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# Interactions Among Production Planning Decisions

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# INTERACTIONS AMONG PRODUCTION PLANNING DECISIONS

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## Abstract

Traditionally the different phases of operations planning have been treated as separate problems. Though there have been some studies that consider integrated models and investigate possible interactions among these various phases, the extent of integration did not exceed two levels. There are few studies that integrate lower levels of operations planning.

This study considers a job shop with MRP framework to analyze the main effects of and interaction effects among planning decisions – lot sizing, offsetting and dispatching – with tardiness, inventory and total cost as performance criteria. Under the conditions of normal capacity utilisation (about sixty percent) with no seasonality of demand, all the main effects of all planning decisions and all the second order interaction effects among these decisions are statistically significant. Lot sizing decision has the strongest influence on all the performance criteria, though the degree of influence varies with performance criterion. Among the interactions, the one between lot sizing and offsetting decisions is the strongest. Thus, it appears that, at least for the type of problems studied here, lot sizing is the most important decision and lot sizing-offsetting decisions should be made jointly.

Sensitivity analysis is carried out with respect to capacity utilization, seasonality of demand, product structure, and product set. With lower capacity utilization, lot sizing emerges to be a significant decision. Dispatching assumes greater significance with increasing seasonality of the demand. As the product structure is made more flat, the importance of dispatching and offsetting trends to increase. The interactions among planning decisions are influenced by the set of products being produced. Hence, it appears that the planning decisions vary with product sets.

Key Words: MRP, simulation, interactions among planning decisions, capacity utilization, seasonality of demand, alternative product structures

# 1 INTRODUCTION

Traditionally the different phases of operations planning have been treated as separate problems. Of late there seems to be growing realisation of the possible interactions among these various phases (Billington et al, 1979, Chase 1980, Miller and Graham 1981) and, hence, attempts are being made to build and solve integrated models (Collier 1980, Bahl and Ritzman 1984, Billington et al 1983, Grasso and Taylor 1984, and Biggs 1979). Many of these studies considered capacity planning, aggregate planning and master scheduling and the extent of integration did not exceed two levels

There are very few studies that integrate lower levels of operations planning. Biggs (1979) considered lot sizing and dispatching to study the main effects and interaction effects of these decisions. Enns (2001) studied the impact of lot sizing, offsetting decisions in a job shop condition but limited dispatching to one rule (earliest due date) only. In general, most of the research work does not consider dispatching in integrated study of MRP systems. Modeling difficulty and computational complexity seem to be the reasons for this omission (Baker 1993 and Enns 2001).

A review of the field practices revealed that decisions at each phase of operations planning are made independent of the decisions made at other phases (Murty 1987). The reason given for this independent decision-making is lack of knowledge of possible interactions among those decisions. The decision-makers are of divided opinion about the relative importance of the lot sizing, offsetting and dispatching decisions, and existence of possible interaction among them. Even those decision-makers that believed in the possible interactions among various decisions did not know how to use such knowledge in decision-making.

In view of the above, the objective of this study is to analyze the main effects of and interaction effects among lot sizing, offsetting and dispatching in MRP systems. The next section describes the simulator developed to investigate the main and interaction effects. In the following section, the design of experiment used in this study is described. Section 4 presents the method of analysis used. The results are presented in section 5. Section 6 presents sensitivity analysis with respect to capacity utilization, seasonality of demand and product set. The last section presents the conclusion.

# 2 THE SIMULATOR

The simulator developed for the purpose of this study has five modules (see fig. 1), namely, the Bill of Materials Preprocessor (BOMP), Master Production Scheduler (MPS), Capacity Planner (CP), Materials Requirement Planning (MRP) module, and Shop Floor Control (SFC) module. These modules are briefly described below:

**BOMP module** generates BOM (Bill of Materials) information like the product structure with quantity requirements for immediate next assembly, the routing of items through the shop floor, the set up and processing times for each item, the bought-out component of the value of the item etc. Common items are allowed within and across products. BOMP also creates data files for use by other modules.

**MPS module** generates master production schedule for all products.

**CP module** computes the resource requirements for the given master production schedule. It then determines the number of machines required in each work center for a given number of 8-hour-shifts per day.

**MRP module** performs the basic MRP functions – netting, lot sizing, offsetting and exploding. Lot sizing and offsetting are performed by subroutines. Hence it is possible to run any method of lot sizing and offsetting. The output of the MRP module is the order release schedule that drives the SFC module.

**SFC module** essentially is a job shop simulator using next-event approach. It accepts any method of dispatching. At the end of every simulated year, it gives the profile of weekly utilization of each work center as well as the overall shop, the total system inventory, total system tardiness. The output also includes item-wise and work-center-wise inventory of work-in-process and finished goods.

The simulator is so designed that for any given problem set, the lot sizing, offsetting and dispatching alternatives are systematically varied to generate all combinations and collect the required data. However, only the required combinations also can be simulated, through a proper choice of the initial seeds.

The following are the major assumptions made while developing the simulator:

a. The process times are deterministic.
b. A component can be of two types: namely, a detailed part made of raw material or a sub-assembly made of some detailed parts and/or sub-assemblies.
c. The shop consists of eight work centers and the machines have an availability index of unity. And work centers 1, 7 and 8 may be interpreted as raw material preparation area, assembly area and finishing area respectively. Thus, a detailed part enters the shop through work-center-1 and exits through work center-8 but does not visit work center-7. On the other hand, a sub-assembly does not enter the shop through work-center-1, exists through work-center-7 but does not visit work-cener-8. But for these conditions, the next work-center to be visited by a component is chosen at random.
d. The number of machines is so determined that the availability is at least ten per cent more than the requirements of the resource. This is in line with the capacity planning practices observed.
e. Product structure shows only the items to be made in-house. Raw materials and bought-out-finished (BOF) items are assumed to be available on time. BOF items include sub-contract items also so that for capacity planning only the items that appear in the product-structure have to be considered.

f. For a product raw material forms fifty per cent of total cost. The allocation of raw material and BOF items across different stages, however, is random.

## 3 DESIGN OF EXPERIMENT

The model used for the purpose of this study is as follows:

$$
\begin{aligned}
x(p,l,o,d,r) = {} & m(p) \\
& + a(p,l) + b(p,o) + c(p,d) && \textit{main effects} \\
& + ab(p,l,o) + ac(p,l,d) + bc(p,o,d) + n && \textit{interaction effects} \\
& + e(p,l,o,d,r) && \textit{error term}
\end{aligned}
$$

The subscripts are:

p = performance criterion (system tardiness, system inventory value, system total cost)
l = lot-size rule
o = offset rule
d = dispatching rule
r = replicate

The variables are:

x : value of the performance criterion
m : grand mean of the performance criterion
a : main effect of lot-size rule
b : main effect of offset rule
c : main effect of dispatching rule
ab : interaction effect between lot-size and offset rules
ac : interaction effect between lot-size and dispatching rules
bc : interaction effect between offset and dispatching rules
n : non-additivity term
e : error term

The parameters of problem sets used in this study are presented in table 1a. The product structures used in these problem sets are presented in table 1b.

