Cellular and Functional Production Environments :

Design Methodology and Comparison

by

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(ABSTRACT)

A hybrid methodology was developed to fairly compare functional and cellular production environments with respect to the production of machined parts which constitute the indivisible components of some final products. The methodology provides a means of designing each production environment at the lowest possible cost and then comparing the two environments with respect to cost and non-cost performance measures. The results show that the long-held belief that the cellular manufacturing or group technology method of production may be superior to that of the traditional functional or job shop layout may not be correct. A detailed comparison using four problem sets with different job and machine mixes failed to indicate a clear case in which the cellular environment performed better than the functional.

The methodology consists of two stages. Stage one has six hierarchical steps which systematically determine machine requirements and layout planning of each environment through mathematical modelling. External and internal operation constraints and inputs such as stochastic daily demand and operation times were considered. Stochastic programming was used in handling uncertain daily demand and operation times by specifying a desired minimum probability of meeting the demand for each job type in both environments. The MPSIII package was used in solving large mixed integer problems that resulted once non-linear terms, due to the chance-constrained nature of the segments of the models, were linearized. Because of the large problem sizes, MPSIII input files had to be created using FORTRAN codes.

In stage two, the SIMAN simulation language was used to determine the feasibility of stage one decisions and to obtain other system information. In simulation, some approximations were made to implement stage one decisions. For example, jobs received an average processing time in each operation class area rather than the exact operation time of the specific machine type to which the jobs were assigned in stage one. The effect of material handling distances and the use of limited number of work-in-process carriers were considered. Although the methodology was mainly developed for the comparison of the two production environments, it is readily usable for individual design of either production environment.

In addition to the two main stages of development, this research also required the development of two other procedures: unitizing daily demands and the modifiying the previously available job/cell grouping methods.

Dedication

I dedicate this research to my wife, Nanette. She provided the major support, both emotional and financial, which enabled me to complete this degree. Nanette went to work in the afternoon of the day of our marriage and never complained about commuting seventy miles a day to and from work. My doctoral work would have been much more difficult without her help and love over the years.

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- Dr. C. D. Pegden and the VPI user services staff with re-installation of the simulation package on the mainframe.
- Mr. Emin Demirbag with probability.

Above all, I would like to express my love and affection for my family : Little Leyla whose arrival last year added a new dimension of difficulty (and inspiration) to my doctoral work, to my wife, to my parents, and my brother, and other relatives. They provided tremendous encouragement during the course of this study.

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1.0 Introduction

1.1.1 The Scope of the Problem

A manufacturing firm has a number of options for selecting a new production environment or layout to meet product demand. These options include the traditional process or functional layout (Job shop), Flexible Manufacturing Systems (FMS), product or mass production layout (transfer line), and group technology or cellular manufacturing, or a variation of these production environments or production facilities. If the demand mix is composed of many low to medium volume parts, then the product layout (dedication of a line of machines just for one product) can usually be eliminated ruled out [167] since this option would require too many machines and incur excessive cost. The FMS, on the other hand, represents a significant capital investment, and its introduction involves a major project for the firm. While FMS provides considerable flexibility in production and introduction of new products, some firms may simply disregard FMS due to reasons such as complex automation and material handling, and sophisticated operation requirements, and high costs.

If these two environments can be ruled out, one of the remaining two options, functional or cellular production environments, must be chosen by the firm given that a hybrid combination of the two is not permitted. The combination of the two production environments or hybrid environments possesses the features of both options. Therefore, the combination option should be excluded from consideration if the goal, as is in this research, is to compare and contrast functional and cellular production environments and recommend either one for a given situation. Figure 1 on page 3 shows both production environments in their perceived forms. These two production environments are considerably different from each other. The cellular layout (physical cells as opposed to logical cells) is compact and composed of different machine types combined to fully manufacture a set of similar parts called a family. The cells in a cellular layout correspond to departments of the functional layout which are composed of similar machines combined to perform one of the required operations (drilling, milling etc.). A department receives and processes all the parts that need the operation(s) provided by that department's machinery. The advantages and the disadvantages of each layout have been widely reported in the literature, usually, in discussion and case study formats ([122] and [139] for example).

A common disadvantage of cellular layout applications is the implementation cost [156]. Part coding and data collection, required by cellular layout, are time consuming and expensive activities whether carried out by available staff or outside consultant. Rearrangement of machinery into cellular form is also expensive and disruptive. Cell structure may create highly and sometimes poorly specialized production zones [8]. In practice, many production facilities use a certain combination of functional, cellular, and product layouts.

