life cycle, competition is often based on cost and delivery performance. The cost of lost sales is simply the lost contribution margin of the lost sales. The safety factor can be set at a mediate level to meet expected service level, say 90 percent to 95 percent. If the products are relatively new to the market, delivery performance may have significant implications for capturing market share while cost is less important. The safety factor can be set to meet stringent service target. Moreover, if a product is more standardized and has many competitive substitutions in the same market, higher safety factor is needed to guarantee supply, because unavailability of such product can directly lead to lost sales—customers switch to buy other available substitutive products. If a product is more customized and unique in terms of features or functions, the safety factor can be kept at a relatively low level for unsatisfied demand is more likely to turn into backlogs rather than lost sales. In addition, since safety factor, k, reflects the safety stock covers the demand variation, the choice of k indicates how often the manager is willing to resort to other solutions to cover demand variability. To decide the particular safety factor, detailed analysis is required to tradeoff the inventory holding cost and cost of lost sales and backlogs. The optimal choice is on the condition that the minimum total cost of inventory holding, lost sales and backlogs is achieved, or a predetermined service level is guaranteed with the minimum inventory holding cost. Since the penalty cost of lost sales or backlogs is very difficult to be assessed in reality, companies usually determine optimal inventory policy by setting desired service levels.

4.3.2. Literature review

According to A, B, C analysis, optics family falls into category of A. Optics family then has the most priority to implement commonality to deal with demand uncertainty. Assuming common module of optics family has come into being through innovative product design, the next step is to optimize the inventory of the common module in the supply chain. Inventory-driven cost factors, such as material devaluation, scrap costs, write-offs, and fire sale discount have become a big detriment to profitability. To improve inventory management, the Telecom should give up the buffer policy of equal time supply and take account of service levels, demand and supply uncertainties, and end-to-end process time across the supply chain to reduce inventory-driven costs. The most difficult part of minimizing the inventory-driven costs in the supply chain is identifying the location and size of buffer inventory at each point in the supply chain. Too much inventory of the wrong components, or at the wrong place in the supply chain can increase inventory holding costs and obsolescence costs while too little of the components in demand can create backlogs and lost sales. Since common module of optics is made up of many components, which are produced in different stages, the inventory issue of the common module is to determine the inventory in the divergent inventory systems and to optimize multistage inventory placement.

Many authors have provided their proposals or inventory models to optimize multistage inventory placement. Simpson (1958) modeles a supply chain as a serial network. Using an all-stage policy under base stock policy the author builds a model to minimize total holding cost of safety stock subject to a predetermined service level of end-item and maximum internal buffer stock by setting safety factors for upstream stock points. Safety stock can be optimized by dividing up the overall end-item replenishment lead-time to local replenishment times at each stock point where demand uncertainties are covered by local safety stock. Ett et al (2000) use the replenishment time to minimize the total expected inventory capital in a multistage inventory system. To model non-stationary demand, they assume the horizon can be divided into a set of stationary periods and use a rolling-horizon approach to optimize each demand period. Inderfurth (1991) builds a model to optimize multistage inventory in arbitrary divergent systems and this model comprises two steps. The first step is to get a set of efficient replenishment time, $\{T_i *\}$, subject to minimum holding cost of safety stock. Let E stands for end-items, U for upstream items, P(j) for all predecessors of item j inclusive, the optimization problem can be formulated as:

$$\mathrm{Min}_{T_i} \sum_{i \in U \cup E} h_i f_i \sigma_i \sqrt{T_i} \qquad (17)$$

Subject to

$$\sum_{i \in P(K)} T_i = \sum_{i \in P(K)} l_i \quad \forall k \in E \qquad (18)$$

$$\sum_{i \in P(j)} T_i \leq \sum_{i \in P(j)} l_i \quad \forall k \in U \tag{19}$$

$$Ti \geq 0 \;\; \forall k \in U \cup E \tag{20}$$

Where h_i and f_i represent holding cost and safety factor of safety stock at stock point i respectively. σ_i denotes the standard deviation of demand at stock point i and l_i refers to fixed lead time of stage i. The second step is to get optimal safety stock by using the solution $\{T_i *\}$ of the first step. The optimal safety stock at stock point i is:

$$I_i * = f_i \sigma_i \sqrt{T_i *} \tag{21}$$

However, this model has an obvious limitation that in most circumstances the replenishment time T_i is fixed rather than changeable because it is decided by upstream production cycle time and inbound service time.