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*Tables 1a and 1b to come here*

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All the three problem sets have more or less the same number of components. In each of the problem set, for each component, the number of operations, the routing, the set up and operation times, quantity required per unit of next assembly etc. are all generated from the same distributions. The only variation across the problem sets is the complexity of the product structure. For a given number of components in a system, other things being same, the complexity of the product structure is inversely related to the number of the final products.

### *3.1 Performance Indicators*

System performance is measured by the following three criteria:

#### 3.1.1 System Tardiness

If a batch of end product is delivered after the due date, then the batch is said to be tardy. The number of days by which the actual date of delivery exceeds the due date is known as tardiness of the batch. This tardiness as defined here is a non-negative integer. If t(b,p) is the tardiness of batch-b of end product-p, then system tardiness T is given by

$$T = \Sigma\, t(b,p)$$

#### 3.1.2 Average System Inventory:

If W(i) and C(i) are the values of the component-i when it is in-process and when it is finished respectively, then system average inventory

$$\text{Average Inventory} = \Sigma\, [X(i,t)W(i) + I(i,t)\; C\,(i)]$$

where X(i,t) and I(i,t) are the number of pieces of component-i in in-process and in finished goods store respectively at the end of period (week)-t.

#### 3.1.3 System Total Operation Cost:

Let, during a period of 52 weeks,

n(i) be the number of setups for component-i
AI be the system average inventory
S(i) be the unit set up cost for component-i
f be the inventory charge (Rs/Re. Yr)

Then, the system total cost is given by:

$$TC = [n(i)S(i) + fAI]$$

### *3.2 Decision variables*

The three factors considered in this study are lot sizing, offsetting, and dispatching. The major purpose of this study being the determination of the relative importance of lot sizing, offsetting and dispatching decision, no attempt is made to develop new methods or rules for these planning phases. Instead, most popular rules (i.e., those which are known to practitioners or those frequently referred by academicians) are chosen. The rules chosen are such that they are easy to understand and easy to implement.

The factors are described below:

#### 3.2.1 Lot sizing

The following single-stage, multi-period lot sizing rules are considered in this study:

1. Least total cost (LTC) rule
2. Least Unit Cost (LUC)

3. Wagner-Whitin (WW) algorithm
4. Least cost per period (LCP) rule
5. Lot-for-Lot (L4L) rule
6. Economic order quantity (EOQ) rule
7. Periodic order quantity (POQ) rule
8. Part period balancing (PPB) rule

### 3.2.2 Offsetting

The offset (planned lead time) for each lot is provided according to the following rule:

$$\text{Offset} = \text{TPT} + k*n$$

where

TPT : Technological processing time
k : Waiting time allowance per operation
n : Number of operations

k is varied from 0.5 to 2.5 days per operation in steps of 0.5 days per operation. Thus, this factor has five levels.

### 3.2.3 Dispatching

Eight dispatching rules are considered. Some of these are selected from those rated as overall best performers by Blackstone et al (1982) and others are those which are found to be applied in practice. The rules used in this study are:

1. Shortest processing time (SPT) rule
2. Minimum Slack (SLK) rule
3. Minimum slack per operation (SPO) rule
4. First-in-first-out rule
5. Least number of remaining operations (LRO) rule
6. Maximum number of remaining operations (MRO) rule
7. Dynamic slack per operation (DSPO) rule
8. Earliest due date (EDD) rule

## 4 METHOD OF ANALYSIS

The objective of this work is to study the main and interaction effects of lot sizing, offsetting and dispatching. Hence, ANOVA (Analysis of Variance) is chosen as the statistical tool to establish the presence or absence of the main and interaction effects.

Treating lot sizing, offsetting and dispatching as three factors a (8x5x8) factorial experiment is conducted on each of the three problem sets (i.e. S011, S021 and SO32). That is, in all, 960 (3x8x5x8) combinations are run. Each combination is run for two years at about sixty percent of capacity utilization. So, data for 1920 years of shop experience is generated. Since each run takes considerable amount of computer time, it was decided to have single replicate of each combination for each problem set and use Tukey's test of non-additivity (Tukey, 1949) to establish higher order interaction effects. NONADD in ANOVA tables refers to the third order interaction which is defined by the linear cross product of the main effects. This test was performed for all three sets separately, for each of the three performance criteria, i.e., tardiness, average inventory and total cost. The main and interaction effects are also studied when overall shop utilization and seasonality of demand are changed. In addition, effect of alternative product structure and product sets are also studied. %SS is the sum of squares of the relevant source of variation expressed as a percentage of total sum of squares.

# 5 RESULTS

The simulator described in the previous section was used to simulate three problem sets, namely, SO11, SO21 and SO32, to assess the impact of lot sizing, offsetting, and dispatching decisions on three performance criteria, namely, tardiness, system inventory, and total cost.

## *5.1 TARDINESS*

Table 2 shows the results of analysis of variance with tardiness as performance criterion. The main effects of the three planning decisions, i.e., lot sizing, offsetting and dispatching are consistently significant across all problem sets. This means that not all decision rules, in each factor, have the same impact on tardiness criterion. As the percentages of sum of squares indicate, lot sizing decision has the highest impact on tardiness followed by offsetting and dispatching in that order. This counter-intuitive to the common thought that lead-time is the primary determinant of tardiness. It is interesting to note that even though lot sizing decision is made with a criterion that is limited to only set up cost and inventory carrying cost, it contributes most to tardiness.

*Table 2: Analysis of variance table for tardiness* to come here

All the second order interaction effects among the planning decisions in all problem sets except the offsetting dispatching interaction in problem set SO32, are significant. Higher order interactions are significant only in the case of problem set SO11. Thus, the impact of a decision made at one planning phase depends on the decisions made at other planning phases also. The percentage sum of squares suggest that the interaction between lot sizing and offsetting is the strongest among all interactions. This means that lot sizing and offsetting decisions can not be made in isolation.

To illustrate the impact of the interaction effects, an indicator called Percent Extra Tardiness Incurred (PETI) is constructed. Let the optimal combination of lot size rule and dispatching rule be C(i) for a given level of operation allowance t(i) and the corresponding tardiness be T[t(i), C(i)]. Then, if the operation allowance is changed from t(i) to t(j) without changing the lot size rule and dispatching rule combination then tardiness incurred is T[t(j), c(i)]. PETI is given as

$$PETI = \frac{T[t(j), c(i)] - T[t(j), c(j)]}{T[t(j), c(j)]} * 100$$

Thus, PETI may be interpreted as the per cent regret for not recognizing the fact that the optimal combination of lot size rule and sequencing rule also changes with operation allowance.