As an example for one of the many differences between the two production environments, on a conventional machine, set-up may only take few minutes between two very similar parts, but it can easily take thirty minutes or more if the parts are very different. Therefore, set-up is usually less with a cellular layout because the parts are usually very similar. The selection of the optimum machine loading sequence is desirable for these obvious reasons. With functional layout it is harder to obtain and implement the optimum or even a good sequence

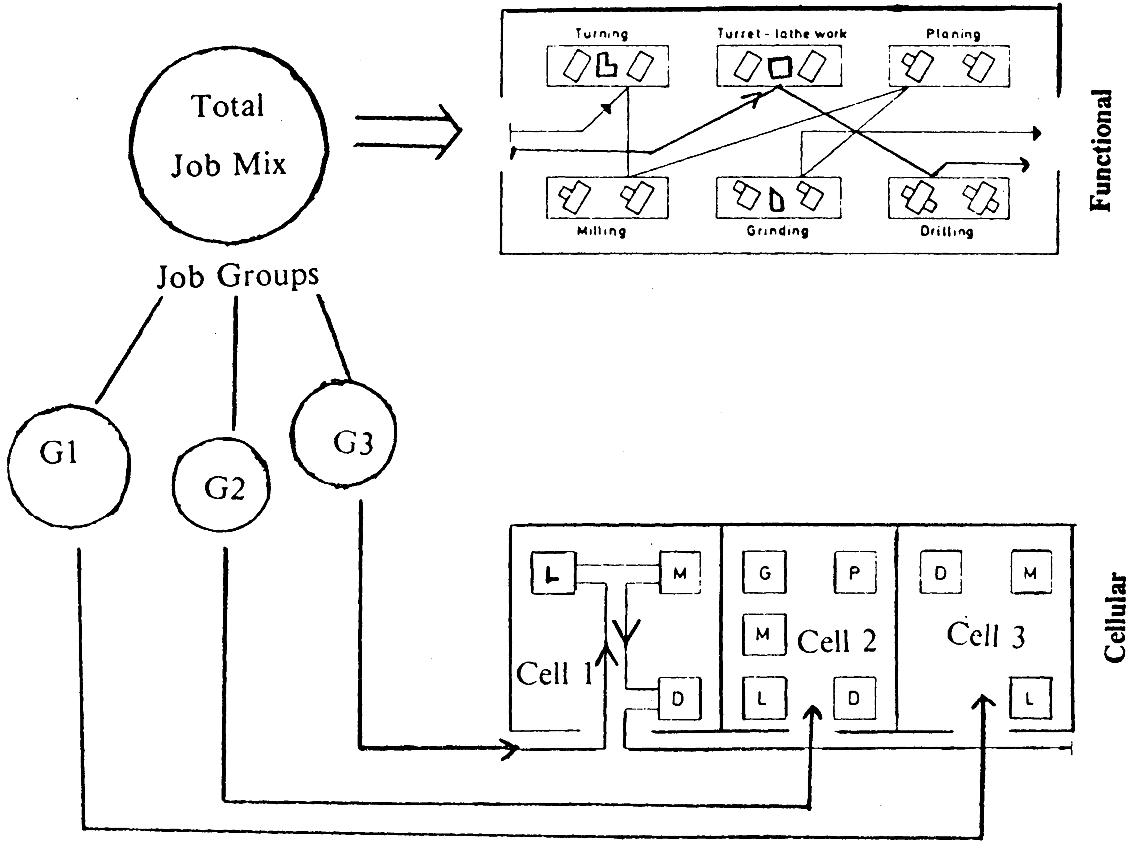


Figure 1. Pictorial Description of Functional and Cellular Environments

with respect to set-up requirements [215]. With group or cellular layout, on the other hand, this task becomes easier.

With respect to material handling requirements, distances between successive machines in different departments are large in a functional layout. The only economical material handling method may be to move jobs in batches using an expensive means such as fork truck material handling. Cellular layout does provide some benefits including continuous part transfer found in line layouts and usually requires a simpler and cheaper material handling system. Table 1 on page 6 compares the various features of these two production environments. There are only few items in Table 1 (No. 4, 6, 7, 8, 9, 18, and 23) for which consensus exists in the literature. Question marks designate those features that are disputed by many authors.