4.4. Multistage inventory placement in the Telecom

4.4.1. Methodology

Graves and Willems (2000) continue the idea of evaluating the inventory requirements as a function of time and develop performance evaluation models of a multistage inventory system, where they assume a periodic-review base-stock policy is used. The authors extend the work of Simpson and of Inderfurth by treating the supply chain more generally in terms of spanning trees, and, similar to the model of Ettl et al, they use lead times within the supply chain as the most important variables to minimize the inventory requirements in each stage. To keep the model simple but robust, the authors assume:

1. The production lead-time is not impacted by the size of the order.
2. There is no time delay in replenishment of orders in each period.
3. The safety stock is set to cover all demand within an upper demand bound of end item in each stage and the average demand per period is μ.

For example, in stage j, the average demand is μ_j.

4. Each demand node i promises a guaranteed service time or maximum service time, S_i, by which the stage i will satisfy customer demand. In other words, the service time for the stage i is the amount of time allowed for the stage to fulfill a demand requesting from an adjacent downstream stage.
5. Stage i quotes the same service time to all its downstream customers.
6. End item is given a maximum service time set by the marketplace. Violations of the guaranteed service times are not permitted.
7. The production lead time, T_i, includes the waiting and processing time at the stage, plus any transportation time to put the item into inventory.

The authors propose that the inventory shortfall in each stage is the difference between the cumulative replenishment from upstream stage and the cumulative shipment to downstream stage. Therefore, in stage j, the least base stock, B_j, can be termed as:

$$B_j = D_j(SI_j + T_j - S_j) \qquad (22)$$

where SI_j is inbound service time and $D_j(t)$ is the maximum demand in period t. The average inventory shortfall in stage j is:

$$M_j = \mu_j(SI_j + T_j - S_j) \qquad (23)$$

Thus, the safety stock, $E[I_j]$at stage j equals:

$$E[I_j] = B_j - M_j = D_j(SI_j + T_j - S_j) - u_j(SI_j + T_j - S_j) \qquad (24)$$

For example, if the upper demand bound, $D_j(t)$, is $\mu t + k\sigma\sqrt{t}$, the safety stock is $k\sigma\sqrt{SI_j + T_j - S_j}$. Since the inbound service time is the maximum upstream service time, and the production cycle time in each stage is fixed, the decision variables for minimum safety stock are the service times. Therefore, the authors model the multistage system by assuming that the production cycle time, the means and bounds of the demand processes, and the maximum service time for each demand node are known input parameters. To find the optimal service time in each stage that minimizes holding cost of total safety stocks in the supply chain, the N-stage model is formulated as follows:

$$\min \sum_{j=1}^{N} h_j \left\{ D_j(SI_j + T_j - S_j) - u_j(SI_j + T_j - S_j) \right\} \quad (25)$$

Subject to:

$$S_j - SI_j \le T_j \qquad \text{for} \quad j = 1, 2, \ldots, N \quad (26)$$

$$SI_j - S_i \ge 0 \qquad \text{for} \quad \text{all}(i, j) \in A \quad (27)$$

$$Sj \le s_j \qquad \text{for all demand nodes } j \quad (28)$$

$$SI_j, S_j \ge 0 \qquad \text{and integer for } j = 1,2,\&,N \quad (29)$$

where h_j stands for the holding cost per-unit for inventory at stage j and s_j represents the guaranteed service time for demand node j. Expression (26) constrains the net replenishment in stage j is non-negative, or no inventory is required in stage j for the service time, S_j, is long enough to allow make-to-order. Expression (27) explains that the inbound service time equals the maximum upstream service time. Expression (28) states that the service time in stage j must fall into the guaranteed service time of the stage. The authors also develop an optimization algorithm in terms of dynamic programming for finding the optimized service times that minimize the safety stock holding cost. Next, optimal multistage inventory placement can be calculated based on the optimized service times in all stages using Expression (24).

4.4.2. Base model

Regarding the Telecom, a graph of simplified supply chain of the common optics is shown in Figure 14 and the options of production time and cost added at each stage are shown in Table 3:

