IMPACT OF SYSTEM PARAMETERS AND SCHEDULING POLICIES ON SYSTEM PERFORMANCE IN MATERIAL REQUIREMENTS PLANNING SYSTEMS

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ABSTRACT

We study the impact of lot sizes, product structure depth, and frequency of rescheduling, as well as the interaction among these factors, in Material Requirements Planning Systems. We analyze single-product arborescent assembly systems with stochastic demand and measure the performance of the system using a fill-rate criterion. The results indicate that there are substantial interactions among these factors including some compensating effects.

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EXECUTIVE SUMMARY

We study the impact of lot sizes, product structure depth, and frequency of rescheduling, as well as the interaction among these factors, in Material Requirements Planning Systems. We analyze single-product arborescent assembly systems with stochastic demand using simulation and measure the performance of the system using a fill-rate criterion.

The results indicate that there are substantial interactions among these factors including some compensating effects. The deeper and more complex the product structure, the smaller the service level achieved for a given level of finished product safety stock. However, provided that finished product safety stock is adequate, the absolute size of the impact may be small. In addition, allowing frequent rescheduling may help to offset the service level decline, but at the expense of additional setups.

Choices regarding frequency of rescheduling strongly influence the service level achieved from any lot size combination. Therefore, rescheduling frequency and lot sizing must be optimized jointly in order to achieve the best overall policy.

The interactions are numerous and complex, but some of the results and insights reported in this paper, along with future research, will begin to clarify these issues.

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1. INTRODUCTION

Controllable input parameters for Material Requirements Planning (MRP) systems and the frequency of rescheduling used in such systems often are selected without consideration of the effects of such choices on system performance. A primary reason for this lack of systematic decision-making in MRP environments is that little research has been done, and what has been done is not widely distributed. Wagner (1980) states, among other things, that "clearer insights about design and decision tradeoffs" in MRP systems are needed.

We investigate the collective effects of product structure (bill of materials) depth, lot-sizing, and frequency of rescheduling in a single-product arborescent assembly system with stochastic demand. Literature in this area is limited. Bannerjee (1979) reports on a simulation study which indicates that scheduling policies (lot-sizing and sequencing) have a significant effect on system performance measured by his multi-criteria scores.

We describe the problem in Section 2 and the simulation model used to study these effects in Section 3. We then discuss the impact of product structure depth and lot-sizing in Sections 4 and 5, respectively. The effects of frequency of rescheduling are incorporated into these sections, also. We conclude with a discussion in Section 6.

2. ELEMENTS OF THE PROBLEM

We study a single-product arborescent assembly system with stochastic demand. We assume that there are no production or storage capacity constraints, that only demand is uncertain, and that all unfilled demand is backlogged. The parameters to be varied are product structure depth, lot sizes, and frequency of rescheduling. We consider two different product structures, one with two levels and the other with three levels, as illustrated in Figures 1 and 2.

FIGURES 1 AND 2

Lot sizes are varied by changing the "natural cycle." The term "natural cycle" was coined by Baker (1977). It is equal to $(2S/Dh)^{.5}$, where S is the setup cost, D is the expected demand per period, and h is the unit holding cost per period. It can be viewed as the Period Order Quantity (POQ) interval, or the average time between production setups. The service level is measured as percent of demand filled immediately from stock, also known as "fill-rate." The interaction of rescheduling frequency with product structure depth and natural cycle lengths also is analyzed.

These effects are studied within a rolling horizon framework. A rolling production schedule or plan is composed of the first-period plan of each of a series of finite-horizon plans. Operationally, one would establish a plan on the basis of known demand requirements or forecasts for a finite horizon and implement only the plan for the first period in that horizon. Forecasts may be updated and additional forecasts included before a new plan is devised. The process continues in this manner. Most MRP systems use a rolling horizon.

Two rescheduling policies are used in this study. We refer to the first as "fixed scheduling," while the second is called "flexible scheduling." Under fixed scheduling, the timing of planned setups is fixed far in advance, eliminating "nervous" schedules in which the timing of planned setups changes as the schedule rolls forward. In the fixed scheduling environment neither emergency orders nor expediting is allowed. However, planned production quantities are allowed to vary until the production run is begun, at which time the quantity is fixed.

In the flexible scheduling environment, replanning occurs each period. Both timing and quantity of production runs may change. Emergency setups may occur but are not scheduled solely to replenish safety stock.

3. SIMULATION MODEL

We developed a simulation model to analyze the effects of product structure depth, natural cycle lengths, and scheduling policies on service levels. We vary end-item safety stock levels and level of demand variability in order to evaluate their effects as well. While the simulation model also tabulates costs, in this paper we are concerned only with the effects of these parameters on service levels. Optimization of the cost-service level tradeoff is addressed elsewhere (Carlson and Yano 1981a,b).

Demand is distributed normally with mean μ equal to 200 per period and and standard deviation σ of 10, 30, or 50. We consider this range of standard deviations sufficiently large to cover many demand scenarios. It seemed reasonable to use a stationary demand process from which to infer general relationships.

Natural cycles of the end-item take on values of 2 and 4 in the two-level product structure, with each second-level component having a natural cycle of 1, 2, or 3 times that of its parent. We set the end-item natural cycle to 2 for the three-level product structures to permit a greater range of natural cycle lengths on the second and third levels. Second-level components have natural cycles of 2, 4, or 6, while each third-level component has a natural cycle of 1, 2, or 3 times that of its parent, up to a maximum of 12.

We use the Wagner-Whitin (1958) algorithm for each item in the product structure, starting with the end-item and continuing toward the raw materials. The desired natural cycle is achieved by setting the setup cost so that $(2S/\bar{D}h)^{.5}$ equals the desired natural cycle. Since demand is assumed to be stationary and normally distributed, the demand forecast in each period is equal to mean demand.

Order quantities are updated as necessary to reflect deviations in demand from the forecast. When demand is stationary (but stochastic), this type of updating policy results in order quantities which are equal to demand since the last such order was placed. Therefore, this is effectively an "order-up-to" or single critical number type of policy. For each item, the critical number is equal to mean demand during the leadtime plus natural cycle, plus safety stock (if any).