PETI matrix for the problem set SO11 is presented in the table 3. Clearly PETI is not a symmetric matrix. This means that the relative performance of various combinations of lot size rule and dispatching rule varies with the operation allowance. Hence, whenever operation allowance is changed (for whatever reasons), the combination of lot size rule and sequencing rule also should be accordingly changed and vice-versa.

*Table 3: PETI Matrix for problem set SO11* to come here

### 5.2 SYSTEM INVENTORY

The results of the analysis of variance with system inventory as response variable are presented in table 4.

*Table 4: Analysis of variance table for System Inventory* to come here

As shown in table 4 the main effects of all planning decisions, in all the problem sets, are significant. However, the percentages of sum of squares suggest that lot sizing decision has significant impact on system inventory.

All the second order interaction effects among the planning decisions, in all the problem sets (except offsetting-dispatching interaction in problem sets SO11 and SO32) are significant. Higher order interactions are significant only in case of problem set SO11. Among these interactions, the lot sizing offsetting interaction is the strongest.

### 5.3 TOTAL COST

The results of the analysis of variance with total cost as the response variable are presented in table 5.

*Table 5: Analysis of variance table for Total Cost* to come here

The main effects of all the planning decisions, in each of the problem set, are significant. However, the percentages of sum of squares suggest that lot sizing has strongest impact on total cost criterion.

All the second order interaction effects among the planning decisions, in all the problem sets (except offsetting-dispatching interaction in problem sets SO11 and SO32) are significant. Higher order interactions are significant only in case of problem set SO21. Among these interactions, lot sizing-offsetting interaction is the strongest.

# 6 SENSITIVITY ANALYSIS

The sensitivity of the results obtained is tested with respect of four parameters, namely, capacity utilisation, seasonality of demand, alternative product structures, and product set.

## *6.1 Effect of capacity utilisation*

In all the problem sets presented in the previous section, the overall shop utilisation was about sixty percent. In order to study the effect of capacity utilisation three more problem sets S010, S020 and S030 (see table 1a) were studied. The capacity utilisations for these problem sets are set at about 40%, 10% and 20% respectively. The only difference between the problem sets (S011, S021 and S032) and problem sets (S010, S020 and S030) is the corresponding capacity utilisations.

The manufacturing system is simulated for these new problem sets and the performance of the system in terms of tardiness, system inventory and total cost was recorded. Analysis of variance with respect to each of these criteria was conducted. The results are discussed below.

### 6.1.1 Tardiness

Table 6 shows the results of the analysis of variance treating tardiness as response variable. A comparison of table 6 with table 2 reveals that the main and interaction effects of the planning decisions remain significant despite the reduction in capacity utilisation. The percent sum of squares suggest that at lower capacity utilisation, the impact of lot sizing on tardiness increases and that of dispatching decreases. Even at reduced level of capacity utilisation, lot sizing has the strongest impact on tardiness.

*Table 6: Analysis of variance table for Tardiness (Reduced capacity utilisation)*
to come here

The interaction effect, in case of problem set SO10, is presented in table 7 in the form of PETI matrix. The table 7 and table 3 together indicate that the optimal combination (of lot size rule and dispatching rule) for a given level of operation allowance (t) varies with capacity utilisation. PETI matrix of SO10 is less sparse than that of SO11 which implies that there is more likelihood of regret in case of low capacity utilisation if the combination of lot sizing and dispatching rules is not changed corresponding to a change in operation allowance. Thus the interaction effects continue to remain important even at lower level of capacity utilsation.

*Table 7: PETI Matrix for Problem Set S010* to come here

Table 8 presents the percent regret in tardiness if the same operations planning decisions are continued when the capacity utilisation is changed. The regret is more when the capacity utilisation is reduced as compared to when it is increased. Thus, it is important to revise the operations planning decisions when the capacity utilisation changes, particularly when it reduces.

*Table 8: Percent regret in Tardiness* to come here

### 6.1.2 System Inventory

Table 9 shows the results of the analysis of variance treating system inventory as response variable. A comparison of table 9 with table 4 reveals that the main effects of the planning decisions are significant despite the reduction in capacity utilisation. However, the interaction effects became less significant. Lot sizing remained to be the most significant factor to contribute to system inventory. The strong impact of the lot sizing dispatching interaction in problem set SO30 could not be explained. It appears that at lower capacity utilsation, it is sufficient to manipulate lot-sizes in order to control the system inventory.

*Table 9: Analysis of variance System Inventory (Reduced capacity utilisation)* to come here

### 6.1.3 Total Cost

Table 10 shows the results of the analysis of variance treating total cost as the response variable. A comparison of table 10 with table 5 reveals that the main effects of the planning decisions remained to be significant even at reduced level of capacity utilisation, and the interaction effects became less significant. It appears that lot sizing alone has very strong impact on total cost at lower levels of capacity utilisation.

*Table10: Analysis of variance for Total Cost (Reduced capacity utilisation)* to come here

## *6.2 Effect of Seasonality of Demand*

Consider the variation of demand as shown in figure 2. The ratio of amplitude of this variation expressed as a percentage of mean is termed as degree of 'seasonality of demand'. The seasonality of demand for problem set SO11 is zero (i.e. constant demand). Problem sets SO12 and SO14 (see table 1) are identical to SO11 except that their seasonality of demand are 30% and 40% respectively.

*Figure 2: Seasonality of demand* to come here

The manufacturing system is simulated for problem sets SO12 and SO14 and the performance of the system in terms of tardiness, system inventory and total cost was recorded. The results of analysis of variance with respect to each of these performance criteria are presented below:

### 6.2.1 Tardiness

Table 11 shows the results of analysis of variance treating tardiness as response variable. A comparison of the results of problem sets SO11 (table 2) SO12 and SO14 (table 11) reveals that as the seasonality of demand increases, the main and second order interaction effects (except lot –sizing dispatching interaction in case of problem set SO14) remain significant. The importance of lot sizing decreases and that of dispatching increases with increasing seasonality of demand. It is interesting to note that the impact of offsetting has initially increased with increasing seasonality and later dropped suddenly. The impact of both the second order interactions involving dispatching (i.e., lot sizing-dispatching and offsetting-dispatching) increased with increasing seasonality of demand. Thus it appears that, under the conditions of seasonality of demand, dispatching is the most important decision followed by offsetting.