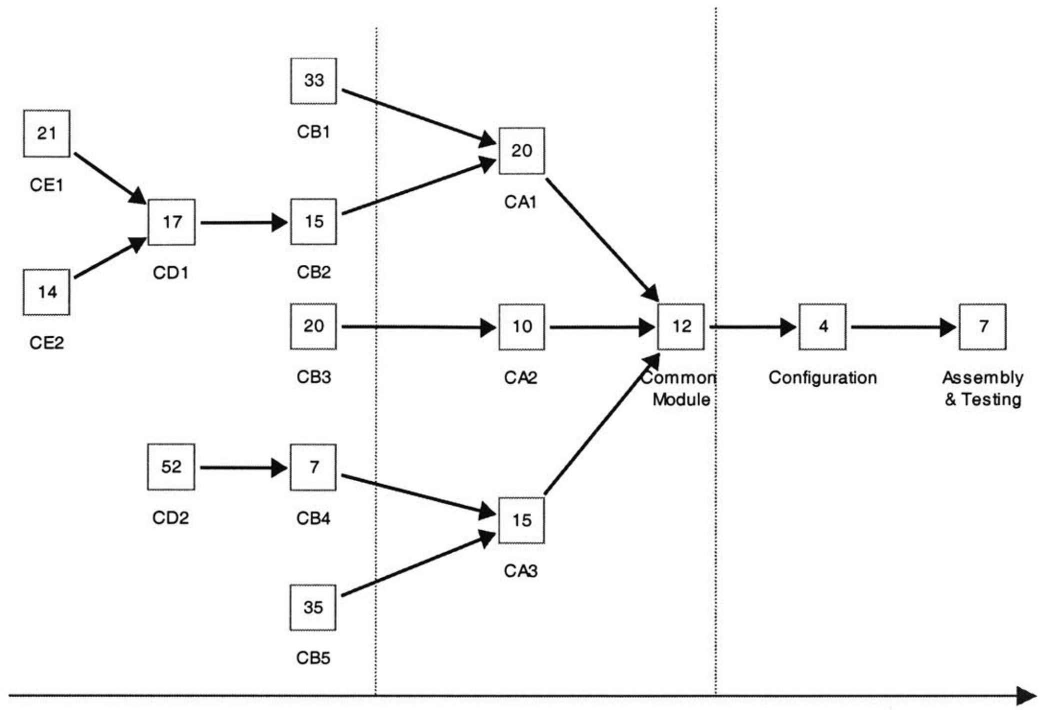

Figure 14: Spanning tree network supply chain of common optics

Phase	Stage Name	Production Time (Day) T_j	Cost Added ($)
Tier 2 Supplier	CE1	21	750
	CE2	14	200
	CD1	17	350
	CD2	52	1500
	CB1	33	1100
	CB2	15	250
	CB3	20	400
	CB4	7	150
	CB5	35	700
Tier 1 Supplier	CA1	20	2000
	CA2	10	950
	CA3	15	200
	CM*	12	300
Assembly Plant	Configuration	4	150
	A & T*	7	300

CM* refers to common module

A & T* refers to assembly & testing

Table 3: Production time and cost added in each stage

Figure 14 represents a stylized and simplified supply chain for common optics in terms of spanning tree. In the part of tier 2 supplier, 5 final modules, CB1, CB2, CB3, CB4 and CB5, are produced as initial components for tier 1 supplier. In particular, CB2 is processed by CD1 which has two components, CE1 and CE2. The main component of CB4 is CD2. In the part of the tier 1 supplier, common optics is the final product, which is assembled by CA1, CA2 and CA3. CA1 is manufactured by CB1 and CB2, CA2 by CB3, and CA3 by CB4 and CB5. Table 2 lists the options of production time and cost added at each stage in the supply chain.

We assume that all stages adopt periodic-review base-stock policy with a daily review period. Each stage receives demand orders either from an external customer or from its downstream stage, and places an order on its upstream stage to replenish the orders. The mean demand of end-item, common optics, is 10 units per day and the standard deviation of demand is 7 units in a certain future period according to forecast. The demand is normally distributed and the predetermined service level is 95% for external demand. The guaranteed delivery time or maximum service time to customers is 15 days, meaning that the company has a maximum of 15 days for the product to arrive to the customer after the order has been placed. Inventory holding cost is 20% annually and Table 2 gives the production time and cost added in each stage. Based on these assumptions, we are able to build a base model by referring the model developed by Graves and Willems (2000) to optimize multistage inventory placement in the supply chain in terms of minimum safety stock holding cost.

First, the function of holding cost per unit, h_j, the maximum demand in stage j, D_j, and the mean demand in stage j, u_j, can be given as:

$$h_j = \text{Holding cost rate} * \text{Cumulative cost per unit} = 20\% * C_j \quad (30)$$

$$D_j(t) = u_j(t)*t + k*\sigma*\sqrt{t} = u_j(t)*t + 1.64*7*\sqrt{t} \quad (31)$$

$$u_j = u_j(t)*t \quad (32)$$

where C_j is cumulative cost per unit.