It is usually hypothesized that group cohesiveness exists in a cell because cell workers normally see a product fully completed or machined in one location, the cell, with common effort including job rotation. Cell workers are responsible for jobs assigned to their cells. Hence, the quality is usually higher since any defect is easily traceable to only one source in the shop when compared to functional production environment where the defect may be due to several departments which may all be unwilling to accept any blame.

In countering the above pro-cellular manufacturing (CM) arguments, reference [62] claims that job satisfaction can markedly decrease with CM when a proper and fair comparison is made between the two environments :

- Due to part grouping, cell workers work on very similar parts and feel restricted to almost the same work.
- Group work causes difficulties with incentive schemes when one worker's earnings are restricted by the pace of the others because of the teamwork concept of cellular manufacturing.

- Job rotation does not increase productivity or worker enrichment. A skilled worker will feel loss of status when asked to perform a task requiring lesser skill in the name of job enrichment, rotation, or teamwork.

It can be assumed that production control is easier under cellular manufacturing once jobs are assigned to their proper cells [122,123,173]. Unlike the department foreman of a functional layout who must be an expert of only the operations his department provides, the supervisor of a cell has to have experience in all the different operations the cell must perform. Even the advocates of CM agree that machine utilization is lower with CM than in a functional layout because a typical cell contains more machines than operators. Cellular manufacturing distributes similar machines across many cells. Assuming work content can not be transferred across the cells, two identical machines in different cells may be over and under loaded at the same time period.

A typical question that arises is how can one determine a set of jobs that will benefit more from being processed in a functional layout rather than a cellular layout and vice-versa ? Is it possible or meaningful to develop some kind of a "measure of shop group-ability or index " that tells which shop type (pure functional or pure cellular (group)) is the best for the given job-mix ? In other words, if changes are likely to occur in job-mix and the volume and routing of most jobs in the mix, which of the two production environments should be selected at the planning time such that some performance criteria can be optimized? While this research does not fully address the above issue, it provides a methodology applicable to segments of this issue.

Table 1. Comparison of Functional and Cellular Production Environment Features

	Functional Layout	Cellular Layout
1	Highly Labor intensive	Labor intensive
2	Skilled/semi-skilled labor	Same
3	General purposes machines	Same with more automation
4	Disorganized flow	Much more organized flow
5	W.I.P. high	Lower (?) *
6	Throughput time long	Much shorter
7	Individual component tooling	Family component tooling
8	Machine utilization high	Lower
9	High set-up times	Much lower set-up times
10	Intermittent production of parts	More continuous production
11	Low volume production of each part	Low to mid volume of each part
12	Usually made to order inventory	Same, but some for stock
13	Large product mix	Small product mix per cell
14	Extensive material handling	Lesser need for material handling
15	Conveyor use difficult	Easier
16	Production control/scheduling difficult	Easier (?) *
17	Maintenance/reliability not very critical	Critical
18	Flexible to changes	Less flexible
19	Job satisfaction higher/lower(?) *	Higher/lower(?) *
20	EOQ for lot size	Smaller lot sizes possible
21	Quality better/worse (?) *	Better/worse(?) *
22	Incentives widely used	Incentives difficult to implement
23	Lesser responsibility for foreman	Higher responsibility

(*) : No consensus exits on these attributes.

1.1.2 Objective

Since investment in machine tools is a major manufacturing expenditure, this research was partly concerned with developing a basis for determining machine requirements planning of the overall production activity. More specifically, a set of normative mathematical models have been developed for resolving the primary issues of: 1) selecting of the types and number of machines assigned to each section of each facility, and 2) selecting more economical facilities (functional or cellular layout) for a given case. The main objective, then, was the development of a methodology which can calculate the total cost of each layout and recommend one under a given set of external and internal constraints. Also, this methodology can be used to determine the ranges of inputs and the nature of the constraints that favor the adoption of either production layout.

Various parts of the following tools and concepts were applicable in this research.

- Machine requirements planning,
- Group technology and cellular manufacturing,
- Mathematical modelling and programming,
- Stochastic programming,
- Integrated and multi-stage, multi-product production planning,
- Facilities design and layout, and
- Simulation.

Chapter two provides a current literature review on some of these topics.

1.1.3 Capacity Planning, Facility Design and Production Control

The following resources are essential to process a job or batch of jobs on a machine at any facility :

- The machine itself along with necessary tools, jigs, and fixtures.
- A labor force whether direct and/or indirect and necessary instructions.
- Raw materials and/or work-in-process from previous production stages.