*Table 11: Analysis of variance for Tardiness (Increased seasonality of demand)*
to come here

### 6.2.2 System inventory

Table 12 shows the results of analysis of variance with system inventory as the response variable. A comparison of the results of problem sets SO11 (table 4), SO12 and SO14 (table 12) suggests that as the seasonality of demand increases, the main effects of planning decisions on system inventory remain statistically significant and the interaction effects among the planning decisions become insignificant. As the seasonality of demand increases the impact of lot sizing decreases while that of dispatching and offsetting increase. The dispatching decision has the strongest impact on system inventory followed by offsetting. It appears that at high level of seasonality, the planning decisions do not seem to interact to affect system inventory.

*Table 12: Analysis of variance for Average Inventory (Increased seasonality of demand)*
to come here

### 6.2.3 Total Cost

Table 13 shows the results of analysis of variance with total cost as the response variable. A comparison of the results of the problem sets SO11 (table 5), SO12 and SO14 (table 13) reveals that as seasonality of demand increases the main effects of planning decisions on the total cost remain significant and the interaction effect become insignificant. At higher level of seasonality of demand, total cost is more influenced by dispatching decision than by other decisions. The combined effect of the planning decisions is negligible.

*Table 13: Analysis of variance for Total Cost (Increased seasonality of demand)*
to come here

## *6.3 Effect of Alternative Product Structures*

When a product is designed, the designer requires that certain components be assembled together to make the final product. However, the sub-assemblies are identified taking into account certain factors like raw materials or components involved, shop layout, shop procedures (like store crediting and withdrawal) etc. So the product structure as given by the designer can be different from that used by production planner. It is interesting to see the effect of alternative product structure on the performance criteria. All the alternative product structures preserve the composition of the product.

A problem set PO11 is constructed with product structures alternative to those contained in the problem set SO11. The product structures in PO11 are more flat compared to those in SO11 (see table 1b). Five lot size rules (LUC, WW, LCP, L4L, and EOQ), three dispatching rules (SPT, SPO, EDD), and five levels of operation allowance are used in this experiment. The results of analysis of variance are presented in table 14. Dispatching affects tardiness more when the product structure is more flat. Offsetting impacts the system inventory and total cost more.

*Table 14: Analysis of variance for alternative product structure* to come here

The optimal decisions corresponding to SO11 and PO11 are presented in table 15. Clearly the system performance and optimal decisions vary with product structure.

*Table 15: Effect of product structure on optimal decisions and performance criteria*
to come here

### 6.4 Effect of Product Set

It would be interesting to know if the set of products handled by the production system affects the operations planning decisions and the performance of the system. In other words, are operations planning decisions and performance of the system dependent on the set of products being produced? As an attempt to answer this question, a four-factor experiment (with lot sizing, offsetting, dispatching and problem set as factors) is conducted treating the tardiness as response variable. Three problem sets: SO11, SO21 and SO32 represent three product sets. The results of the analysis of variance are presented in table 16.

*Table 16: Analysis of variance table for Tardiness (Effect of Product Sets)*
to come here

As table 16 indicates, the main effect of product set is statistically significant. That is, the production system may become more tardy with certain product sets than with others. Product set factor contributes about 16 percent of total variation in the tardiness. Several of interactions involving product set are statistically significant. That is, the product set influences the interaction among the planning decisions. Among the interactions, lot sizing-offsetting-product set interaction appears to be strongest. Thus, the joint decision on lot sizing and offsetting is influenced by the set of products being made. This implicitly means that there may be no combination of decisions that perform well in all situations (or product sets). The decisions are likely to vary from one production environment to another.

# 7 CONCLUSION

This research has certain implications for operations planners. The findings point out that lot sizing is the most important decision and that lot sizing and offsetting decisions have combined effect on the three performance criteria, viz., tardiness, system inventory and total cost. If the seasonality of demand is high, the operations planner should shift the emphasis from lot sizing to dispatching decision and make the lot sizing and offsetting decisions jointly with dispatching decision.

Table 17 presents the ranking of the lot sizing rules in each problem set (SO11, SO21 and SO32) with respect to various performance criteria. It suggests that LCP, L4L and EOQ rules are good for minimizing tardiness and system inventory. However, L4L rule is least preferred for total cost criterion. POQ rules is consistently bad for all criteria. A test of concordance has proved that the relative performance (or ranking) of lot sizing varies with problem sets for all criteria at 0.001 significance level.

*Table 17: Ranking of lot sizing rules* to come here

Table 18 presents the ranking of dispatching rules in each problem set (SO11, SO21 and SO32) with respect to various performance criteria. It suggests that SPT is the best rule for all criteria. SLK and DSPO are worst performers. A test of concordance has proved that the relative performance (or ranking) of dispatching rules varies with problem sets for all criteria at 0.001 significance level.

*Table 18: Ranking of dispatching rules* to come here

Lead-times have a unique characteristic. Vollmann et al (1992) argue that planned lead-times have a self-fulfilling effect. Longer planned-times result in more orders on shop floor causing the actual lead-times to be longer. Because of this uniqueness, the choice of operation allowance becomes very critical. Hence, it is suggested that having made the lot sizing decision and dispatching decisions, the operation allowance should be set by trial and error.

Tables 17 and 18 and the above paragraph indicate that the planning decisions vary with problem sets. However, fortunately, at least for the problem sets studied, there are some rules that are certainly better than other rules. For example, SPT rule is consistently the best among the dispatching rules studied, with respect to all criteria. Similarly, L4L rule is consistently the best rule for minimizing system average inventory. However, it should be noted that the rankings shown in tables 17 and 18 are based on the marginal averages and hence ignore the effects of interactions. So, it is better to consider some of the top performers and choose the best among them by trial and error. Thus, it is sufficient to consider L4L, LCP and EOQ rules to minimize tardiness and system average inventory. However, it is hard to identify few good performers with respect to total cost. Similarly, it is hard to choose the operation allowance a priori.

For the problem sets considered in this study the best performers are presented in Table 19. Since there are no rules that are best for all problem sets (refer to section 6.4), the operations planner should resort to a search of a best combination of the best performers. It appears that it would be difficult, if not impossible, to simulate the production system for several combinations of planning decisions. To reduce the computer time requirements, it is suggested that while modeling the production system, greater detail may be incorporated only for bottleneck operations and all non-bottleneck operations may be aggregated.

*Table 19: Best Performers* to come here

Lastly, lot sizing decision is consistently a strong determinant of tardiness in various experimental conditions. However, almost all lot size models in the literature consider only setup (or ordering) cost and inventory carrying cost in the objective function. This study points out the need to extend the scope of the objective function to include tardiness (or its surrogate) in future studies.