We use a planning window of 24 periods, which in all cases is at least twice the length of the natural cycle of the component with the largest natural cycle. Notice also that 24 is an integral multiple of all natural cycles in each product structure. Therefore we would expect that near-optimal lot-sizing results would be obtained (see Baker (1977) and Blackburn and Millen (1980,1982)).

The "fixed schedule" is achieved by fixing the timing of all orders for an interval equal to the largest integral multiple of the natural cycle less than the length of the planning window. For instance, an item with a natural cycle of 4 periods would have its schedule fixed for 20=((24/4)-1)x4 periods. This technique limits any instability to the periods near the end of the planning window, thereby eliminating "nervousness" in the production schedule.

Each observation from the simulations represents the results of rolling the horizon forward 24 times. Actual backorders and demand are tabulated and used to calculate fill-rates.

We begin with an analysis of the impact of product structure depth on service levels in Section 4. This is followed by results of a study of the effects of natural cycle lengths and their combinations on service levels.

The following notation is used throughout the paper:

T_i = natural cycle of item i

L_i = leadtime for item i

k_i = safety stock multiplier for item i where

$$\text{safety stock quantity} = k_i\sqrt{T_i+L_i}\ \sigma$$

4. IMPACT OF PRODUCT STRUCTURE DEPTH ON SERVICE LEVELS

Product structure depth may appear to be a non-controllable factor in MRP systems, but indeed, it is not. The product structure depth may be decreased in a number of ways: increasing job diversification (number of tasks done by a particular worker or at a particular work station), and collapsing those portions of the product structure where parts need not be treated separately for scheduling purposes. In either case, this reduction necessitates a redefinition of components to a lesser degree of detail for the MRP explosion.

We first analyze service levels in a two-level product structure with a fixed schedule on level 1 in order to determine whether the presence of the second level with positive leadtime causes deterioration of the service level from the "theoretical value." To make a fair comparison, we calculate the "theoretical" service level as if there were a single level with the actual cumulative leadtime of the product. The cumulative leadtime is the total time required to produce the product from the earliest raw materials and components orders to completion. All leadtimes are set equal to one period, the smallest possible positive leadtime. Second-level component safety stocks are set equal to zero to isolate the effect of the presence of the second level.

We examine situations in which the natural cycles of all items in the product structure are equal. These situations are most similar to the hypothetical single-level product structure on which the theoretical service level is based. We measure the statistical significance of the difference between the average service level from the simulations and the theoretical service level using t-statistics.

These t-statistics are based on 120 observations and are presented in Tables 1 through 4 for a range of end-item safety stock levels and levels of demand variability. The corresponding levels of statistical significance are indicated by the value of α. It is clear that the presence of the second level causes deterioration of the service level beyond that which would be caused by the increased leadtime alone. The differences are statistically significant when either rescheduling policy is used on the second level. The impact is more significant statistically when small quantities of end-item safety stock are used, and the level of statistical significance decreases as end-item safety stock increases. The reason for this trend may be that when large quantities of end-item safety stock are present, shortages of second-level components are less critical because the end-item safety stock can absorb demand fluctuations more easily. Small quantities of end-item safety stock cannot absorb the impact of both end-item and component shortages.

TABLES 1 THROUGH 4

We next analyze service levels in a three-level product structure in two different situations. The first uses fixed scheduling on all three levels, while the second uses flexible scheduling only on level three. Again we examine only situations in which the natural cycles of all components are equal. The intent here is to analyze the impact of the third level when schedules on the first and second level are relatively stable.

We did not study scenarios with other scheduling policies because simulation results for situations in which flexible scheduling is used on more than one level indicated that the resulting chaotic schedules perform poorly.

Summary statistics using 60 replications are presented in Tables 5 and 6. The t-statistics are used to measure the statistical significance of the difference between the simulated service levels and theoretical service levels. Observe that for small quantities of end-item safety stock, the presence of the second and third levels with positive leadtime causes statistically significant deterioration of the service level from the theoretical value. The level of statistical significance is not as high as in the two-level product structure for two reasons. First, the variability of the service level is much higher in the three-level product structure than in the two-level product structure. This is partially attributable to the smaller number of replications available for the three-level structure. However, the magnitude of the effect exceeds that which can be attributed to this factor alone. Therefore, it appears that there is an increase in service level variability due to the addition of the third level.

TABLES 5 AND 6

Although the levels of significance are somewhat lower than in the two-level product structure, it is evident that the presence of additional levels in the product structure causes measurable service level deterioration when either scheduling policy is used on the third level.

5. IMPACT OF NATURAL CYCLE COMBINATIONS ON SERVICE LEVELS

The impact of natural cycle lengths of second- and third-level components upon service levels depends primarily upon the frequency of rescheduling. We analyze a large number of two-level product structures and a moderate number of three-level product structures, varying demand variability and the end-item safety stock level and natural cycle lengths of the components on the lowest level. We set the second- and third-level safety stock at zero in order to isolate the effects of the natural cycle lengths upon service levels. Leadtimes are set equal to one period. Throughout this section we will present representative results, generally choosing one value of demand variability. A complete set of results is available from the authors.

We first study the two-level product structures. Each data point is the mean of a large number of problems with randomly generated demand, each having a 24-period horizon. The number of problems is 120, composed of 6 sets of 20 problems, in the cases of

$\underset{\sim}{T} = (2,2,2)$ $\qquad$ $\underset{\sim}{T} = (4,4,4)$

$\underset{\sim}{T} = (2,4,4)$ $\qquad$ $\underset{\sim}{T} = (4,8,8)$

$\underset{\sim}{T} = (2,6,6)$ $\qquad$ $\underset{\sim}{T} = (4,12,12)$

and 240 problems, composed of 12 sets of 20 problems, in the cases of

$\underset{\sim}{T} = (2,2,4)$ $\qquad$ $\underset{\sim}{T} = (4,4,8)$

$\underset{\sim}{T} = (2,2,6)$ $\qquad$ $\underset{\sim}{T} = (4,4,12)$

$\underset{\sim}{T} = (2,4,6)$ $\qquad$ $\underset{\sim}{T} = (4,8,12)$

The reason for the difference is the manner in which loops were implemented in the simulation code. We chose to use all available results. A set of 20 randomly generated problems was simulated for each natural cycle and various holding cost combinations. The mean service level for each set provides one observation which is assumed to be distributed approximately normally. Figure 3 illustrates, for a typical case, the effect of second-level natural cycle combinations when fixed scheduling is used throughout.