Second, by introducing the functions of h_j, D_j and u_j, the base model can be formulated as follows. And the purpose of the base model is to find the optimal service time in each stage that minimize the safety stock holding cost in the supply chain.

$$\min \sum_{j=1}^{N} 0.2 * C_j * \left(1.64 * 7 * \sqrt{SI_j + T_j - S_j}\right) \tag{33}$$

Subject to:

$$S_j - SI_j \leq T_j \quad \text{for} \quad j = 1, 2, ..., N \tag{34}$$

$$SI_j - S_i \geq 0 \quad \text{for} \quad \text{all}(i, j) \in A \tag{35}$$

$$Sj \leq s_j \quad \text{for all demand nodes j} \tag{36}$$

$$SI_j, S_j \geq 0 \quad \text{and integer for j = 1,2,\&,N} \tag{37}$$

Where S_j is the service time in stage j, SI_j is the inbound service time of stage j and they are variables in this model. The cumulative cost, C_j, and production time, T_j, can be quoted or calculated from Table 2. Expression (36) is an important constraint in the model. We can calculate optimal inventory placement in two scenarios, local optimization and global optimization, by adjusting the guaranteed service time in particular stages.

4.4.3. Scenario analysis and sensitivity analysis

In the first scenario (Scenario 1), since the tier 1 supplier, the tier 2 supplier and the assembly plant belong to different production units, their inventory placement is managed separately and each of them focuses on its own local optimization. Assuming that the information of forecasted customer demand is shared in the supply chain, all production units make use of the forecast to make to stock, and use the stock to meet the orders from downstream production unit. Then the downstream production units can get the products they ordered instantly from its upstream production unit. In other words, the guaranteed service times in the stage of final products in upstream production units turn to be zero if we don't take account of lead time of transportation. Namely, the guaranteed service times in the stage of common optics (CM), CB1, CB2, CB3, CB4 and CB5 are zero. Thus, expression (36) can be defined as:

$$S_{CB1} = S_{CB2} = S_{CB3} = S_{CB4} = S_{CB5} = 0$$

$$S_{CM} = 0$$

$$S_{A\&T} \leq 15 \qquad (38)$$

Based on the new definition of expression (38), we run the base model in scenario 1 and get the optimized service time of each stage as shown in Table 4. The minimum safety stock holding cost in the supply chain is $198,663. Moreover, the multistage inventory allocation is shown in Figure 15, where we find that safety stock is hold in the stage of final products of tier 1 and tier 2 suppliers.