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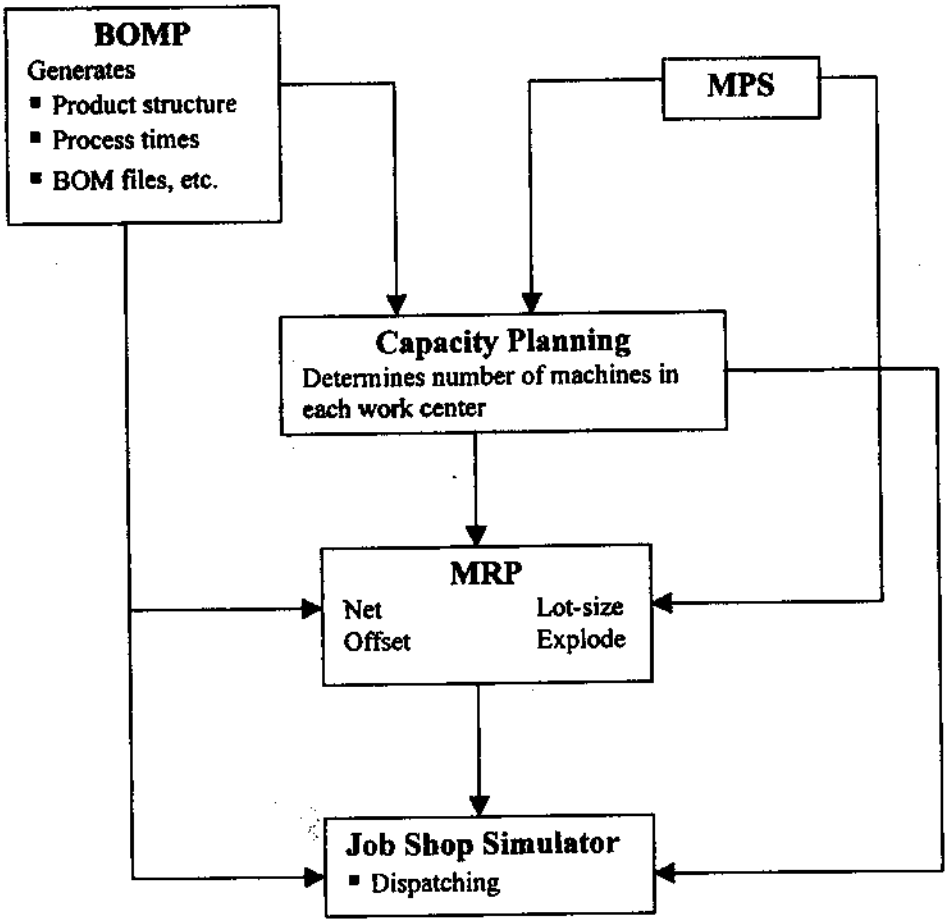


**Fig. 1 Block Diagram of the Simulator**

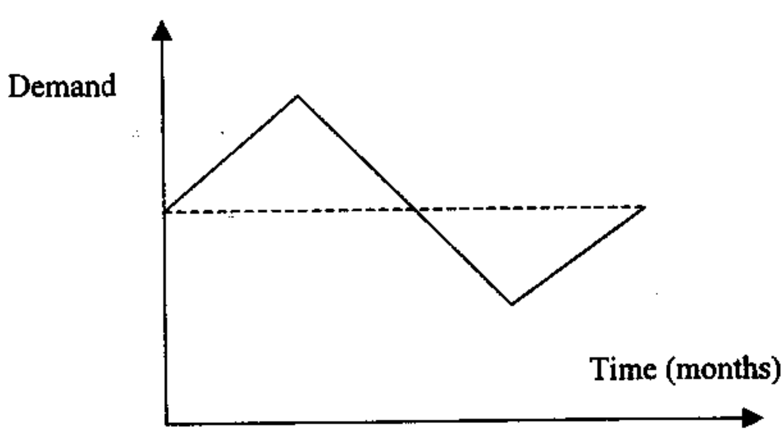


**Figure 2: Seasonality of demand**

| Parameters | Problem Set | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | S010 | S011 | S012 | S014 | P011 | S020 | S021 | S030 | S032 |
| Product Set | A | A | A | A | D | B | B | C | C |
| Utilization (%) | 40 | 60 | 60 | 60 | 60 | 12 | 60 | 18 | 60 |
| Seasonality of demand (%) | 0 | 0 | 30 | 40 | 0 | 0 | 0 | 0 | 0 |
| Number of products | 4 | 4 | 4 | 4 | 4 | 2 | 2 | 1 | 1 |
| Number of components | 17 | 17 | 17 | 17 | 17 | 15 | 15 | 18 | 18 |

**Table 1a: Parameters of different Problem Sets**

| Product Set A | | Product Set B | | Product Set C | | Product Set D | |
|---|---|---|---|---|---|---|---|
| Level | Item | Level | Item | Level | Item | Level | Item |
| * | 1 | * | 1 | * | 1 | * | 1 |
| ** | 17(3) | ** | 9(3) | ** | 5(3) | ** | 17(3) |
| ** | 13(3) | ** | 3(3) | *** | 18(1) | ** | 13(3) |
| ** | 9(3) | *** | 7(3) | ** | 6(3) | ** | 9(3) |
| *** | 14(3) | *** | 8(3) | ** | 8(3) | ** | 14(9) |
| ** | 15(3) | **** | 9(3) | *** | 10(3) | ** | 15(3) |
| * | 2 | **** | 10(3) | *** | 11(3) | * | 2 |
| ** | 16(3) | **** | 11(3) | *** | 12(3) | ** | 16(3) |
| ** | 10(3) | **** | 15(3) | *** | 14(3) | ** | 10(3) |
| *** | 16(3) | *** | 9(3) | *** | 15(3) | *** | 16(3) |
| *** | 12(3) | ** | 10(3) | *** | 17(3) | *** | 12(3) |
| ** | 8(3) | ** | 11(3) | *** | 18(3) | ** | 8(3) |
| ** | 5(3) | * | 2(3) | ** | 2(3) | ** | 5(3) |
| *** | 7(2) | ** | 4(3) | *** | 4(3) | ** | 7(6) |
| **** | 11(3) | ** | 5(3) | **** | 10(2) | *** | 11(3) |
| * | 3 | *** | 6(3) | **** | 11(2) | * | 3 |
| ** | 6(2) | **** | 12(3) | **** | 13(2) | ** | 6(2) |
| *** | 11(3) | **** | 14(3) | **** | 15(2) | *** | 11(3) |
| *** | 12(3) | *** | 12(3) | *** | 11(3) | *** | 12(3) |
| *** | 16(3) | *** | 8(3) | *** | 8(3)@ | *** | 16(3) |
| ** | 16(2) | **** | 9(3) | *** | 7(3) | ** | 16(2) |
| ** | 10(2) | **** | 10(3) | **** | 14(2) | ** | 10(2) |
| *** | 12(3) | **** | 11(3) | **** | 18(2) | *** | 12(3) |
| *** | 16(3) | **** | 15(3) | *** | 12(3) | *** | 16(3) |
| * | 4 | *** | 13(3) | *** | 9(3) | * | 4 |
| | | ** | 15(3) | **** | 11(3) | | |
| | | | | **** | 16(3) | | |
| | | | | ** | 9(3)@ | | |
| | | | | ** | 3(3) | | |
| | | | | *** | 5(3) | | |
| | | | | *** | 9(3)@ | | |
| | | | | *** | 11(3) | | |
| | | | | *** | 14(3) | | |
| | | | | *** | 16(3) | | |

@: Further explosion not repeated.