Machine Requirements Planning:

In general, the machine requirements planning problem is defined as determining the number of each type of machine required for a production process for each time period during a planning horizon. The main reason for machine requirements planning is the need to determine the number of machines needed such that a prespecified production requirement is met for each product. The specific definition of a machine requirements planning problem depends on factors such as production constraints (financial, plant space, etc.), production processes, number of products, and the number of operations needed by the products. Machine requirements planning may be thought of as subset of the general production planning area; but, here, the main goal is determining the capacity needed rather than capacity allocation and control.

The capacity available limits the production levels while sales may fluctuate. The capital investment in machines may be either for capacity maintenance or expansion. Capacity maintenance belongs to the general area of equipment replacement. Firms need to match requirements and available capacity in an efficient manner. Most short term or unexpected capacity requirements may be handled by resorting to means such as overtime and subcontracting.

Usually, the machine requirements concept is associated with those production environments where actual machining activity takes place. Machine requirements planning is affected by other factors such as lot sizes, scheduling and job sequencing, and lost sales and rework costs. An important, resulting decision involves the fractional number of machines which may be needed to meet the demand. These fractional machines cause difficulty due to the integer machine requirements. Thus, either excess or under capacity at any production period is normally unavoidable. Depending upon the nature of the problem, fractional machine assignments are either rounded up at the expense of idle machine cost or rounded down at the expense of loss of sales, due date unattainment, and lost customer goodwill. The general goals of machine requirements planning are to minimize discounted investment cost, minimize operating costs, or maximize profit.

In the context of this research, Material Requirements Planning (MRP) and manpower planning are not considered explicitly, but MRP can sometimes mix inseparably with the general areas of capacity planning and capacity loading. MRP systems generate a time-phased material requirements plan. It can also process the material requirements against the routing files for the materials to produce a time-phased Capacity Requirements Plan (CRP). Infinite loading of the capacity is not the same as the CRP, as infinite loading does not take planned orders into account; it only considers the released orders without taking limited capacity into account [158]. Finite loading, on the other hand, is a method for loading orders into a plant in a priority order within the capacity constraints . The total consideration of all the factors make the overall machine requirements planning problem complex. Given an extended demand forecast, deterministic or probabilistic, the firm has to determine both timing and the magnitude of capacity increments, assuming growth, to be made.

Almost all of the analytical approaches to the machine requirements planning problem found in the literature take a quite simplistic view of the production systems. These studies usually pay little attention to the interrelations between the underlying subproblems such as the number of machines used, in-process inventory levels, scheduling rules, product quality, and other system constraints [71]. Furthermore, the competition among the various work centers for limited production resources is either ignored or treated in a cursory fashion [22,70]. Such cursory treatment may be due to the size of the resulting problems when even just a few of the real-life considerations are jointly considered.

Machine Requirements Planning Under Deterministic and Probabilistic Inputs:

It is likely that not only demand, but also other inputs such as operation times and machine efficiencies will be probabilistic. For example, if a given machine i is to process operations No.1 and 2 of job A and operation No.1 of job B, the number of machines of type i, M_i, needed, deterministicly, is :

$$M_i = [\,\overline{D}_A(\overline{T}_{1,A} + \overline{T}_{2,B}) + \overline{D}_B(\overline{T}_{2,B})\,] \,/\, [\,\overline{AMT_i}\,] \tag{1.1}$$

Where $\overline{D}_A$ and $\overline{D}_B$ represent mean demand per period for jobs A and B and $\overline{T}_{1,A}$, $\overline{T}_{2,A}$, and $\overline{T}_{2,B}$ represent the operation times on machine i. $\overline{AMT_i}$ is the mean minutes of production time available on one machine of type i for the time period given. In reality, the use of such estimates may not be sufficiently accurate. If the probability density function or distribution of each input is considered, M_i can not be found as easily as in (1.1). The distribution of M_i, $f(M_i)$, may be expressed as the function of other input distributions :

$$f(M_i) = F[\,f(T_{1,A});\ f(T_{2,A});\ f(T_{2,B});\ f(AMT_i)\,] \tag{1.2}$$

Either an analytical method or simulation may be used in finding the structure of $f(M_i)$ This task can prove to be rather complex since it involves the division and multiplication of the input distributions.