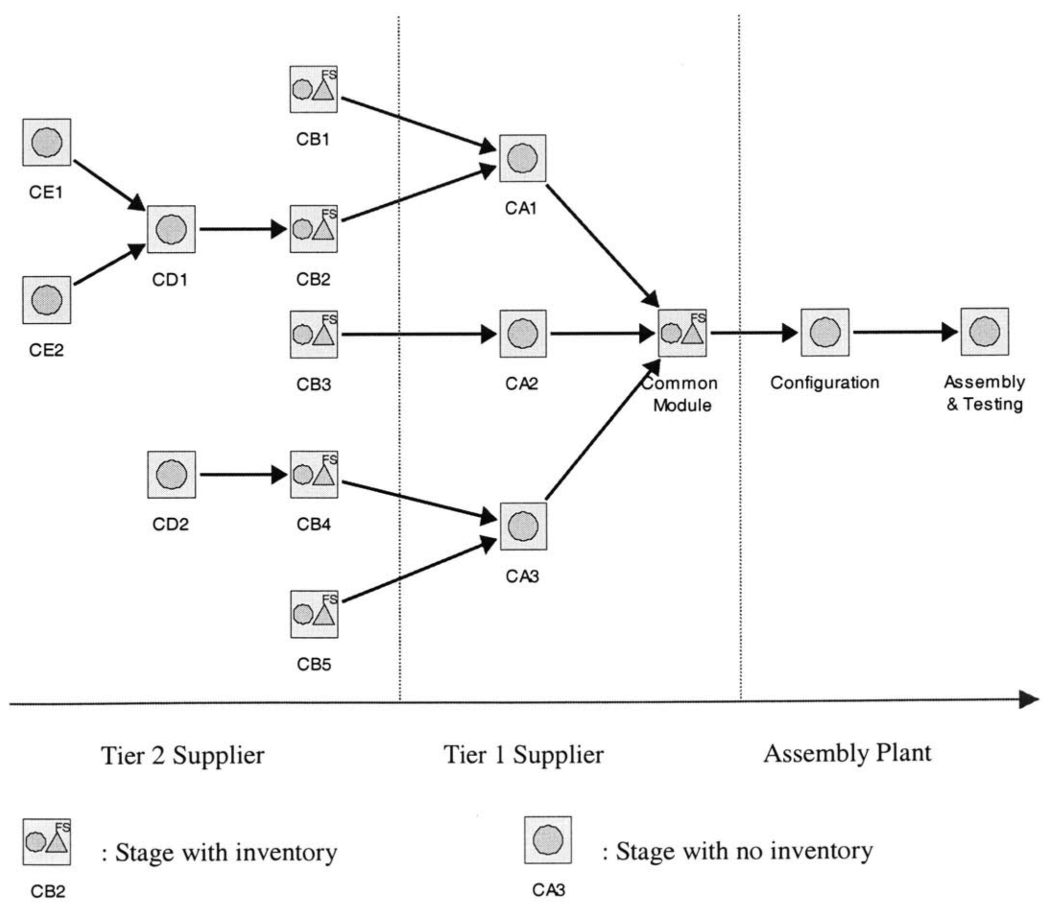

Figure 15: Multistage inventory placement in Scenario 1

Phase	Stage Name	Production Time (T_j)	Cost Added	Service Time (S_j)	Net Replenish-ment Time	Safety Stock	Cummula-tive Cost	Holing cost of Safety Stock
Tier 2	CE1	21	$750	21	0	0	$750	$0
Supplier	CE2	14	$200	14	0	0	$200	$0
	CD1	17	$350	38	0	0	$1,300	$0
	CD2	52	$1,500	52	0	0	$1,500	$0
	CB1	33	$1,100	0	33	66	$1,100	$14,551
	CB2	15	$250	0	53	84	$1,550	$25,985
	CB3	20	$400	0	20	51	$400	$4,119
	CB4	7	$150	0	59	88	$1,650	$29,185
	CB5	35	$700	0	35	68	$700	$9,536
Tier 1	CA1	20	$2,000	20	0	0	$4,650	$0
Supplier	CA2	10	$950	10	0	0	$1,350	$0
	CA3	15	$200	15	0	0	$2,550	$0
	C.M.	12	$300	0	32	65	$8,850	$115,285
Assembly	Config.	4	$150	4	0	0	$9,000	$0
Plant	A. & T.	7	$300	11	0	0	$9,300	$0
							Holding Cost of Total safety Stock:	**$198,663**

Table 4: Optimized inventory placement in Scenario 1

In the second scenario (Scenario 2), we integrate the supply chain as a whole by breaking through the boundaries of production units. Namely, the goal is to achieve global optimization of multistage inventory placement in terms of minimum holding cost of total safety stock. Therefore, the guaranteed service times in the stage of final products in the tier 1 and tier2 suppliers are not limited to zero, and the expression (36) can be defined as:

$$S_{A\&T} \leq 15 \qquad (39)$$

We run the base model under Scenario 2 with the new defined constraint (expression 39) and get the optimal service time in each stage as stated in Table 5. The minimum holding cost of total safety stock reduces to $184,384, which represents more than 7% improvement compared to the holding cost under Scenario 1 in terms of local optimization. Moreover, as shown in Figure 16, the optimal inventory placement in the supply chain is different from that in Scenario 1. In detail, no inventory is placed in the final stages in the tier 2 supplier, CB1, CB2, CB3, CB4 and CB5. Alternatively, inventory is placed in the stages of lower level components.