**Table 1b: Product Structures (in Indented Form) for various Problem Sets**

| Source of variation | Problem Set | | | | | |
|---|---|---|---|---|---|---|
| | SO11 | | SO21 | | SO32 | |
| | % SS | F-ratio(p) | % SS | F-ratio(p) | % SS | F-ratio(p) |
| A | 43.6 | 213.7 (0.001) | 49.8 | 327.3 (0.001) | 28.1 | 63.1 (0.001) |
| B | 9.0 | 44.4 (0.001) | 13.8 | 90.8 (0.001) | 3.9 | 8.8 (0.001) |
| C | 22.2 | 190.6 (0.001) | 22.7 | 261.3 (0.001) | 14.3 | 74.7 (0.001) |
| AB | 3.1 | 2.2 (0.001) | 2.9 | 2.7 (0.001) | 5.7 | 1.8 (.001) |
| AC | 14.7 | 18.0 (0.001) | 5.6 | 9.2 (0.001) | 37.6 | 28.2 (0.001) |
| BC | 1.2 | 1.4 (0.100) | 0.9 | 1.5 (0.050) | 1.1 | * (0.001) |
| NONADD | 0.6 | 20.6 (0.001) | 0.1 | * | 0.0 | * |

A: Lot sizing B: Dispatching C: Offsetting
P: Significance level * : Not significant

**Table 2: Analysis of variance table for tardiness.**

| From t(i) | To t(j) | | | | | C | T |
|---|---|---|---|---|---|---|---|
| | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | | |
| 0.5 | --- | 37.3 | 0.0 | 27.0 | 0.0 | LCP-SPT | 122 |
| 1.0 | 247.5 | --- | 9.7 | 49.4 | 287.5 | L4L-LRO | 204 |
| 1.5 | 0.0 | 37.3 | --- | 27.0 | 0.0 | LCP-SPT | 154 |
| 2.0 | 92.6 | 88.2 | 83.1 | --- | 81.3 | LTC-SPT | 73 |
| 2.5 | 0.0 | 37.3 | 0.0 | 27.0 | --- | LCP-SPT | 48 |

**Table 3: PETI Matrix for Problem Set S011**

| Problem Set | | | | | | |
|---|---|---|---|---|---|---|
| Source of variation | SO11 | | SO21 | | SO32 | |
| | % SS | F-ratio(p) | % SS | F-ratio(p) | % SS | F-ratio(p) |
| A | 81.3 | 2152.8 (0.001) | 95.5 | 4564.4 (0.001) | 67.9 | 212.5 (0.001) |
| B | 2.0 | 52.2 (0.001) | 1.9 | 90.8 (0.001) | 2.0 | 6.2 (0.001) |
| C | 12.1 | 557.1 (0.001) | 0.5 | 38.4 (0.001) | 3.8 | 27.5 (0.001) |
| AB | 0.6 | 2.5 (0.001) | 0.5 | 3.1 (0.001) | 3.1 | 1.4 (0.050) |
| AC | 2.9 | 19.1 (0.001) | 1.0 | 11.8 (0.001) | 15.7 | 16.3 (0.001) |
| BC | 0.1 | * | 0.1 | 1.4 (0.100) | 0.9 | * |
| NONADD | 0.0 | 4.2 (0.001) | 0.0 | * | 0.1 | * |

A: Lot sizing B: Dispatching C: Offsetting
P: Significance level * : Not significant

**Table 4: Analysis of variance table for System Inventory.**

| Source of variation | Problem Set | | | | | |
|---|---|---|---|---|---|---|
| | SO11 | | SO21 | | SO32 | |
| | **% SS** | **F-ratio(p)** | **% SS** | **F-ratio(p)** | **% SS** | **F-ratio(p)** |
| A | 64.5 | 830.5 (0.001) | 64.3 | 428.1 (0.001) | 78.0 | 364.1 (0.001) |
| B | 3.8 | 48.9 (0.001) | 13.9 | 92.7 (0.001) | 1.3 | 6.2 (0.001) |
| C | 19.9 | 449.0 (0.001) | 10.1 | 117.4 (0.001) | 2.1 | 22.5 (0.001) |
| AB | 1.2 | 2.3 (0.001) | 3.3 | 3.2 (0.001) | 2.1 | 1.4 (0.100) |
| AC | 8.2 | 26.3 (0.001) | 3.3 | 5.5 (0.001) | 11.5 | 17.8 (0.001) |
| BC | 0.2 | * | 0.8 | 1.4 (0.100) | 0.6 | * |
| NONADD | 0.0 | * | 0.1 | 3.4 (0.100) | 0.0 | * |

A: Lot sizing B: Dispatching C: Offsetting
P: Significance level * : Not significant

**Table 5: Analysis of variance table for Total Cost.**

| Source of variation | Problem Set | | | | | |
|---|---|---|---|---|---|---|
| | SO10(40%)u | | SO20(10%)u | | SO30(20%)u | |
| | **% SS** | **F-ratio(p)** | **% SS** | **F-ratio(p)** | **% SS** | **F-ratio(p)** |
| A | 64.5 | 499.0 (0.001) | 95.0 | 7432.8 (0.001) | 49.9 | 75.1 (0.001) |
| B | 6.5 | 50.5 (0.001) | 0.1 | 8.2 (0.001) | 2.2 | 3.3 (0.001) |
| C | 13.9 | 188.4 (0.001) | 2.8 | 335.6 (0.001) | 12.5 | 44.0 (0.001) |
| AB | 4.0 | 4.4 (0.001) | 0.4 | 3.6 (0.001) | 8.1 | 1.7 (0.100) |
| AC | 6.6 | 12.8 (0.001) | 1.2 | 19.7 (0.001) | 10.9 | 5.5 (0.001) |
| BC | 0.8 | 1.5 (0.001) | 0.1 | * | 2.4 | * |
| NONADD | 0.1 | 7.4 (0.001) | 0.0 | * | 0.1 | * |

A: Lot sizing B: Dispatching C: Offsetting
P: Significance level * : Not significant