FIGURE 3

There are two factors which contribute to the discrepancy between the theoretical and average simulated service levels. One factor is the deterioration from the theoretical level resulting from the presence of the second level with some positive leadtime, as discussed in the last section. The second factor is the combination of natural cycles of second-level components and their relationship to the end-item natural cycle. This is the effect of concern here.

Statistical analyses of the differences are done using Bonferroni t-statistics for multiple comparisons. There are C_2^6 = 15 pairwise comparisons for the two-level product structures, and C_2^7 = 21 pairwise comparisons for the three-level product structures. Notice that there are 6 combinations of second-level natural cycles in the two-level product structure, and seven combinations of third-level natural cycles in the three-level product structure.

Only a few of the differences are statistically significant at the = .10 level because of the large number of comparisons.

A portion of the t-statistics is presented in Table 7 along with the relevant data. The t-statistics decline as end-item safety stock increases, so it is necessary to calculate only a few values in each table to determine which differences are significant.

TABLE 7

The t-statistics for cases in which $T_1 = 2$ indicate that the natural cycle vector $\underset{\sim}{T} = (2,4,2)$ yields significantly worse performance than the natural cycle vectors $\underset{\sim}{T} = (2,2,2)$ and $\underset{\sim}{T} = (2,4,4)$ at the same end-item safety stock level. One possible reason for this is that when $\underset{\sim}{T} = (2,4,2)$, one second-level component suffers frequent shortage occasions resulting from frequent setups every two periods while the other suffers from the relatively more severe shortages which may occur every four periods.

We can make a few additional generalizations. First, service levels tend to deteriorate from the "baseline" natural cycle vector $\underset{\sim}{T} = (2,2,2)$ whenever the natural cycles of second-level components are not equal to one another. Second, the extent of the deterioration decreases in absolute value and in statistical significance as the end-item safety stock level increases.

None of the t-statistics for cases in which $T_1 = 4$ is significant at the $\alpha = .10$ level. However, the same trends exist as for $T_1 = 2$. The reader is referred to Yano (1981) for details.

We now turn to two-level product structures using fixed scheduling on level 1 and flexible scheduling on level 2. Figure 4 illustrates, for a typical case, the effects of second-level natural cycle combinations in this environment. From an examination of the figure it is clear that serious deterioration of service levels from the baseline does not occurs. For some combinations of second-level natural cycles, service levels may actually exceed that of the baseline case. It appears that the use of flexible scheduling on the second level provides such high availability of components that the negative influence on service levels of the presence of the second level is offset, either partially or entirely, by the positive impact of increased availability.

FIGURE 4

t-statistics for some scenarios in which $T_1 = 2$ are presented in Table 8. One generalization that can be made is that natural cycle combinations in which at least one second-level component has a natural cycle equal to the end-item natural cycle result in lower service levels than other natural cycle combinations. It appears that the frequent setups for one second-level component produces frequent stockout situations, and emergency setups cannot improve availability.

TABLE 8

t-statistics for T_1=4 are presented in Table 9. The same trends exist as for T_1=2 but the differences are less significant statistically. It appears that as the natural cycle of the end-item increases, the relative impact of natural cycle lengths of second-level components decreases. Recall that this trend also was evident in the scenarios with fixed scheduling throughout.

TABLE 9

We now turn to an analysis of natural cycles of third-level components. We examine the natural cycle combinations $\underset{\sim}{T}$ = $(2,2,2,T_4,T_5,T_6,T_7)$, and $\underset{\sim}{T} = (2,4,4,T_4,T_5,T_6,T_7)$, where T_4 through T_7 may take values equal to 1, 2, or 3 times the natural cycle of the parent. These configurations enable us to isolate the effects of third-level natural cycle combinations in a systematic manner. We set all component safety stock to zero, and all leadtimes equal to one period. Two scheduling policies are examined. The first utilizes fixed scheduling on all three levels and the second uses fixed scheduling on levels 1 and 2, with flexible scheduling on level 3.

For each combination of natural cycles of third-level components, we simulated several sets of 10 problems. The number of sets available for each combination of natural cycles follows:

Natural Cycle Combinations	Number of Sets of Problems
$T_4 = T_5 = T_6 = T_7$	6
$\{T_4, T_5, T_6, T_7\}$ composed of two elements	7
$\{T_4, T_5, T_6, T_7\}$ composed of three elements	12

The average of each set is treated as one observation which is distributed approximately normally.

The results for a typical case for each scheduling policy are illustrated in Figures 5 and 6 . The natural cycles of the third-level components have the same impact on service levels as do the second-level components qualitatively. However, statistical analyses using Bonferroni t-statistics indicates that the differences among service levels are not significant at the

α = .10 level.

FIGURES 5 AND 6

We conclude, therefore, that the impact of natural cycle combinations of third-level components on service level is not significant. Moreover, it appears that the impact of natural cycle lengths decreases as one moves further into the product structure.

6. DISCUSSION

The results in Section 4 confirm common intuition. One would expect that the deeper and more complex the product structure, the smaller the service level achieved for a given end-item safety stock level. One result of interest is that the impact of additional levels in the product structure appears to decrease as end-item safety stock levels are increased. Therefore, provided end-item safety stock levels are sufficiently large, the effect of additional product structure depth or complexity on service levels may be small. This result may, at first appear to be counterintuitive. However, observe that components on levels deeper in the product structure generally have longer natural cycles. In real applications, this is true primarily because of large setup costs or long setup times. Since demand in each period is assumed to be independent, the coefficient of variation of total demand during a cycle decreases as the cycle length increases. The level of service for an individual component will increase as the cycle length increases, resulting in declining (detrimental) effect on the ultimate service level to the customer.

Another interesting result is that flexibility in rescheduling partially or entirely offsets the effect of additional product structure depth. This fact can be important in implementation of MRP systems, particularly when the deepest levels of the system pertain to raw materials or parts purchased in large quantities. Occasional early setups may be acceptable when orders are placed infrequently, and a flexible ordering schedule may provide for important increases in the service level at very little cost.

The results regarding the effects of natural cycle lengths and their combinations are important. Often frequency of setups is determined as if the demand were deterministic. In such situations natural cycle combinations do not affect service levels. However, when demand is stochastic, situations may arise (as we have seen here) wherein there are tradeoffs between safety stock on one level and lot sizes on another level. These interactions are extremely difficult to model, but even more difficult is the development of procedures or algorithms which can provide tools that are useful to the practitioner. This remains a fertile research area.