Group Technology and Cellular Manufacturing:

Researchers have defined group technology in many ways for over two decades. Group technology is the organization and the grouping of common technological products and tools in order to reduce the complex production problems seen in job shops [86]. Group technology consists of three rather different areas:

1. Classification and coding of parts (jobs).
2. Design of jigs and fixtures.
3. Celluar manufacturing.

The first two areas deserve only limited attention in this research while the cellular manufacturing concept constitutes the foundation for one of the production environments considered. A cell is a group of manufacturing resources and is based on the commonalty in manufacturing requirements and/or design/shape of jobs assigned to each cell. The basic concept is the physical division of a plant's manufacturing machinery into production cells in order to realize the benefits of group technology. Such benefits, though not universally agreed on, include the elimination of some indirect costs, reduction of set-up and throughput times, and improvement of labor productivity and job enrichment [155].

Cell Characteristics:

There is no clear way of knowing how many cells should be used in order to obtain the maximum benefits from cellular manufacturing. According to some, roughly one-third of the facility should remain as a general job shop and not be converted into special cells thus creating an hybrid shop [91]. Cell sizes may vary from three to fifteen machines with six being the average number [123]. The remainder cell is the portion of the production facility that is not converted into the cellular form. The remainder cell is thought of as a back-up cell that usually contains at least one of every machine type, and is used to meet excessive demand or directly complete some jobs if they, for some reason, can not be fully processed in their original cells [39,86].

Cellular shops are said to have two major drawbacks low machine utilization and inability to cope with input changes effectively (e.g. changes in demand levels and mixes). Cellular manufacturing's reputation for low machine utilization is not as serious as it sounds. Such a statement ignores the fact that a machine in a cellular shop may indeed be manned at a lower percentage than in functional shop, but it is very likely that a higher percent of the manned time will be spent on actual cutting activity due to reduced set-up requirements inherent in all group technology applications.

Cellular Manufacturing versus changes in job-mix or demand:

The impact of changes in demand mix for which the facility has been designed is one of the primary concerns of this research. The comparison of functional and cellular production environments will be partly based on stochastic daily demand levels. The functional production facility or job shop is normally designed to withstand major changes in production requirements while the cellular facility is expected to experience the followings [100,104]:

- Any significant change in demand levels may lead to machine imbalances and reduce shop performance. Excessive idleness may occur if demand changes considerably.
- GT/CM can not typically afford machine breakdowns, and especially of unique demand mix changes, operator absenteeism as well as FL can.
- Facility performance is more tenuous if the products are highly dissimilar across all cells.
- Highly specialized small cells may be more vulnerable to changes in demand mix as opposed to more generic larger cells which can accommodate larger job mixes.
- If the demand level change is a small increase, then delays in deliveries will occur.
- Use of overtime or outside capacity (other cells, subcontract) may be needed to accommodate changes in demand or mix.
- Deferred maintenance of machines, loss of sales, and change of prices may be necessary to counter the effects of major changes in demand levels.

Design of Cellular Manufacturing Systems:

As in other production system designs, cellular manufacturing system design is composed of four major facets :

1. Job grouping for each cell.
2. Capacity planning of each cell.
3. Layout design of each cell.
4. Production scheduling in each cell.

Job grouping may be accomplished using a tool such as classification and coding system based the on design similarities or the commonalty of processing requirements. A group or family of groups should provide enough work to justify the existence of a cell. Capacity planning should precede layout design so that the designer can know the type and the number of machines to be laid out in each cell. Preferably, a given machine should be utilized no less than what would be expected under functional production facility. There may be several, sometimes conflicting, objectives in layout design such as attempting to minimize backtracking and the material handling of jobs. Next, once jobs are assigned to cells, cell scheduling represents the last major design segment. Actually, it is unclear between the scheduling and the layout design as to which one should precede the other one because they are an iterative process.

Possible Remedies to the Effects of Changes in Job-mix of Cells

1. Inter-cell work-load transfer at the expense of material handling cost and loss of production control.

2. If manufacturing for in house assembly, make products for stock when demand goes down and use that stock when demand goes above the forecasted level.

3. Design a highly flexible CM system at the expense of even higher machine idleness.

4. Design cells based on "cascade principle" [100] (again, higher idleness) which is a joint consideration of cell system design and cell loading procedures.

5. Use fewer but larger cells each with larger family of components to reduce overall variance which reflects the variance in demand of each job.

6. Attempt to group jobs with independent or near independent demand patterns while still meeting main grouping criteria (e.g., mixing orders of distinct customers together in a cell).

Therefore, the success of any cellular manufacturing is correlated with its ability to cope with significant changes in the demand mix.