**Table 6: Analysis of variance table for Tardiness (Reduced capacity utilisation)**

| From t(i) | To t(j) 0.5 | 1.0 | 1.5 | 2.0 | 2.5* | C | T |
|---|---|---|---|---|---|---|---|
| 0.5 | --- | 58.6 | 117.2 | 184.0 | 38.5 | LCP-SPT | 150 |
| 1.0 | 119.3 | --- | 400.0 | 32.0 | 0.0 | L4L-SPO | 70 |
| 1.5 | 9.3 | 52.9 | --- | 8.0 | 0.0 | WW-SPT | 29 |
| 2.0 | 69.3 | 98.6 | 55.2 | --- | 92.3 | LUC-SPT | 25 |
| 2.5 | 74.7 | 2.9 | 127.6 | 212.0 | --- | L4L-SPT | 0 |

**Table 7: PETI Matrix for Problem Set S010**

| Operation Allowance | Change in utilization from | |
|---|---|---|
| | Low to high (S010 to S011) | High to low (S011 to S010) |
| 0.5 | 0.0 | 0.0 |
| 1.0 | 19.6 | 121.4 |
| 1.5 | 59.7 | 117.2 |
| 2.0 | 31.5 | 1544.0 |
| 2.5 | 150.0 | 38.5 |

**Table 8: Percent regret in Tardiness**

| Source of variation | Problem Set | | | | | |
|---|---|---|---|---|---|---|
| | SO10(40%)u | | SO20(10%)u | | SO30(20%)u | |
| | **% SS** | **F-ratio(p)** | **% SS** | **F-ratio(p)** | **% SS** | **F-ratio(p)** |
| A | 86.3 | 260.9 (0.001) | 98.9 | 6326.0 (0.001) | 38.8 | 847.5 (0.001) |
| B | 1.5 | 5.4 (0.001) | 0.1 | 5.0 (0.001) | 0.1 | 2.5 (0.001) |
| C | 5.7 | 51.3 (0.001) | 0.2 | 16.6 (0.001) | 7.8 | 398.7 (0.001) |
| AB | 2.0 | * (0.001) | 0.1 | * | 0.5 | 1.6 (0.010) |
| AC | 0.4 | 1.3 (0.250) | 0.2 | 3.5 (0.010) | 51.6 | 375.3 (0.001) |
| BC | 0.5 | * | 0.1 | 1.2 (0.250) | 0.1 | * |
| NONAD D | 0.0 | * | 0.0 | * | 0.1 | 20.5 (0.001) |

A: Lot sizing B: Dispatching C: Offsetting
P: Significance level * : Not significant U: Capacity utilisation

**Table 9: Analysis of variance System Inventory**
(Reduced capacity utilisation)

| Source of variation | Problem Set | | | | | |
|---|---|---|---|---|---|---|
| | SO10(40%)u | | SO20(10%)u | | SO30(20%)u | |
| | **% SS** | **F-ratio(p)** | **% SS** | **F-ratio(p)** | **% SS** | **F-ratio(p)** |
| A | 51.4 | 43.9 (0.001) | 99.9 | 70777.0 (0.001) | 93.1 | 16746.3 (0.001) |
| B | 5.3 | 5.4 (0.001) | 0.0 | 5.0 (0.001) | 0.0 | 2.2 (0.050) |
| C | 20.0 | 51.3 (0.001) | 0.0 | 18.0 (0.001) | 0.6 | 256.0 (0.001) |
| AB | 6.9 | * | 0.0 | * | 0.1 | 1.4 (0.050) |
| AC | 3.1 | 1.3 (0.250) | 0.1 | 8.2 (0.010) | 6.1 | 363.4 (0.001) |
| BC | 1.8 | * | 0.0 | 1.2 (0.250) | 0.0 | * |
| NONADD | 0.0 | * | 0.0 | * | 0.0 | * |

A: Lot sizing B: Dispatching C: Offsetting
P: Significance level * : Not significant U: Capacity utilisation

**Table10: Analysis of variance for Total Cost**
(Reduced capacity utilisation)

| Problem Set | | | | |
|---|---|---|---|---|
| Source of variation | SO12(30%)s | | SO14(40%)s | |
| | **% SS** | **F-ratio(p)** | **% SS** | **F-ratio(p)** |
| A | 21.1 | 97.3 (0.001) | 21.4 | 37.4 (0.001) |
| B | 17.7 | 46.6 (0.001) | 54.5 | 54.4 (0.001) |
| C | 40.4 | 248.9 (0.001) | 4.8 | 16.6 (0.001) |
| AB | 4.3 | 2.8 (0.001) | 5.2 | * |
| AC | 9.8 | 15.0 (0.250) | 2.7 | 2.3 (0.050) |
| BC | 2.3 | 2.0 (0.010) | 3.2 | 1.6 (0.100) |
| NONADD | 0.0 | * | 0.4 | * |

A: Lot sizing B: Dispatching C: Offsetting
P: Significance level * : Not significant S; Seasonality of Demand

**Table 11: Analysis of variance for Tardiness**
(Increased seasonality of demand)

| Problem Set | | | | |
|---|---|---|---|---|
| Source of variation | SO12(30%)s | | SO14(40%)s | |
| | **% SS** | **F-ratio(p)** | **% SS** | **F-ratio(p)** |
| A | 65.0 | 395.4 (0.001) | 33.6 | 86.0 (0.001) |
| B | 12.8 | 44.5 (0.001) | 34.0 | 49.7 (0.001) |
| C | 9.2 | 74.6 (0.010) | 22.7 | 116.2 |
| AB | 2.3 | 2.0 (0.010) | 2.2 | * |
| AC | 5.3 | 10.7 (0.001) | 0.5 | * |
| BC | 1.5 | 1.7 (0.050) | 1.5 | * |
| NONADD | 0.5 | 12.9 (0.001) | 0.1 | * |

A: Lot sizing  B: Dispatching  C: Offsetting
P: Significance level  * : Not significant  S; Seasonality of Demand

**Table 12: Analysis of variance for Average Inventory**
(Increased seasonality of demand)

| Problem Set | | | | |
|---|---|---|---|---|
| Source of variation | SO12(30%)s | | SO14(40%)s | |
| | **% SS** | **F-ratio(p)** | **% SS** | **F-ratio(p)** |
| A | 50.4 | 185.7 (0.001) | 26.1 | 59.1 (0.001) |
| B | 18.40 7.0 | 38.7 (0.001) | 37.9 | 49.0 (0.001) |
| C | 3.3 | 34.5 (0.001) | 25.0 | 113.1 (0.001) |
| AB | 13.1 | 1.8 (0.050) | 2.5 | * |
| AC | 2.1 | 16.2 (0.001) | 0.9 | * |
| BC | | * | 1.6 | * |
| NONADD | 0.0 | * | 0.0 | * |

A: Lot sizing B: Dispatching C: Offsetting
P: Significance level * : Not significant S; Seasonality of Demand