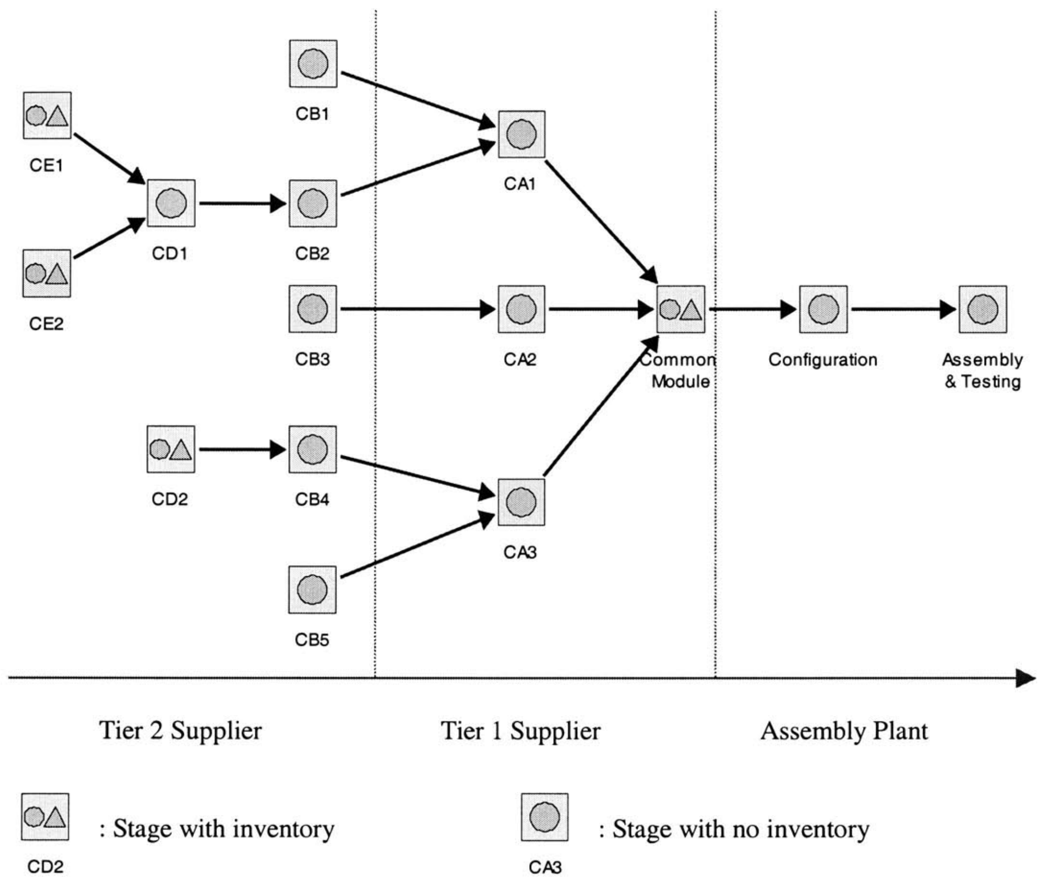

Figure 16: Multistage inventory placement in Scenario 2

Phase	Stage Name	Prod. Time (T_j)	Cost Added	Service Time (S_j)	Net Replenish-ment Time	Safety Stock	Cummula-tive Cost	Holding Cost of Safety Stock
Tier 2	CE1	21	$750	1	20	51	$750	$7,724
Supplier	CE2	14	$200	1	13	42	$200	$1,661
	CD1	17	$350	18	0	0	$1,300	$0
	CD2	52	$1,500	31	21	53	$1,500	$15,829
	CB1	33	$1,100	33	0	0	$1,100	$0
	CB2	15	$250	33	0	0	$1,550	$0
	CB3	20	$400	20	0	0	$400	$0
	CB4	7	$150	38	0	0	$1,650	$0
	CB5	35	$700	35	0	0	$700	$0
Tier 1	CA1	20	$2,000	53	0	0	$4,650	$0
Supplier	CA2	10	$950	30	0	0	$1,350	$0
	CA3	15	$200	53	0	0	$2,550	$0
	C.M.	12	$300	4	61	90	$8,850	$159,171
Assembly	Config.	4	$150	8	0	0	$9,000	$0
Plant	A. & T.	7	$300	15	0	0	$9,300	$0
				Holding Cost of Total Safety Stock:				**$184,384**

Table 5: Optimized inventory placement in Scenario 2

According to the comparison of Scenario 1 and Scenario 2, the global optimization of multistage inventory placement can achieve lower safety stock holding cost than the combination of local optimization under the same demand environment. The Telecom can take advantage of this observation and collaborate with the tier 1 supplier, the tier 2 supplier and the assembly plant to determine the optimized inventory placement based on an integrated supply chain.

Besides the mechanism of global optimization, another important issue that leverages the inventory placement in the supply chain is the maximum service time to customers. We use the base model under scenario 2 (global optimization) and provide a sensitivity analysis to exploit the relationship between the maximum service time to customers and the minimum holding cost of total safety stock in the supply chain. First, we assume different maximum service times to customers. Then we run the model under various service times to see how sensitive the safety stock holding cost is to the service time. The corresponding results are listed in Table 6 and Figure 17 demonstrates the relationship graphically.

Guaranteed service time to customers (Day)	1	7	8	9	10	11	12	13
Total safety stock holding cost ($)	209,833	196,616	195,521	194,419	193,311	188,994	187,892	186,783

Guaranteed service time to customers (Day)	14	15	16	17	40	60	95	97
Total safety stock holding cost ($)	185,668	184,384	183,074	181,753	100,351	54,917	6,612	0

