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Material planning for production kits under uncertainty

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Abstract. A kit is a specific collection of components and/or tools needed for completing a procedure or producing a product. A multiperiod material planning system for production kits under the demand and procurement lead-time uncertainty is considered when component sharing among kits is plausible. Simulation experiments show that component sharing improves the system's service measure of average kit availability and average backorder quantity per period. Also, carrying component safety stock only enhances the benefits of component sharing by reducing the average backorder quantity at the expense of increased inventories, but does not improve the average kit availability.

1. Introduction

A kit is a specific collection of components and/or tools, and possibly instructions needed for completing a procedure or producing a product. Kits are commonly used in medical and dental fields, as well as in product field repair and electronic assembly. In the medical and dental fields, kits are prepared for specific surgical and dental procedures, and they often consist of a combination of tools and supplies (components). For product field repair, kits are prepared to handle multiple repair needs, and in product assembly, kits are prepared for assembling of specific products. Repair and assembly kits often consist of a combination of components and instructions (blue prints).

The primary impetus for using kits is the need for having all the necessary components and instructions available before a procedure is started. In the medical and dental fields, the need is created by the time-critical nature of procedures. For product field repair, the need is created by the desire to provide timely repair with minimal trips to stockroom for additional spare parts. In the product assembly field, the need is created by

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the necessity of improving production and operations management. From an operational standpoint, the benefits of using kits include better control of the work-in-process (WIP) inventory, more efficient use of production workers and machines, better use of shop floor, easier product changeover on a mixed-model line, and better streamlining of component-flow on the shop floor. Most of these benefits could be realized if kits are available for planned and unplanned demand. The focus of this paper is on the material planning for assembly kits.

In a kit-type production environment, the bill-of-material (BOM) of an end product often consists of a number of different kits and (possibly) some unique components not suitable to be kitted. The set of components that form a kit is referred to as its bill-of-kit (BOK). Unlike a BOM that could have multiple levels, a BOK has only two levels. Clearly, requirements for kits are dependent demands as they are tied to the demand for end-products (independent demands). Since the focus of this research is on the material planning for kits, in the experimental studies it is assumed that the demand for kits is analogous to independent demands and the BOKs are akin to the BOMs used in a material requirements planning (MRP) system.

A kit may be prepared by picking components from on-hand stock (picked kit), or by gathering components in a staging area as they arrive in the plant (staged kit). Kits that consist of small-size components are generally picked kits; while those consisting of large-size components are often staged kits. Picked kits are akin to staged kits when no component safety stock is maintained. Without loss of generality the focus of this research is toward staged kits, or just simply kits, and furthermore the impact of component safety stock on the system performance is investigated.

In a production environment that uses kits, the kit itself could be viewed as a subassembly whose material (components) requirements planning is based on a forecast of product demand, and whose preparation is driven by the actual product demand. This hybrid of forecast-based planning of components and observation-based preparation of kits is likely to emerge in both pull and push production systems when preparation times for kits are fairly small and component procurement lead times are fairly substantial. More specifically, in a production system operating according to the pull principle, the demand for a final product (upon receipt) is assigned a promised ship date on the basis of the availability of kits and the product total flow time (i.e., the maximum of the kits' preparation times plus the production time). The kit-preparation orders are then released accordingly. However, since the kits' preparation times are fairly small, kits are in effect prepared (pulled) by the product demand. In a push-type of production system, the orders for end products are planned and released to the shop based on a demand forecast. In practice, most push systems utilize firm planned orders or a frozen time interval to mitigate the nervousness impact of frequently changing forecasts on the entire planning system and ensure stability of production schedules. Analogously, this inclusion of frozen time interval in push systems has the effect of the products' firmed demand orders pulling their respective kits through the BOM structures. Thus, regardless of whether the push or pull principle is applied at the end product level, kits are pulled by demand orders when their preparation times are fairly small and components are acquired based on a demand forecast when their procurement lead times are significant.

In the case of time critical and lumpy demand, large quantities of safety stock must be carried to assure availability of kits when they need to be pulled. The use of component safety stock and/or kit safety stock is a common way of increasing the availability of kits. Thus, increased availability is achieved at the expense of increased inventory costs. Medical and dental fields are good examples of production-like environments where the importance of inventory investment is dwarfed by the urgency of performing the procedure. However, demand for most assembly products is neither lumpy nor time critical, and penalty cost for late delivery is not surmountable. Therefore a reasonable tradeoff between inventory holding cost and availability must be achieved.