The interaction between natural cycle combinations and scheduling policies is also an important finding. This result become "intuitively obvious" after some analysis, but otherwise is very subtle. It is well-known that emergency setups or expediting can influence service levels. However, the fact that the degree of scheduling flexibility affects the number of emergency setups, which in turn affect the service level, is less evident. Further research is needed to jointly optimize lot sizes and frequency of rescheduling.

We have discussed the effects of various system parameters and their interactions on the level of service ultimately provided by the production system. An understanding of these effects permits systematic analytical modeling and optimization of such systems considering costs as well as service. Some of these findings motivated the development of algorithms to determine near-optimal safety stock levels for second-level components (see Yano and Carlson, 1981a and b), and to examine the economics of rescheduling frequency (Yano and Carlson 1984). Further research is needed to understand these issues more fully.

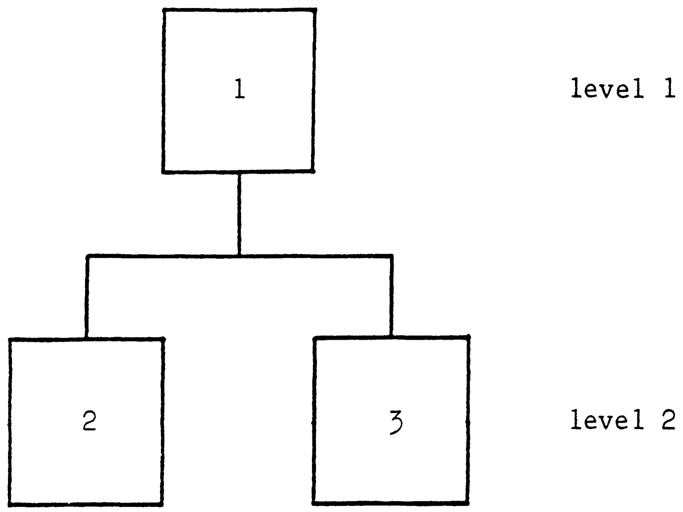

Figure 1

Two-Level Product Structure With Component Numbers

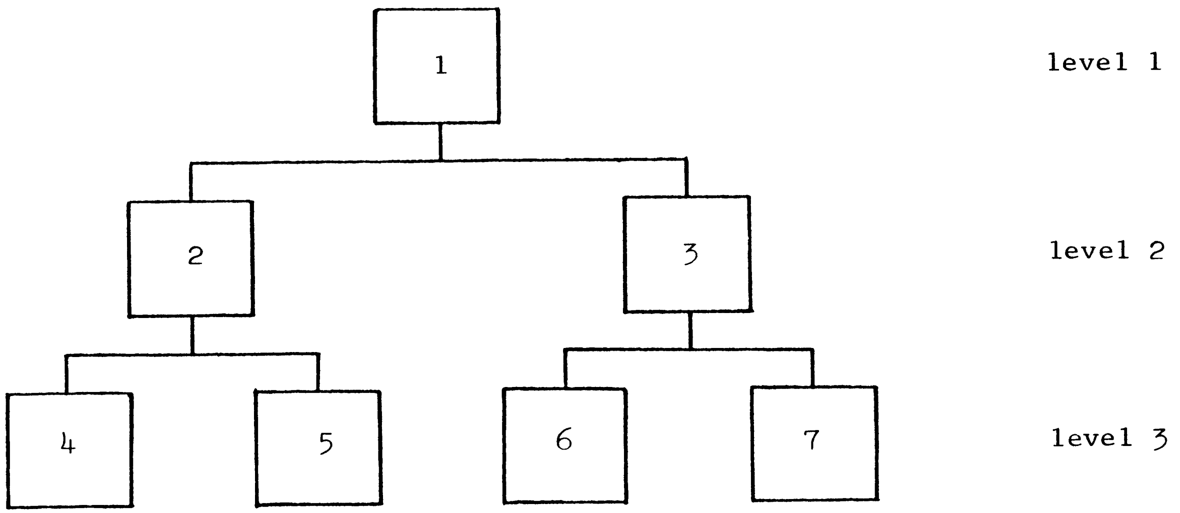

Figure 2

Three-Level Product Structure With Component Numbers

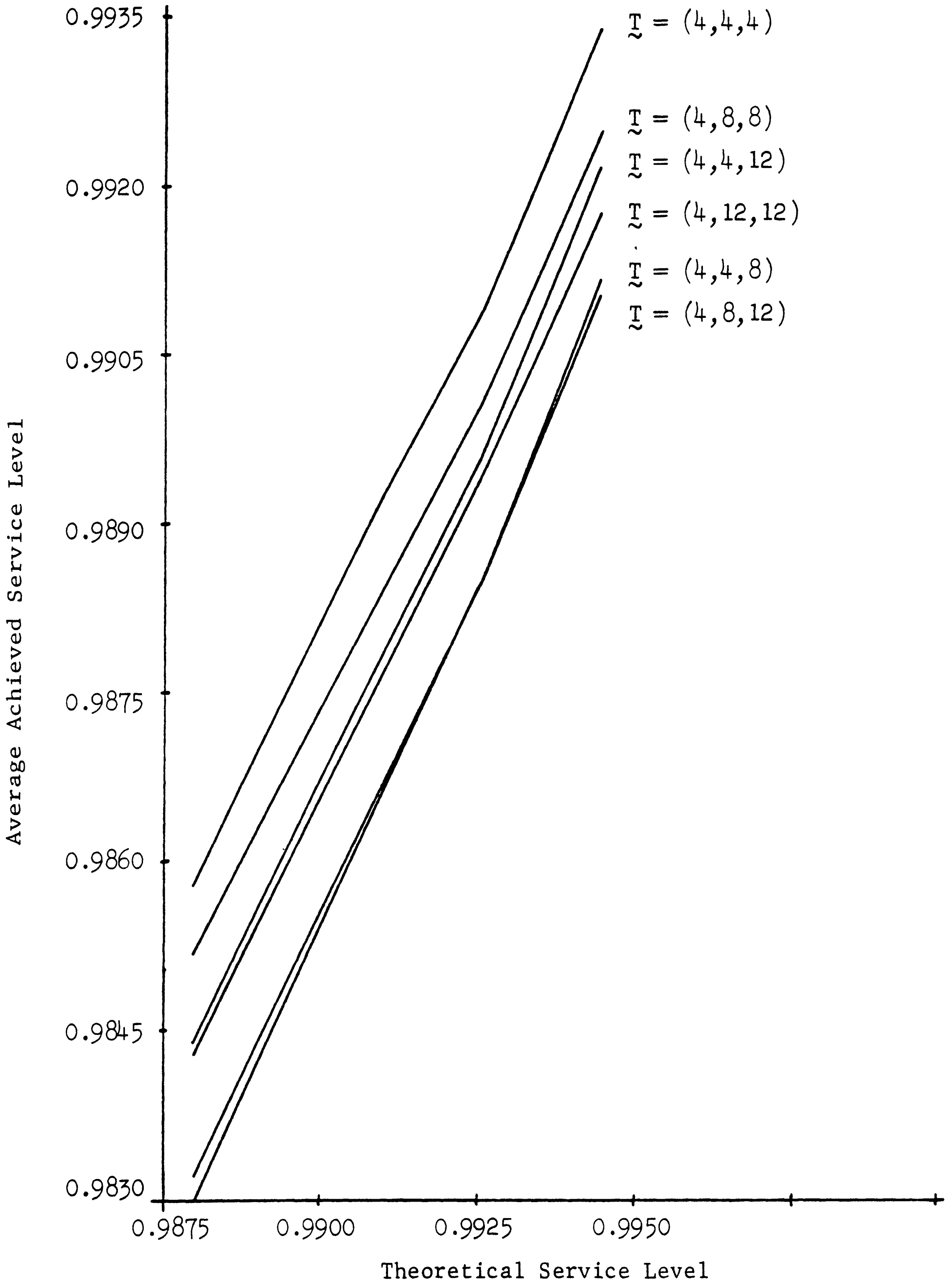

Figure 3

Average Achieved Service Level as a Function of Theoretical Service Level: $T_1 = 4$, $\sigma = 10$ With Fixed Scheduling

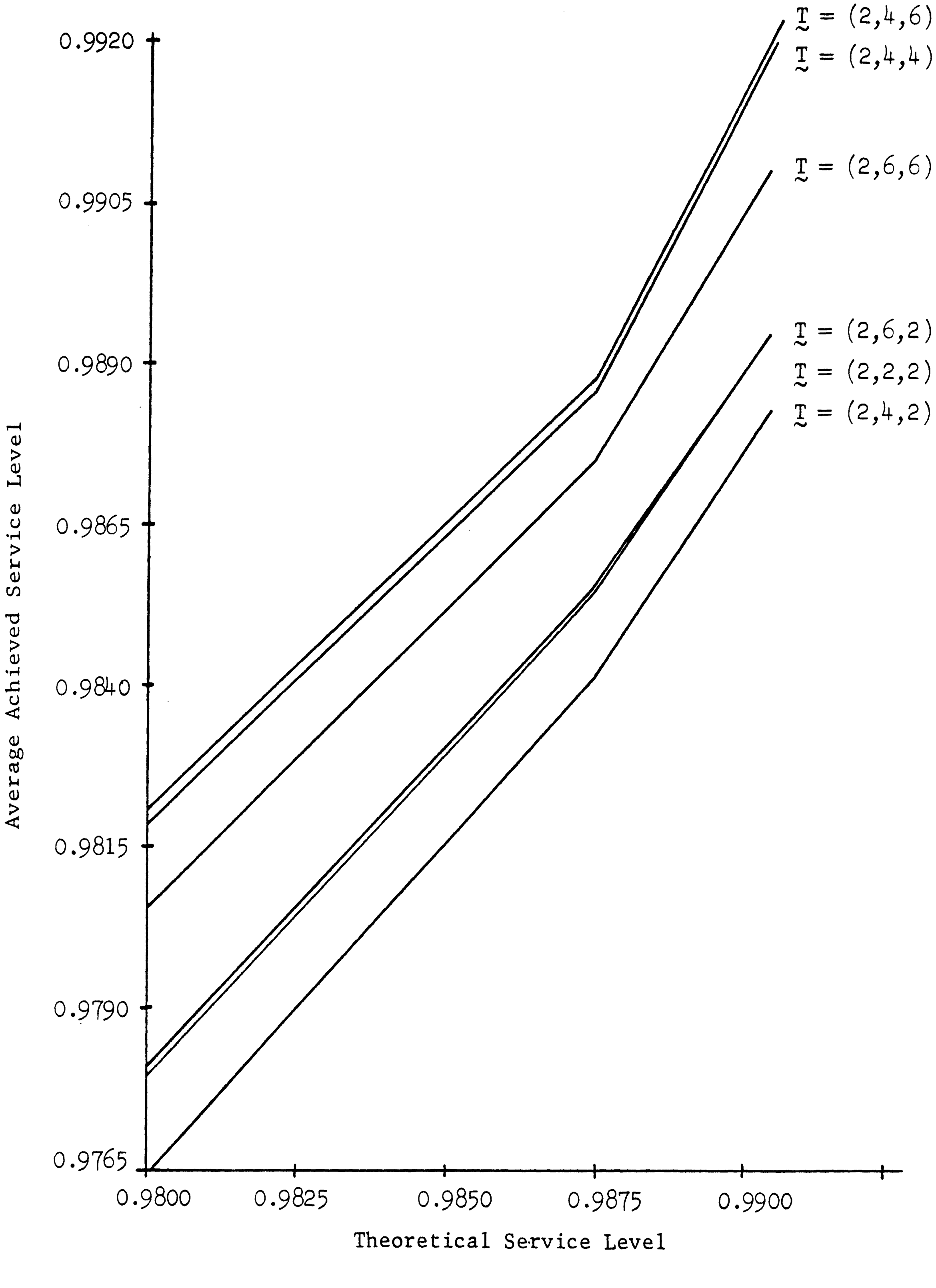

Figure 4

Average Achieved Service Level as a Function of Theoretical Service Level: $T_1 = 2$, $\sigma = 10$ With Fixed Scheduling on Level 1 and Flexible Scheduling on Level 2