**Table 13: Analysis of variance for Total Cost**
(Increased seasonality of demand)

| Source of variation | Criteria | | | | | |
|---|---|---|---|---|---|---|
| | Tardiness | | System inventory | | Total cost | |
| | %SS | F (p) | %SS | F (p) | %SS | F (p) |
| A | 12.7 | 19.8 (0.001) | 55.7 | 188.9 (0.001) | 43.1 | 117.1 (0.001) |
| B | 36.5 | 114.3 (0.001) | 5.6 | 38.0 (0.001) | 7.0 | 38.3 (0.001) |
| C | 22.3 | 34.9 (0.001) | 25.8 | 87.5 (0.001) | 23.8 | 64.7 (0.001) |
| AB | 7.3 | 5.7 (0.001) | 2.2 | 3.7 (0.005) | 2.8 | 3.7 (0.001) |
| AC | 12.2 | 4.8 (0.001) | 6.4 | 5.4 (0.001) | 17.9 | 12.2 (0.001) |
| BC | 3.6 | 2.8 (0.025) | 2.0 | 3.4 (0.010) | 2.5 | 3.4 (0.001) |
| NONADD | 0.5 | * | 0.0 | * | 0.0 | * |

A: Lot sizing B: Dispatching C: Offsetting
P: Significance level * : Not significant

**Table 14: Analysis of variance for alternative product structure**

| Problem set | Optimal decisions | | | Criterion value |
|---|---|---|---|---|
| | Lot size | Dispatching | Operation allowance | |
| *Criterion*: Tardiness | | | | |
| SO11 | LCP | SPT | 2.5 | 48 |
| PO11 | LCP | SPT | 1.5 | 54 |
| *Criterion*: System inventory | | | | |
| SO11 | L4L | SPT | 0.5 | 221 |
| PO11 | L4L | SPT | 0.5 | 197 |
| *Criterion*: Total cost | | | | |
| SO11 | LCP | SPT | 0.5 | 402 |
| PO11 | WW | SPO | 2.0 | 367 |

**Table 15: Effect of product structure on optimal decisions and performance criteria**

| Source of variation | % SS | F-ratio | P |
|---|---|---|---|
| A | 20.3 | 176.9 | 0.001 |
| B | 4.7 | 41.0 | 0.001 |
| C | 10.0 | 203.8 | 0.001 |
| D | 16.6 | 505.5 | 0.001 |
| AB | 2.1 | 2.6 | 0.001 |
| AC | 7.4 | 21.5 | 0.001 |
| AD | 7.2 | 21.0 | 0.001 |
| BC | 0.3 | * | * |
| BD | 0.7 | 3.2 | 0.001 |
| CD | 3.1 | 32.0 | 0.001 |
| ABC | 2.3 | * | * |
| ABD | 2.3 | * | * |
| ACD | 17.5 | 25.4 | 0.001 |
| BCD | 0.7 | * | * |
| NONADD | 0.0 | * | * |

A: lot sizing B: Dispatching C: Offsetting
D: Product Set *: Not significant

**Table 16: Analysis of variance table for Tardiness**
(Effect of Product Sets)

| Performance criterion | Problem set | Lot sizing rule | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | LTC | LUC | WW | LCP | L4L | EOQ | POQ | PPB |
| Tardiness | SO11 | 4 | 2 | 7 | 3 | 1 | 5 | 8 | 6 |
| | SO21 | 4 | 5 | 6 | 1 | 3 | 2 | 7 | 8 |
| | SO32 | 7 | 5 | 6 | 3 | 1 | 2 | 8 | 4 |
| | W= 0.741 CS = 15.56 (0.050)* | | | | | | | | |
| System inventory | SO11 | 7 | 4 | 6 | 3 | 1 | 2 | 8 | 5 |
| | SO21 | 6 | 4 | 5 | 2 | 1 | 3 | 8 | 7 |
| | SO32 | 6 | 5 | 7 | 3 | 1 | 2 | 8 | 4 |
| | W= 0.0926 CS= 19.44 (0.010)* | | | | | | | | |
| Total cost | SO11 | 6 | 2 | 5 | 4 | 7 | 1 | 8 | 3 |
| | SO21 | 3 | 6 | 4 | 1 | 8 | 2 | 7 | 5 |
| | SO32 | 4 | 2 | 3 | 5 | 8 | 6 | 7 | 1 |
| | W= 0.608 CS= 12.77 (0.100)* | | | | | | | | |

Legend:

W: Kendall's coefficient of concordance; CS: Chi-square statistic

* : The number in parenthesis indicates the significance level at which the hypothesis that there is concordance among problem sets about the ranking of lot sizing rules is rejected (Siegel, 1956).

**Table 17. Ranking of lot sizing rules**

| Performance criterion | Problem set | Dispatching rule | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SPT | SLK | SPO | FIFO | LRO | MRO | DSPO | EDD |
| Tardiness | SO11 | 1 | 8 | 5 | 3 | 6 | 4 | 7 | 2 |
| | SO21 | 1 | 8 | 6 | 2 | 3 | 5 | 7 | 4 |
| | SO32 | 1 | 5 | 4 | 3 | 8 | 7 | 6 | 2 |
| | W= 0.767 CS = 16.11 (0.010)* | | | | | | | | |
| System inventory | SO11 | 1 | 8 | 6 | 4 | 2 | 5 | 7 | 3 |
| | SO21 | 1 | 8 | 6 | 2 | 3 | 5 | 7 | 4 |
| | SO32 | 1 | 6 | 4 | 3 | 7 | 5 | 8 | 2 |
| | W= 0.0810 CS= 17.00 (0.005)* | | | | | | | | |
| Total cost | SO11 | 1 | 8 | 6 | 4 | 2 | 5 | 7 | 3 |
| | SO21 | 1 | 8 | 6 | 2 | 3 | 5 | 7 | 4 |
| | SO32 | 1 | 6 | 4 | 3 | 7 | 5 | 8 | 2 |
| | W= 0.810 CS= 17.00 (0.005)* | | | | | | | | |

Legend:

W : Kendall's coefficient of concordance; CS : Chi-suqare statistic

* : The number in parenthesis indicates the significance level at which the hypothesis that there is concordance among problem sets about the ranking of lot sizing rules is rejected (Siegel, 1956).

**Table 18. Ranking of dispatching rules**

| Performance criterion | Best Performers | | |
|---|---|---|---|
| | Lot-sizing rule | Offset | Dispatching rule |
| Tardiness | L4L, LCP, EOQ | * | SPT, EDD,FIFO |
| System inventory | L4L,EOQ,LCP | * | SPT,EDD,FIFO |
| Total cost | * | * | SPT,EDD,FIFO |

* : Choose by trial and error

**Table 19. Best Performers**