Table 6: Sensitivity analysis of guaranteed service time and holding cost

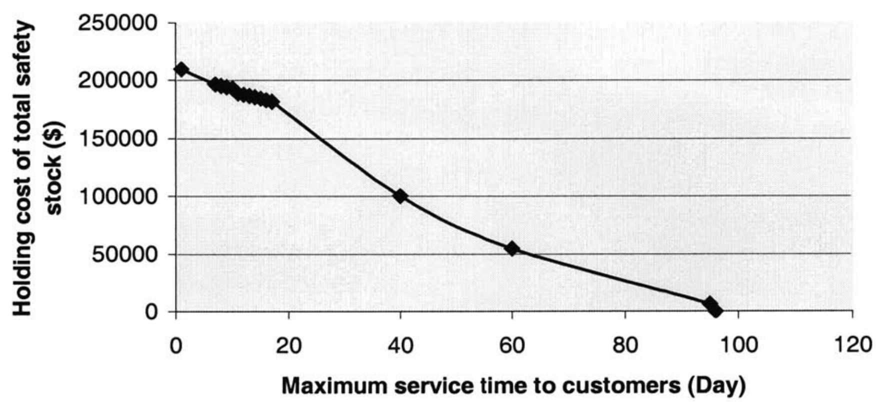

Figure 17: Relationship between service time and holding cost

Generally, the longer the service time that customers require, the lower holding cost of total safety stock can be achieved in the supply chain. Nevertheless, the relationship between the two variables is nonlinear. For example, when the maximum service time increases from 10 days to 11 days, the reduction of holding cost of total safety stock is $4317, whereas the reduction of holding cost of total safety stock is $1102 when the maximum service time increases from 11 days to 12 days. This observation suggests that the Telecom should take account of both customers' requirement of service time and sensitivity analysis of service time and safety stock holding cost to decide the guaranteed service time.

4.5. Conclusion

The second approach to buffer management is to reduce demand uncertainty by implementing postponement and commonality strategy. The basic principle is that aggregate demand is more stable than disaggregate demand. Namely, forecast of aggregate demand is more accurate than that of disaggregate demand. Thus, if a common module instead of various individual modules in a module family acts as MPS item, the demand of the common module will represent the aggregate demand of all individual modules in the module family and more accurate forecast can be made based on the demand of the common module. By making use of the forecast of demand distribution of the common module, we can figure out detailed safety stock policy of the common module to buffer demand uncertainty. On the other hand, the configuration of customized demand is postponed to the time period that actual order is received. In effect, by implementing postponement and commonality strategy, we change the push-pull boundary from the stage of assembly and testing to the stage of common module production and leave more demand uncertainty to the pull part of the system.

Moreover, to implement commonality, we should tradeoff the cost and the anticipated benefits. Commonality may not be applicable to all module families. The most important module family, optics family, which falls in to category of A according to A, B, C analysis has the foremost priority to implement commonality.

In addition, assuming the common module of optics family, common optics, is realized by product design, the next critical step is to optimize multistage inventory placement to achieve minimum holding cost of total safety stock under a certain forecasted demand distribution of the common optics. By making use of the model proposed by Graves and Willems (2000), a base model of the common optics is built to figure out the optimal multistage inventory placement in the supply chain where the forecasted demand distribution is given. Furthermore, we compare the inventory placements in different scenarios and get the conclusion that more savings on holding cost of total safety stock can be achieved if we implement global optimization based on an integrated supply chain. Finally, we provide a sensitivity analysis to illustrate the relationship between the maximum service time to customers and the corresponding holding cost of total safety stock. According to the analysis, we suggest that the Telecom decides the maximum service time to customers by taking account of both customers' requirements and the relevant safety stock holding cost, especially when the marginal effect of service time to safety stock holding cost is big.

5. Final conclusion and next steps

5.1. *Final conclusion*

Based on a particular case study of the Telecom, this paper has presented two approaches to buffer management under demand uncertainty, which is characterized by lumpiness, dispersion and volatility. The common theme of both of the two approaches is not to find an advanced statistical method to improve demand forecast on the basis of historical data. Rather, these approaches provide new business paradigms to deal with demand uncertainty.

The first approach, MTAO, takes advantage of the mechanism of MTO and develops a process that the production is pulled by anticipated orders instead of being pushed by the forecast of unpredictable future demand. The second approach makes use of postponement and commonality strategy to lower demand uncertainty. Compared to lumpy demand of individual modules, the demand of module family is relatively stable and its future demand can be forecasted in terms of a certain demand distribution. Based on the observation, to consolidate the demand of all individual modules in a module family, a common module is designed and acts as a base module that can be further configured to customized module according to customer's demand. Thus, the common module is produced based on forecast and customization of common module is postponed to the time when actual order is received. Demand uncertainty therefore can be buffered by the safety stock of the common module. Optimized multistage inventory placement can achieve minimum holding cost of total safety stock in the supply chain if the safety stock policy of the common module is determined.