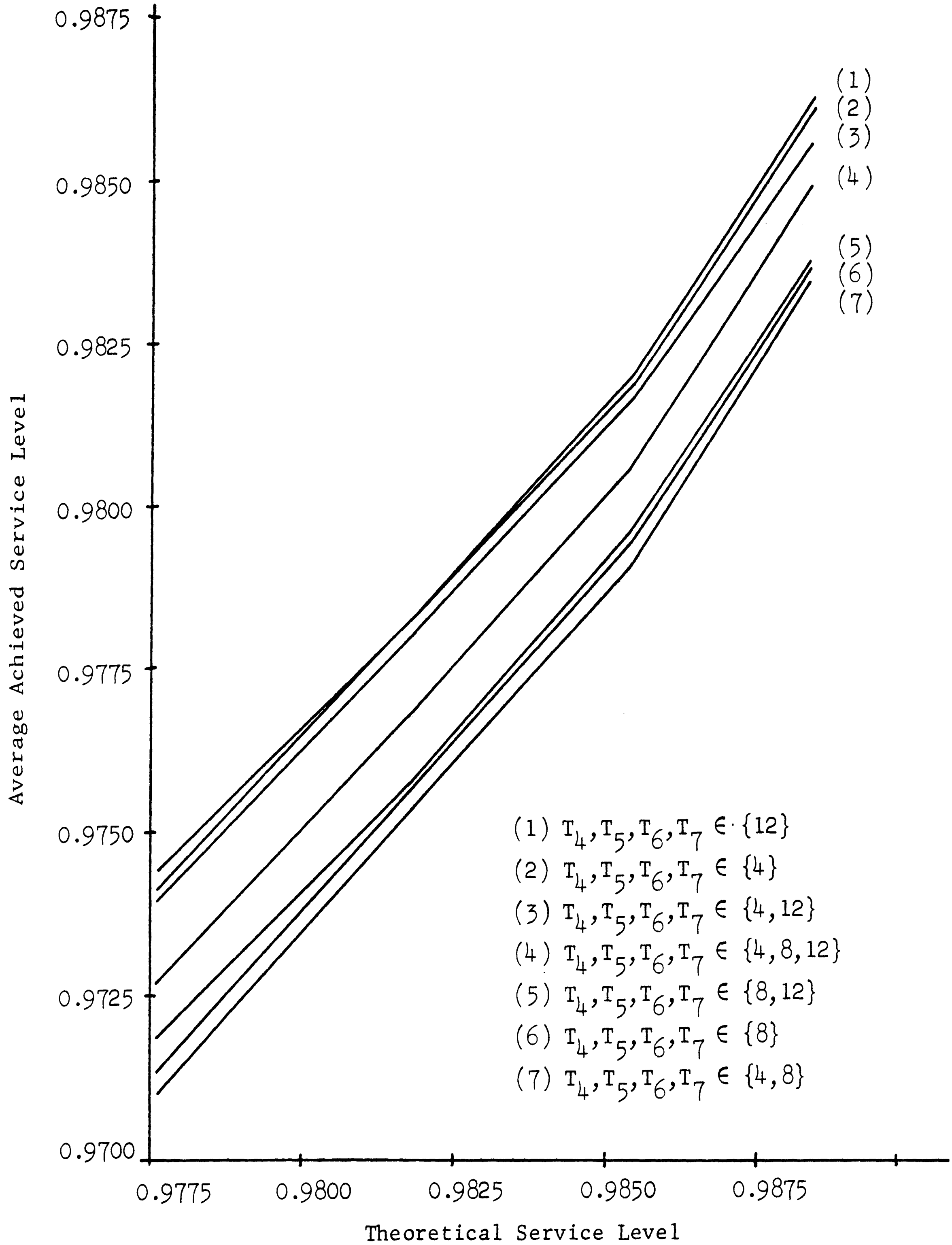

Figure 5

Average Achieved Service Level as a Function of Theoretical Service Level: $T_1 = 2$, $T_2 = T_3 = 4$ With Fixed Scheduling