Production Environments and Layouts:

The production environment refers to the state of job flow between the machines and the machine groups in a manufacturing facility when the machines are already laid out and fixed. Most production environments belong to one of the following classes :

1. Pure job shop (PJS) : Unrestricted flow, entry, and exit of jobs.
2. Job shop (JS) : Slightly restricted form of PJS.
3. Modified Flow Shop (MFS) : Mostly undirectional flow with some backtracking.
4. Flow shop (FS) : Limited backtracks and exits, undirectional flow with forward skipping allowed.
5. Pure Flow Shop (PFS) : No machine skipping in either direction (transfer line), unindirectional flow, one entry and one exit point.

The functional layout considered in this research is not one of randomly routed jobs kind (PJS) and it can be best described by a JS. The process layout or job shop, here, refers to an organization of machines (not necessarily the same type of machines) dedicated to perform a particular class of operations. As discussed in Chapter three, the jobs or the parts have well-defined operation requirements which must be met from the necessary class areas. This assumption precludes any random routing.

The independent single cell obviously posseses many of the characteristics of these five environments. It is hard to state which of these five production environments best describes an ideal Cellular Manufacturing environment. While PFS appears to be the best, it would require too much machine duplication. The real-life case is probably somewhere between a JS and FS since all jobs assigned to a cell do not use all the machines available. Then, internal job flows of cells can be jumbled like a JS or straight like a FS and PFS or may even be centered around just one work center. In fact, Wemmerlov and Hyer [104] state that a FMS can be seen as an example of job shop cells. A transfer line and an assembly line may be classified as cells too. This research, however, considers only the machining cells that best fit MFS type production environment.

Production layout, in only physical machine location sense, refers to the layout of machines in a facility given some job mix and the routing of each job. Historically, there have been two major production layouts :

- Process or Functional layout which is characterized by groups of machine tools that perform the same function.
- Flowline or Product layout in which each product flows from its first operation. to the last operation.

Justification of Production Environment Selection:

CM is typically in the challenger position to a well established functional production facility; therefore, it is commonly assumed that CM should justify itself against the status quo. To do so, it is necessary to identify the costs and the benefits that result from CM in a quantitative manner. The literature and the trade press provide many miraculous CM implementation reports which may or may not be considered totally valid. Such reports tend to blame the previous production facility, usually a functional one, for all the past problems and promote cellular manufacturing as an instant cure without, usually, a detailed comparison.

It is obvious that cellular manufacturing can not induce sudden improvements on the facility performance just by dedicating some machinery to only one or two part families. There is another important issue : If cellular production environment is indeed the challenger to the existing environment, then what kind of cellular manufacturing environment is being considered If it is a hybrid one which includes a job shop like section or a remainder cell, this choice does not provide for a sound comparison since a hybrid layout does not represent a real cellular manufacturing environment.

Machine Requirements Planning and Cellular Manufacturing:

Since each cell is organized to handle a small subset of the total number of parts, it is possible to initially assume that creating cells will increase the number of machines and, thereby, lower the machine utilization (only an integer number of machines may be assigned to each cell). This, however, may not always be true because cells process those jobs with similar set-up and operation requirements and this increases the amount of actual cutting time available on each machine. The actual cutting time may increase while overall machine utilization which includes both cutting and set-up times may seem lower as compared to a functional production environment. Also, cells can be arranged in such a way that some machines are shared by two cells thus avoiding, at the expense of reduced production control, rounding up of two similar and fractional machines in two nearby cells.

Mathematical Programming:

Mathematical programming implies programming in the sense of planning. Obviously, mathematical programming becomes involved with considerable amount of computation because most problems can only been solved by the use of a computer. The fundamental function of mathematical programming is the optimization of some objective function subject to a set of constraints. Most production planning problems can be modelled and solved by using some form of mathematical programming models such as linear, non-linear, or integer. Due to the size and the interaction of the variables of a real-life production planning problems, it often becomes necessary to resort to a heuristic approach to solve the model after it has be formulated.

The quality of the model output depends highly on the accuracy of the model structure, the definition of the objective function, and the data used. Unquestioned belief in a model can usually lead to poor or infeasible decisions. The output of a model should be used as a guide in actually developing an acceptable decision set. While most models have a single objective function, it is possible to have models with multiple and conflicting objectives. Some of the most common types of constraints used in production planning are capacity, raw material availability, demand, material balance, and quality which appear in the forms of hard and soft constraints, conflicting constraints, redundant constraints and an either/or type of constraint.