In spite of popularity of using kits in product assembly, there appear to be very few kit-specific material planning studies in the literature. Wilhelm and Wang (1986) considered a single-period, single-kit material planning problem with normally distributed component procurement lead-times. Through a mathematical approximation they showed that (1) the worst-case scenario occurs when the components' lead-times are independent from each other, (2) the expected ready time and expected tardiness of a kit increase at a diminishing rate as the number of components in the BOK increases, and (3) the expected kit ready time decreases as safety lead time is increased but the benefit of safety lead time diminishes as the number of components in the BOK increases. Chen and Wilhelm (1993, 1997), and Gunther *et al.* (1996) studied procedures for allocating components to kits. Bozer and McGinnis (1992), and Brynzer and Johansson (1995) studied component picking for kit formation and related material handling issues. Teunter and Haneveld (2002) studied the planning and control of repair kit inventory for household appliances, and Ding and Puvitharan (1990) demonstrated the benefits of kitting components in a heavy metal industry. The benefits of using a master kit (family kit) in a group technology application were investigated by Carlson *et al.* (1994), and the advantages of using component kits to shift product development and innovation to customers were discussed by Hippel and Katz (2002).

In practice, kit planning is most likely to be performed in an uncertain environment as the actual product demand and component procurement lead-time are often random variables. The planning task is further complicated because of potential for component sharing among kits made plausible by BOKs having common components. However, in spite of the prevalence of kit usage in product assembly, the impact of component sharing in an uncertain multiperiod planning environment remains largely unexplored in the literature. This paper focuses on this problem and develops some insights for kit material planning through simulation experiments. Section 2 contains some background information about the complexity of developing mathematical models capable of accounting for demand and lead time uncertainty and component sharing. The simulation experiment is described in detail in section 3, followed by the experimental results presented in section 4. A summary of the findings is presented in section 5.

2. Background

Suppose that demand for finished products in an MRP system is deterministic (i.e., zero forecast error), and kits and components are 'pegged' to their triggering product demand and kit preparation orders, respectively (i.e., no sharing of components among kits or kits among products is permitted). Let $d_i^k(t)$ denote the planned order for kit i during the planning period t. Furthermore, assume each component $C_j \in S_i$, $j = 1, 2, \ldots, n_i$ of the BOK $S_i = \{C_1, \ldots, C_{n_i}\}$ has a fixed planning procurement lead time of l_j periods, and the MRP logic utilizes a lot-for-lot policy. Hence, the MRP explosion of BOKs will readily transform $d_i^k(t)$ to n_i planned procurement orders for the components in S_i. Let $d_j^c(t - l_j)$ represent the procurement order for component C_j, $j = 1, 2, \ldots, n_i$, planned for release in period $t - lj$. If all procurement orders arrive according to their planned lead times, then $d_i^k(t)$ will be released in full and the required kit will be available on time.

Now, suppose the actual procurement lead time for each component C_j is an independent integer-valued random variable, L_j; which implies that the planned procurement order $d_j^c(t - l_j)$, once released, will arrive at period $t - l_j + L_j$. Assuming that all shortages are backordered, the probability of releasing $d_i^k(t)$ in full and thus, having sufficient units of kit i available on time is $\prod_{j \in S_i} P(L_j \leq l_j)$. It should be noted that this probability decreases as the number of components in the BOK structures increases. The importance of on-time kit availability in production and service industry has been thoroughly discussed in Ronen (1992), and it will be used as a performance measure in this simulation study.

Unfortunately, the above straightforward analysis could be done only under restrictive conditions. For the case of random demand and fixed procurement lead time with component sharing, analytical results under mild assumptions are available (see e.g., Yeung *et al.* (1998) for a review of relevant studies within the MRP environment). In general, however, it is exceedingly difficult to analytically determine the probability of kit availability when demand and lead times are both random variables and component sharing is allowed. This difficulty arises from functional dependencies of random variables which require detailed tracking of outstanding procurement orders (curse of dimensionality) and knowledge of demand during actual lead time. Thus under general conditions, simulation appears to be the viable tool for gaining insights on kit availability during the planned period.