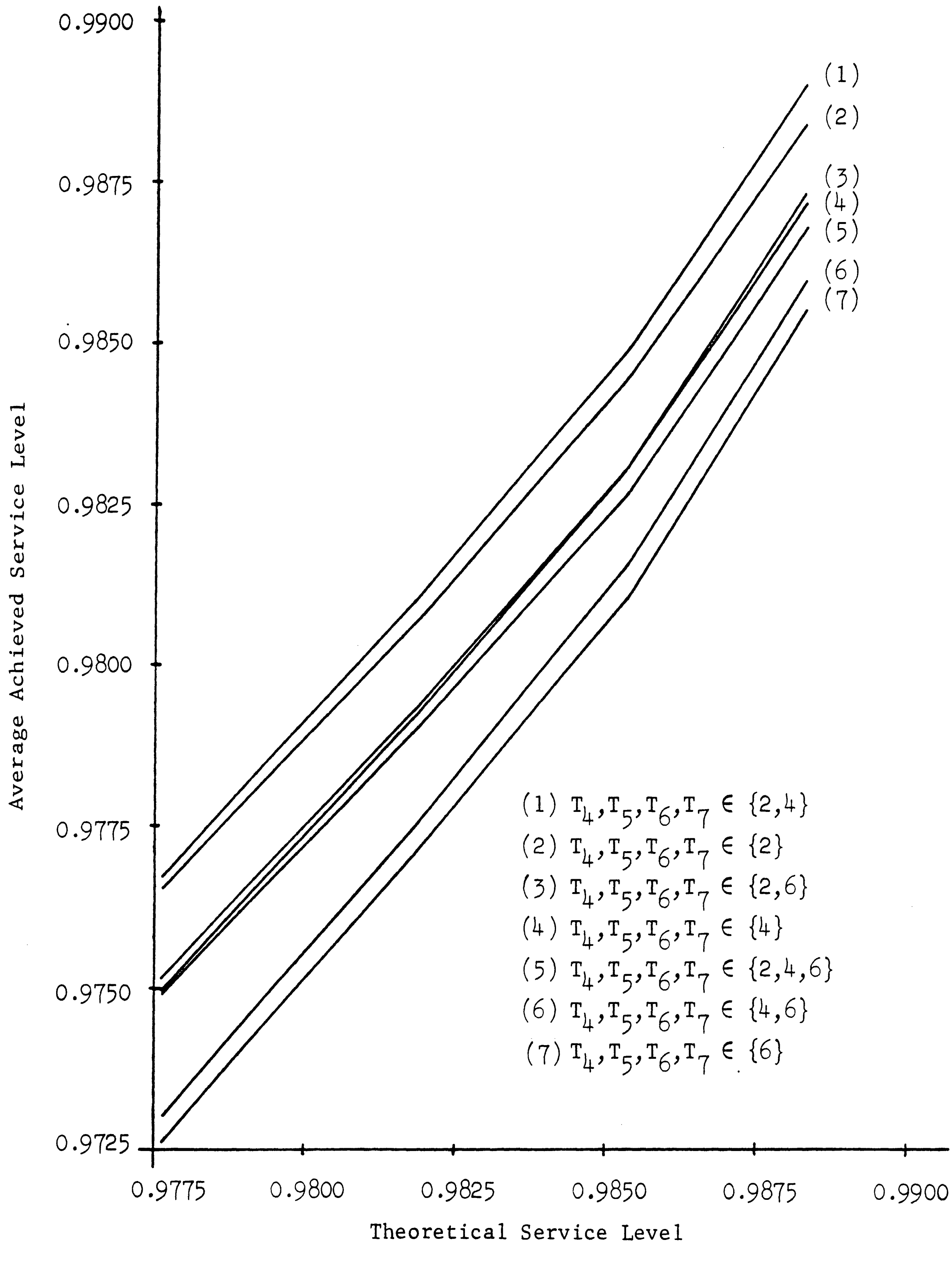

Figure 6

Average Achieved Service Level as a Function of Theoretical Service Level: $T_1 = T_2 = T_3 = 2$ With Fixed Scheduling on Levels 1 and 2 and Flexible Scheduling on Level 3

Table 1

t-Statistics for Difference Between Average Achieved Service Level and Theoretical Service Level: Two-Level Product Structure With $T_i = 2$ for All i and Fixed Scheduling on Both Levels

σ	k_1	t	Significance Level
10	0.0	- 3.855	$\alpha < 10^{-4}$
	0.2	- 4.085	$\alpha < 2.5 \times 10^{-5}$
	0.4	- 4.241	$\alpha < 2.5 \times 10^{-5}$
	0.6	- 2.685	$\alpha < 0.005$
30	0.0	- 3.621	$\alpha < 2.5 \times 10^{-4}$
	0.2	- 3.307	$\alpha < 5 \times 10^{-4}$
	0.4	- 3.027	$\alpha < 0.0025$
	0.6	- 1.900	$\alpha < 0.025$
	0.8	- 1.515	$\alpha < 0.10$
	1.0	- 1.029	*
50	0.0	- 3.510	$\alpha < 2.5 \times 10^{-4}$
	0.2	- 3.032	$\alpha < 0.0025$
	0.4	- 2.555	$\alpha < 0.01$
	0.6	- 1.977	$\alpha < 0.025$
	0.8	- 1.140	*
	1.0	- 1.043	*
	1.2	- 0.321	*

*Not significant at the $\alpha = 0.10$ level.

Table 2

t-Statistics for Difference Between Average Achieved Service Level and Theoretical Service Level: Two-Level Product Structure With $T_i = 2$ for All i, Fixed Scheduling on Level 1 and Flexible Scheduling on Level 2

σ	k_1	t	Significance Level
10	0.0	- 3.110	$\alpha < 0.001$
	0.2	- 3.422	$\alpha < 5 \times 10^{-4}$
	0.4	- 3.626	$\alpha < 2.5 \times 10^{-4}$
	0.6	- 1.819	$\alpha < 0.05$
30	0.0	- 2.865	$\alpha < 0.0025$
	0.2	- 2.474	$\alpha < 0.01$
	0.4	- 2.128	$\alpha < 0.025$
	0.6	- 0.996	*
	0.8	- 0.695	*
	1.0	- 0.405	*
50	0.0	- 2.658	$\alpha < 0.005$
	0.2	- 2.120	$\alpha < 0.025$
	0.4	- 1.649	$\alpha < 0.05$
	0.6	- 1.019	*
	0.8	- 0.292	*
	1.0	- 0.051	*
	1.2	- 0.272	*

*Not significant at the $\alpha = 0.10$ level.

Table 3

t-Statistics for Difference Between Average Achieved Service Level and Theoretical Service Level: Two-Level Product Structure With $T_i = 4$ for All i and Fixed Scheduling on Both Levels

σ	k_1	t	Significance Level
10	0.0	- 3.507	$\alpha < 2.5 \times 10^{-4}$
	0.2	- 3.256	$\alpha < 0.001$
	0.4	- 3.223	$\alpha < 0.001$
	0.6	- 2.016	$\alpha < 0.025$
30	0.0	- 3.296	$\alpha < 5 \times 10^{-4}$
	0.2	- 2.695	$\alpha < 0.005$
	0.4	- 2.253	$\alpha < 0.025$
	0.6	- 1.622	*
50	0.0	- 3.110	$\alpha < 0.001$
	0.2	- 2.507	$\alpha < 0.01$
	0.4	- 1.905	$\alpha < 0.05$
	0.6	- 1.374	*
	0.8	- 1.216	*
	1.0	- 0.900	*

*Not significant at the $\alpha = 0.10$ level.

Table 4

t-Statistics for Difference Between Average Achieved Service Level and Theoretical Service Level: Two-Level Product Structure With $T_i = 4$ for All i, Fixed Scheduling on Level 1, and Flexible Scheduling on Level 2

σ	k_1	t	Significance Level
10	0.0	- 3.507	$\alpha < 2.5 \times 10^{-4}$
	0.2	- 3.256	$\alpha < 0.001$
	0.4	- 3.223	$\alpha < 0.001$
	0.6	- 2.016	$\alpha < 0.025$
30	0.0	- 3.296	$\alpha < 5 \times 10^{-4}$
	0.2	- 2.695	$\alpha < 0.005$
	0.4	- 2.253	$\alpha < 0.025$
	0.6	- 1.622	*
50	0.0	- 3.110	$\alpha < 0.001$
	0.2	- 2.507	$\alpha < 0.01$
	0.4	- 1.905	$\alpha < 0.05$
	0.6	- 1.374	*
	0.8	- 1.216	*
	1.0	- 0.900	*

*Not significant at the $\alpha = 0.10$ level.