1.1.4 Production Planning

For most firms, it is desirable to achieve an effective utilization of manufacturing resources. There are, usually, two levels of resource planning: aggregate and disaggregate.

Aggregate plans are made at the highest levels of an organization and are used to determine weekly, monthly, or quarterly levels of overall manpower, production and inventory. Regardless of the annual production levels, daily production activity needs regular scheduling instructions to operate. Disaggregation, the transformation of an aggregate plan into an usable one for each time period, ties these two extreme procedures into an usable plan. Without the functional interface supplied by disaggregation, high level aggregate planning tools can not be converted into cost effective scheduling fore production floor. Therefore, an aggregate plan is feasible if such a plan can be disaggregated into a feasible detailed plan which meet the detailed demand for the first period and retains the feasibility of the aggregate plan for the remaining periods [68].

A hierarchical approach is a good alternative to the pitfalls of a detailed mathematical model for production planning and scheduling. In an hierarchical planning system, decisions are made in sequence aggregate decisions are made first and used as constraints while more detailed decisions are made later. The consequences of these decisions may be used as feedback to evaluate the effectiveness of the aggregate decision process. Most hierarchical plans use three steps to describe the production planning in medium size manufacturing activities. These steps are:

1. Allocation of production capacity among product types via an aggregate planning model.
2. Disaggregation of the results of the aggregate planning model.
3. Calculation of production allocation of each product once a family production allocation is found from step 2 above.

Linear programming is often used at the aggregate level due to its convenience, efficiency, and availability [43]. The aggregate model is updated with a rolling horizon of some time length. Relevant costs in an aggregate production planning model include: basic production costs, costs associated with changes in production level, inventory holding costs, and the backloging costs. Linear cost models are commonly used to guide the aggregate planning decisions. There are two kinds of linear man power cost models [7] : fixed work force and variable work force models. If the linearity assumptions do not permit the decision maker to deal with the demand uncertainties, quadratic cost models are used to solve the aggregate production problem.

Initial Job and Process Related Decisions:

In both long and short range planning, the following issues must be addressed for each production environment:

- Job-mix decisions on the selection of a suitable job set to process including the proportion of each job within the mix.
- Optimal process planning decisions whenever there are multiple processes available for machining a selected job.
- Job loading and routing decisions involving initial job entries to the facility and assignment of jobs various machines for necessary operations.

Machine Set-up in the Planning Process:

Whenever the manufacturing process is characterized by batch-type production operations (as opposed to continuous production), set-up cost and time have to be considered in lower level planning. Inclusion of the set-up cost in higher planning levels expands the size of any cost model in its usefulness and, usually, forces an additional level of nonlinearity and introduces integer variables. If there is only one product to be produced over a horizon, then an uncapacitated lot size model is used in place of the EOQ (economic order quantity) to handle the changing and uncertain demand level [9]. When there are multiple products over the same horizon, then the products have to compete for limited capacity and the set-up costs become more important. A more complicated model, the capacitated lot size model, is the traditional way of solving this problem. Often, it becomes convenient to apply a dynamic programming method once the production planning problem has been formulated as mixed integer program (linear or nonlinear).

1.1.5 Stochastic Programming

In capacity planning problems, linear programming models are very appropriate when the cost functions are linear and the capacity requirements during the different time periods can best be described by independent probability distributions [66].

A stochastic linear program can be stated as follows :

$$\text{Minimize } f(X) = C^T X = \sum_j c_j X_j \tag{1.1}$$

Subject to :

$$A_i^T X = \sum_j a_{ij} X_j \geq b_i \quad i = 1,2,....m \tag{1.2}$$

where $X_j \geq 0$, and c_j, a_{ij}, and b_i are all random variables with known probability distributions.

Among the several available methods for solving the above problem, two methods have received the most attention :

1. Two-stage programming technique. This method was not used in this research because two-stage models are less sensitive to changes in the parameters [176]. In two-stage programming deterministic solution is first established before the random conditions are specified later.
2. Chance-Constrained programming technique (discussed below).

Chance Constrained Programming:

Chance Constrained Programming is used to solve the problems which may, at least partially, involve certain constraints with a finite probability of being violated. This method allows some violation of the constraints while the other method, two stage programming technique, does not permit any such violation. A typical chance-constrained programming is as follows :

$$\text{Minimize} \sum_j c_j X_j \tag{1.3}$$

Subject to :

$$\Pr\left(\sum_j a_{ij} X_j \leq b_i\right) \geq \alpha_i \quad i = 1,2,..m. \text{ and } \alpha_i \in (0,1) \tag{1.4}$$

where $X_j \geq 0$ and $(1-\alpha_i)$ denotes the allowable "risk" that the constraint will be violated when one of the following conditions exist :

1. Right hand side, b_i, values are random.
2. Input/output coefficients, a_{ij}, are random.
3. Cost coefficients, c_{ij}, are random.
4. Any two or all three of the above are true.