Component sharing becomes plausible when there are common components among BOKs. In the inventory control literature, component sharing is often referred to as component commonality. A brief review of the literature indicates that component commonality has been studied from various standpoints. Collier (1981, 1982) using a set of simulation experiments for two-level BOMs with random demand showed that common components reduce the components safety stock requirements due to risk-pooling effect of demand. Baker *et al.* (1986) for a similar BOM and assuming finished product demands following independent uniform distributions minimized the total units of components in stock subject to a service level constraint and showed that use of common components reduces the total amount of safety stock required to meet a specific service level (Property 1). They also found that while the optimal safety stock level of the common component in their model is lower than the combined optimal stocks of the two components it replaces (Property 2), the combined optimal safety stocks of product specific components increases as commonality is introduced (Property 3). Gerchak *et al.* (1988) showed that neither Property 2 nor 3 holds when the costs of the specialized components are not equal for all products. Tsubone *et al.* (1994) reported that introducing component commonality and/or process flexibility can result in a better control over the required buffer inventory and workload at the lower level of a two-stage assembly system with fixed processing times.

Although much of the existing work that examines the risk-pooling and order-pooling impacts of component sharing in the presence of demand uncertainty is directly applicable to the kit preparation problem, the combined impact of components sharing, random product demand, and random procurement lead time in kit material planning systems is largely unexplored. This paper examines this combined impact through a comprehensive multiperiod, multi-kit simulation study where the kits' demand and the components' procurement lead times are random variables, and component sharing is permitted.

3. Research Design

3.1. *The kitting environment*

The kit availability problem is considered within the context of an MRP system with a rolling planning horizon and no component pegging. Components for three kits are acquired based on the kits' planned requirements, $d_i^k(t)$ $i=1,\ldots,3$, and the ith kit, K_i, is prepared only upon observing its actual demands $D_i^k(t)$, $i=1,\ldots,3$, for each period t. The BOK for each kit comprises four components, and a kit's preparation time is one period. The planned procurement lead-time, l_j, for every component C_j is fixed at four periods, while its actual procurement lead time, L_j, is a random variable. Moreover, L_js are considered to be independently and identically distributed (i.i.d.) random variables. Similarly, the actual demands for kits in each period t, $D_i^k(t)$, $i=1,\ldots,3$, are regarded as i.i.d. random variables following a known probability distribution. The system does not maintain any inventory of prepared kits, and unfulfilled demands are fully backordered.

The MRP simulation model is supplied with a rolling-horizon forecast of the kits' net requirements that is treated as the master production schedule (MPS) of kits. The lot-for-lot method of lot sizing is used. At the beginning of each period t, component stocks are replenished based on the actual lead times of procurement orders. Random sampling from the demand distribution then generates the actual demands for all kits in the current period, and component stocks are allocated accordingly. An MRP explosion is carried out next to update the kits' planned requirements and release component procurement orders. For each procurement order when released, an actual receipt date is determined based on an actual lead time drawn from the lead time probability distribution. Finally since component pegging is not used, the allocation of components at any given period occurs as follows: each component's stock is first allocated to actual demand orders from the smallest to the largest quantity. The remainder of the stock is then used for filling backorders in an ascending order of backorder quantities. It is noted that such allocation policy is more likely to be adopted in environments where the penalty for kit shortages is assessed on a per order basis irrespective of how long a particular demand has been backordered.

3.2. *Experimental factors*

The experimental study consisted of four main factors: random demand (D), random component procurement lead times (LT), component safety stock (SS), and kit structure (KS) as a measure of component sharing. These factors are described below and their combined impacts are investigated through a simulation study.

3.2.1. *The demand factor* (D)

The kits' MPS was created by using a constant forecast of 100 units per kit per period over the planning horizon. The actual demand for each kit ($D_i^k(t)$, $i=1,2,3$) during period t was sampled from a series of discrete uniform distributions. Three cases of demand distributions were considered: D1: $U\sim[90,110]$; D2: $U\sim[80,120]$; D3: $U\sim[70,130]$. The actual mean demand for all cases is 100 units but the variability of actual demand increases from D1 to D3.