Table 5

t-Statistics for Difference Between Average Achieved Service Level and Theoretical Service Level: Three-Level Product Structure With $T_i = 2$ for All i and Fixed Scheduling on All Levels

σ	k_1	t	Significance Level
10	0.0	- 2.003	$\alpha < 0.025$
	0.2	- 2.058	$\alpha < 0.025$
	0.4	- 2.007	$\alpha < 0.025$
	0.6	- 1.342	*
30	0.0	- 1.992	$\alpha < 0.025$
	0.2	- 1.779	$\alpha < 0.05$
	0.4	- 1.552	*
	0.6	- 1.119	*
	0.8	- 0.972	*
	1.0	- 0.830	*
50	0.0	- 1.984	$\alpha < 0.025$
	0.2	- 1.715	$\alpha < 0.05$
	0.4	- 1.434	*
	0.6	- 1.137	*
	0.8	- 0.851	*
	1.0	- 0.710	*
	1.2	- 0.562	*

*Not significant at the $\alpha = 0.10$ level.

Table 6

t-Statistics for Difference Between Average Achieved Service Level and Theoretical Service Level: Three-Level Product Structure With $T_i = 2$ for All i, Fixed Scheduling on Levels 1 and 2, and Flexible Scheduling on Level 3

σ	k_1	t	Significance Level
10	0.0	- 1.973	$\alpha < 0.025$
	0.2	- 1.978	$\alpha < 0.025$
	0.4	- 1.924	$\alpha < 0.05$
	0.6	- 1.300	*
30	0.0	- 1.941	$\alpha < 0.05$
	0.2	- 1.713	$\alpha < 0.05$
	0.4	- 1.489	*
	0.6	- 1.071	*
	0.8	- 0.931	*
	1.0	- 0.810	*
50	0.0	- 1.920	$\alpha < 0.05$
	0.2	- 1.654	$\alpha < 0.05$
	0.4	- 1.377	*
	0.6	- 1.102	*
	0.8	- 0.815	*
	1.0	- 0.683	*
	1.2	- 0.547	*

*Not significant at the $\alpha = 0.10$ level.

Table 7

Bonferroni t-Statistics for Differences Between Mean Service Levels:

Two-Level Product Structure With $T_1 = 2$, $\sigma = 30$

Under Fixed Scheduling

$\tilde{T}$	vs. $\tilde{T}$	k_1					
		0	0.2	0.4	0.6	0.8	1.0
(2,2,2)	(2,4,2)	3.044*	3.091*	3.066*	3.133*	3.134*	3.079*
(2,2,2)	(2,6,2)	2.162					
(2,2,2)	(2,4,4)	0.164					
(2,2,2)	(2,4,6)	2.141					
(2,2,2)	(2,6,6)	0.764					
(2,4,2)	(2,6,2)	1.080					
(2,4,2)	(2,4,4)	3.233*	3.160*	3.041*	2.879*	2.691	2.442
(2,4,2)	(2,4,6)	1.106					
(2,4,2)	(2,6,6)	2.162					
(2,6,2)	(2,4,4)	2.351					
(2,6,2)	(2,4,6)	0.026					
(2,6,2)	(2,6,6)	1.280					
(2,4,4)	(2,4,6)	2.330					
(2,4,4)	(2,6,6)	0.927					
(2,4,6)	(2,6,6)	1.259					

*Significant at the $\alpha < 0.10$ level.

Table 8

Bonferroni t-Statistics for Differences Between Mean Service Levels:

Two-Level Product Structure With $T_1 = 2$, $\sigma = 30$,

Fixed Scheduling on Level 1 and Flexible Scheduling on Level 2

$\tilde{T}$	vs. $\tilde{T}$	k_1 = 0	0.2	0.4	0.6	0.8	1.0
(2,2,2)	(2,4,2)	1.337					
(2,2,2)	(2,6,2)	0.116					
(2,2,2)	(2,4,4)	3.122*	3.022*	2.955*	2.774*	2.592	2.369
(2,2,2)	(2,4,6)	3.344*	3.263*		2.945*	2.748*	
(2,2,2)	(2,6,6)	1.990					
(2,4,2)	(2,6,2)	1.780					
(2,4,2)	(2,4,4)	4.943**	4.911**				4.275**
(2,4,2)	(2,4,6)	5.733**	5.738**				4.886**
(2,4,2)	(2,6,6)	3.634**	3.554**				2.907*
(2,6,2)	(2,4,4)	3.489**	3.457**				2.736*
(2,6,2)	(2,4,6)	3.953**	3.957**				3.002*
(2,6,2)	(2,6,6)	2.181					
(2,4,4)	(2,4,6)	0.262					
(2,4,4)	(2,6,6)	1.308					
(2,4,6)	(2,6,6)	1.047					

*Significant at the $\alpha < 0.10$ level.

**Significant at the $\alpha < 0.01$ level.

Table 9

Bonferroni t-Statistics for Differences Between Mean Service Levels:

Two-Level Product Structure With $T_1 = 4$, $\sigma = 30$,

Fixed Scheduling on Level 1 and Flexible Scheduling on Level 2

$\underset{\sim}{T}$	vs. $\underset{\sim}{T}$	k_1			
		0	0.2	0.4	0.6
(4,4,4)	(4,8,4)	0.107			
(4,4,4)	(4,12,4)	0.997			
(4,4,4)	(4,8,8)	2.837*	2.703		
(4,4,4)	(4,8,12)	3.312*	3.241*	3.004*	2.840*
(4,4,4)	(4,12,12)	1.974			
(4,8,4)	(4,12,4)	1.352			
(4,8,4)	(4,8,8)	3.383*			2.892*
(4,8,4)	(4,8,12)	4.187**			3.795**
(4,8,4)	(4,12,12)	2.386			
(4,12,4)	(4,8,8)	2.279			
(4,12,4)	(4,8,12)	2.835*	2.793*		
(4,12,4)	(4,12,12)	1.282			
(4,8,8)	(4,8,12)	0.036			
(4,8,8)	(4,8,12)	0.864			
(4,8,12)	(4,12,12)	1.032			

*Significant at the $\alpha < 0.10$ level.

**Significant at the $\alpha < 0.01$ level.

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