5.2. *Next steps*

Further research is needed and anticipated to develop the two approaches in the following ways:

1. Since the effectiveness of implementing MTAO heavily relies on the analysis of customers' early purchasing information and signals, further study on establishing a new intercompany relationship with customers is meaningful and important to improve the execution MTAO. The key issue of the research is to find out a strategic cooperation framework to direct tactical management and operational control.
2. More managerial tools are anticipated to evaluate the performance of MTAO and to define the environment where MTAO can be properly adopted. The purpose of the research is to improve the research of MTAO from more empirical analysis to systematic and scientific analysis.
3. In depth analytical models are expecting to be developed to control unexpected orders in MTAO, because uncontrolled unexpected orders can intensively decrease the effectiveness of implementation of MTAO.
4. A systematic evaluation model should be developed to decide whether and how to implement commonality strategy. This study should combine product design, process reengineering and financial analysis. The purpose of this research is to find out the best solution among various commonality solutions.
5. In order to achieve global optimization of multistage inventory placement, there are many challenges on how to collaborate all the production units in the supply chain. It needs innovative managerial strategies to establish the new business paradigm,

Bibliographical References

1. Abardanel, Henry D.I (1996) **Analysis of observed chaotic data**, New York: Springer-Verlag, 1996, pp. 15, 199.

2. Anthony (1965) **Planning and Control Systems: A Framework for Analysis**, Anthony R. N., Harvard University Graduate Scholl of Business

3. Baker, K.R., Magazine, M.J., Nuttle, H.L.,(1986) **The effect of commonality on safety stock in a simple inventory model**. Management Science 32, 982-988

4. Bartezzaghi, Emilio and Roberto, Verganti (1995) **Managing demand uncertainty through overplanning**, International Journal of Production Economics 40 (1995) 107-120

5. Bobko, P.B., and Whybark, D.C., (1985), **The coefficient of variation as a factor in MRP research,** Decision Science, 16(4), 420-427

6. Brown, Alexander O., Hau L. Lee, Raja Petrakian (2000) **Xilinx Improves Its Semiconductor Supply Chain Using Product and Process Postponement**,

   Interface 30**:** 4 July–August 2000 (pp. 65–80)

7. Buzacott, J. A. and Shanthikumar, J.G. (1994) **Safety stock versus safety time in MRP controlled production systems**, Management Science, Vol.40, No.12, 1994

8. Fisher, Marshall L., Janice H. Hammond, Walter R. Obermeyer, and Ananth Raman (1994) **Making supply meet demand in an uncertain world**, Harvard Business Review, May-June, 1994

9. Fogarty, D.W., Blackstone, J.H., and Hoffmann, T.R. (1991), ***Production and Inventory Management***, Second Edition, Cincinnati, OH: South-Western Publishing Co.

10. Graves, Stephen C. and Willems, Sean P. (2000) **Optimizing strategic safety stock placement in supply chains**, Manufacturing & Service Operations Management Vol. 2, No. 1, Winter 2000, pp.68-83

11. Hirakawa, Yasuhiro (1996) **Performance of a Multistage Hybrid Push/pull Production Control System**, International Journal of Production Economics, 44, 129-135

12. Ho, C.J. (1995) **Examining the impact of demand lumpiness on the lot-sizing performance in MRP systems**, International Journal of Production Research, 1995, vol. 33, No.9, 2579-2599

13. Howard, K.A., (1994) **Postponement of packaging and product differentiation for low logistics costs**, Journal of Electronics Manufacturing 4, 65-69

14. Inderfurth, Karl (1991) **Safety stock optimization in multistage inventory system**, International Journal of Production Economics 24 (1991)

15. Kaplan, Daniel and Leo Glass (1995) **Understanding nonlinear dynamics**, New York: Springer-Verlag, 1995, pp.27, 11.

16. Kneppelt, L.R., (1984) **Product structuring considerations for master production scheduling**, Production Inventory Management 1984 83-99 (First Quarter)

17. Lee, H.L. (2002) **Aligning supply chain strategies with product uncertainties**, California Management Review, Vol.44, No. 3 Spring 2002

18. Lee, H.L., Billington, C., (1994) **Designing products and processes for postponement**, Kluwer Academic Publishers, Boston

19. Newman, W Rocky, Mark Hanna, Mary Jo Maffei (1993) **Dealing with the uncertainties of manufacturing: Flexibility, buffers and integration**, International Journal of Operations & Production Management, 1993, Vol.13, Iss.1, 19-35

20. Simpson, K.F. (1958) **In-process inventories**, Operation Research, 6 863-873

21. Tang, Ou and Grubbström, Robert W. (2002) **Planning and replanning the master production schedule under demand uncertainty**, International Journal of Production Economics 78 (2002) 323-334

22. Verganti, R. (1997) **Order overplanning with uncertain lumpy demand: a simplified theory**, International Journal of Production Research, Vol. 35, No. 12, 3229-3248

23. Zotteri, Giulio and Verganti, Roberto (2001) **Multi-Level Approaches to Demand Management in Complex Environment: An Analytical Model**, International Journal of Production Economics 71 (2001) 221-233