3.2.2. *The lead time factor* (LT)

In most real-life kitting operations, operation managers plan on a promised delivery date and try to minimize the amount of on-hand inventory; however, they must be prepared to deal with unexpected random disruptions in the supply chain such as equipment breakdowns, traffic and weather conditions that cause tardy deliveries. The case of early delivery of replenishment orders is ignored since it has no negative impact on the on-time delivery of kits, it increases average inventory, and it occurs much less frequently than the late delivery. Moreover, it is noted that a firm may opt to reject early deliveries to avoid excess inventories. Therefore, in the simulation study a constant planning lead time of four periods is used for the procurement of all components ($lj=4$ for $\forall j$); however, the actual procurement lead time of each component, L_j, is subject to a random delay. That is, $L_j=l_j+\tau$ for $\forall j$, where τ is a non-negative random variable following a discrete distribution. Table 1 shows five cases of discrete probability distributions with increasing mean and probability of lateness that were considered to represent τ.

3.2.3. *The safety stock factor* (SS)

To explore the impact of maintaining component safety stocks in the kit-planning problem the following four safety stock scenarios are considered. SS1: the system carries no safety stock for components; SS2: the

Table 1. Distributions of actual lead time lateness.

Lateness	$\tau=0$	$\tau=1$	$\tau=2$	$\tau=3$	$\tau=4$	Mean $E[\tau]$	$P(\tau>0)$
Level							
LT1	1	0	0	0	0	0	0
LT2	0.60	0.25	0.1	0.05	0	0.60	0.40
LT3	0.45	0.25	0.15	0.10	0.05	1.05	0.55
LT4	0.30	0.25	0.20	0.15	0.1	1.50	0.70
LT5	0.20	0.20	0.20	0.20	0.20	2.00	0.80

system carries nine units of safety stock for all components; SS3: the system carries nine and 20 units of safety stock for unique and common components, respectively; SS4: the system carries nine and 27 units of safety stock for unique and common components, respectively.

3.2.4. *The kit structure* (KS)

Four kit structures (KSs) are considered, each consisting of three kits (K_i, $i=1,2,3$). Component sharing among kits is plausible in three of the four structures since kits in those structures have common components. The BOKs for the four kit structures KS1, KS2, KS3, and KS4 are given in table 2. Note that each kit consists of four components, but the total number of components used in each kit structure varies from 12 components in KS1 to six components in KS4. This difference is due to the use of common components.

3.3. *Performance measures*

A key measure of interest in any kitting operation is the system's responsiveness or its ability to prepare the required kits on time (kit availability). When demand and supply are both deterministic, the MRP logic can be effectively utilized to achieve full responsiveness with no excess inventories. However, when demand and/or supply are uncertain, a tradeoff among system responsiveness, inventories, and backorders needs to be sought. As such, the system performance was studied in terms of the following three simulated performance measures. PM1: average total inventory of components per period; PM2: average proportion of total kits' demand orders fully satisfied per period; PM3: average total backorder of kits per period. It should be noted that PM2 is a surrogate for kit availability.

The above performance measures were obtained over a planning horizon of 50 periods. However, to minimize the impact of initial conditions, simulation experiments were performed for a planning horizon of 70 periods and the results of the first 20 periods were not included in the calculation of performance measures. Each experiment was replicated ten times.

Table 2. Bill-of-kits (BOKs) for the four kit structures (KSs).

	KS1			KS2			KS3			KS4		
	K_1	K_2	K_3	K_1	K_2	K_3	K_1	K_2	K_3	K_1	K_2	K_3
C_1	1			1			1			1		
C_2	1			1			1					
C_3	1			1								
C_4	1											
C_5		1			1			1			1	
C_6		1			1			1				
C_7		1			1							
C_8		1										
C_9			1			1			1			1
C_{10}			1			1			1			
C_{11}			1			1						
C_{12}			1									
C_{13}				1	1	1	1	1	1	1	1	1
C_{14}							1	1	1	1	1	1
C_{15}										1	1	1

4. Experimental results and analysis

A full factorial ANOVA involving 240 experimental scenarios was conducted ($3\mathrm{D}\times 5\mathrm{LT}\times 4\mathrm{SS}\times 4\mathrm{KS}$). The ANOVA results are presented in table 3. The results show that the four main factors significantly influence all three performance measures. The impact of interaction between the lead-time and demand uncertainty on the average inventory and the average kit availability (average proportion of orders fully satisfied per period) is also found to be significant. This two-factor interaction, however, does not appear to significantly influence the average backorders per period. By the same token, although the average inventory per period is not significantly influenced by the interaction between kit structures and lead time uncertainty, it is found that the impact of this two-factor interaction on the average kit availability and the average backorders per period to be significant. All other two- and three-factor interactions among the main factors are found to be insignificant. It should be noted that the calculated Cronbach's alpha (reliability index) for all three performance measures was more than 0.99.

Figure 1 depicts the plots of average proportion of orders fully satisfied per period (average kit availability) versus average total inventory per component per period for each kit structure and various cases of lead time and demand uncertainty when no component safety stocks are carried in the system (i.e., SS1). It is noted that while the average inventory per component in all cases

Table 3. Results of analysis of variance (ANOVA) for the three performance measures.

		PM1		PM2		PM3	
Source	*df*	*F*	*p*	*F*	*p*	*F*	*p*
KS	3	3.49	0.015*	84.15	0.000*	23.80	0.000*
LT	4	295.75	0.000*	3319.63	0.000*	2286.42	0.000*
D	2	86.59	0.000*	3.76	0.023*	11.99	0.000*
SS	3	3.01	0.029*	2.70	0.044*	4.45	0.004*
KSˆLT	12	0.49	0.919	6.12	0.000*	2.69	0.001*
KSˆD	6	0.12	0.994	0.05	1.000	0.38	0.890
LTˆD	8	4.32	0.000*	16.36	0.000*	1.65	0.105
KSˆLTˆD	24	0.05	1.000	0.13	1.000	0.04	1.000
KSˆSS	9	0.55	0.885	0.20	1.000	0.06	1.000
LTˆSS	12	0.01	1.000	0.26	0.995	0.29	0.991
KSˆLTˆSS	35	0.00	1.000	0.01	1.000	0.01	1.000
DˆSS	6	0.00	1.000	0.01	1.000	0.00	1.000
KSˆDˆSS	18	0.00	1.000	0.01	1.000	0.00	1.000
LTˆDˆSS	24	0.00	1.000	0.07	1.000	0.00	1.000
KSˆLTˆDˆSS	72	0.00	1.000	0.01	1.000	0.00	1.000

*Marks statistical significance at the 0.05 level.

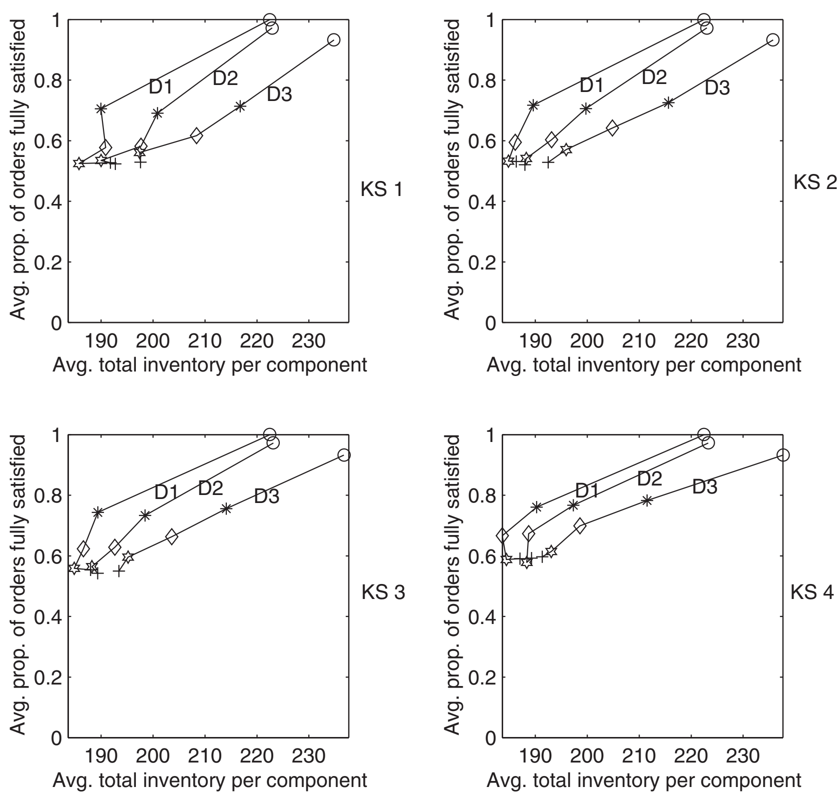

Figure 1. Plots of the average kit availability versus average inventory per component per period with no safety stock (0, LT1; *, LT2; ◇, LT3; *, LT4; +, LT5)

increases with demand uncertainty, the average kit availability displays a mixed behaviour as demand uncertainty increases. As expected, the highest average kit availability in all cases of demand uncertainty is achieved when lead times are deterministic. Accordingly, when lead times are deterministic, the average kit availability slightly decreases as demand uncertainty is increased. However, when lead time delays are random, the average kit availability displays a nondecreasing trend as demand uncertainty increases. It should also be noted that when demand is random, the average inventory per components and the average kit availability tend to decrease concurrently as the lead-time uncertainty increases. Finally, these plots imply that under similar circumstances, kit structures with larger degrees of component commonality (greater component sharing) can generally result in a higher average kit availability as well as a lower average total inventory per period than structures with smaller degrees of commonality (sharing).

Table 4 contains the average values of the three performance measures considered in this study for each case of the kit structures. These values were computed by averaging the observed values of each performance measure over all experimental scenarios that shared the same type of kit structures. These results clearly suggest that more component sharing improves the performance of the kitting operation in terms of the average inventory of components, average kit availability, and average total backorders per period.

To test the statistical significance of the above observations, the following three hypotheses were formed:

Hypothesis 1 (H1): the higher the component sharing among the kits, the lower the average total inventory of components per period.

Hypothesis 2 (H2): the higher the component sharing among the kits, the higher the average kit availability per period.

Hypothesis 3 (H3): the higher the components sharing among the kits, the lower the average total backorders per period.

Each hypothesis was tested through a series of pair-wise comparisons between all possible combinations of the kit structures considered in this study. The power of these tests are: at least 0.99 for the average kit availability, ranged from 0.748 to 0.88 for the average inventory, and ranged from 0.447 to 0.793 for the average backorder quantities. Table 4 presents the t-test results for these hypotheses. Note that while H2 and H3 are supported in the majority of the cases considered, H1 is only supported when the difference in the amount of component sharing among the kits is at a fairly large level (i.e., KS3 and KS4). The test results are in general agreement with earlier findings from ANOVA as they confirm that the primary benefits to be sought from component sharing in stochastic kitting environments lie in improved average kit availability and reduced backorder quantities. However, the average inventory reductions tend to become statistically significant only when component sharing among kits increases substantially.

Table 4. Average values of performance measure for the four kit structures.

KS	KS1	KS2	KS3	KS4
PM				
PM1	2463.25	2434.28	2431.73	2413.41
PM2	0.6699	0.6817	0.7020	0.7274
PM3	143.20	137.44	132.71	120.47

5. Summary

In this paper the focus has been on material planning within the context of a kit-preparation system where kit demands and component procurement lead times are random variables. A comprehensive simulation study was conducted to explore the combined impacts of uncertainty in demand and procurement lead times, component sharing among kits, and components safety stocks on a system's performance. The performance measures considered in the study included average total inventory of components per period, average proportion of total demand orders fully satisfied per period (average kit availability), and average total backorders per period.

The experimental results revealed interesting insights into the nature of the kit material-planning problem when both demand and lead time are subject to uncertainty. The main insights include: (1) component sharing, randomness of demand and lead time, and component safety stock significantly impact all three performance measures; (2) component sharing reduces the average total inventory per period. The inventory reduction, however, is only considered to be statistically significant when component sharing among kits is substantial; (3) the average kit availability increases significantly as component sharing increases; (4) while the impact of component sharing on the average backorder per period is generally significant, nevertheless, the greater the level of component sharing among kit

Table 5. The values of pair-wise t-statistics for the three hypotheses.

	KS2			KS3			KS4		
	H_1	H_2	H_3	H_1	H_2	H_3	H_1	H_2	H_3
KS1	−1.533	0.971	−0.905	−1.680*	3.056*	−1.673*	−2.625*	5.799*	−3.778*
KS2				−0.133	2.078*	−0.763	−1.078	4.819*	−2.856*
KS3							−0.953	2.760*	−2.094*

*The hypothesis is accepted at the 0.05 level.

structures, the more significant the reduction in the average backorder per period; (5) carrying component safety stocks increases the average inventory per period, but reduces the average total backorder, and improves the average kit availability at a significant level.

Overall, this study suggests that when demand and procurement lead times are random variables, the main advantages of utilizing component sharing in kit material planning systems lie in an improved system's service measure such as average kit availability and average backorders per period. Carrying a level of components safety stock can enhance the benefits of component sharing by reducing the average backorder quantities and improving the average kit availability at the expense of increased inventories.

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