Applications of Chance Constrained Programming in this Research:

In all real life cases, the production process has many uncertainties which make the usual linear programming assumptions invalid. For example, product demand per period usually can not be known with hundred percent certainty. The same can be argued about the operation time taken by different, or even the same worker, on an identical machine. If the operation times, demand levels, and the other effectiveness factors are subject to variation, the actual number of machines required will itself be a random variable. It is then necessary to decide what number of machines to install to best meet this varying requirement. Since the decision is generally made before any variations are observed, there will be times when under and over machine capacities will be experienced by the firm. Chance-constrained programming can serve as a tool to actually account for this unavoidable risk.

Typical Solution Methodology for Chance Constrained Programming:

It is commonly assumed that all variables follow a normal distribution in order to easily obtain an important transformation called "deterministic equivalent" of the original probabilistic problem (see Appendix A for details). This process, with the exception when only b_i is random, results in nonlinear mathematical models which may be solved by one of the available methods. It is also convenient to assume that demand and other factors are independent of each other. Then, it becomes possible to ignore the covariance terms of the variance-covariance matrix which result under the normality assumptions. Appendix B presents two ways of solving this type of programs. Appendix C compares the performances of available solutions using two example problems.

2.0 Literature Review

2.1.1 Review of the Most Relevant Literature

When the general concept of group technology was developed, there was a wave of publications claiming benefits realized soon after the companies had adopted group technology. The reader is referred to texts [122,123,139,148,149,173,186] which provide many reports and case studies showing the various production related performance measures both for pre-and post group technology operation periods. The majority of group technology publications originate from the United Kingdom. Beginning in the mid 1970's, researchers began questioning whether group technology was really the solution for production related problems. Previous studies had often compared a newly-designed and efficient group technology layout with the layout that existed in the plant before group technology was introduced. Those existing layouts may or may not have been as efficient as possible, therefore, the high hopes tied to group technology appears to have faded today as more and more publications have sought to invalidate many claims of success attributed to group technology while giving group technology some credit for improvements in limited cases.

The literature reviewed below contains a number of publications which compare these two production environments. These studies have diverse sets of assumptions, and they are either simulation and/or of analytical type. Because this research assumes that all machines are of stand alone (conventional or computer controlled) type; those publications which provide a vague comparison between a highly automated cellular production environment such as a FMC and some other production environment have been disregarded.

Carrie, in 1973, [125] applied taxonomy, the science of classification, in developing a simple and efficient technique which shows which type of layout is most suited to a particular case. His method involves the preparation of a data matrix, computation of a similarity coefficient matrix and the performance of cluster analysis for both layouts using the codes developed. His paper does not conclude as to which layout is better in general. Carrie assumes that the determination of the existence of distinct product families may easily lead to the adoption of, and success by, a group technology layout. Also in 1973, Crawen [19] discussed ways to justify a conversion from process layout to group technology layout and observes that the degree of conviction for actual conversions has been very small compared to the amount of support in both technical and academic literature. The author explains the limited use of group technology layout by suggesting that the benefits of group technology have been overemphasized without adequate attention having been paid to necessary conditions for group technology application.

Ratmill et al [198] compared batch sizes under both environments and concluded that group technology achieves a high level of output and system efficiency for batch production, and can reduce most of the cost parameters concerned with batch sizes. Leonard and Rathmill [62], once defenders of group technology, reversed themselves and claimed that group technology was not the best solution for normal batch manufacture. These authors state that group technology layout actually reduces job satisfaction, increases the machine idle time, and complicates production control. They claim that group technology has caused British Industry to fall behind Germany and Japan which never left the traditional process or functional layout. It is stated that group technology should be restricted to situations when there is a stable demand mix with for large quantity of simple parts.

Later, using an analytical approach, Rathmill and Leonard [81] attempted to fairly contrast group technology with process layout by incorporating queueing theory and batch size selection. The findings of their work indicate that group technology flowline and single machine concept are excellent. But, the potentially more common form of group technology, the cell, is accompanied by a large number of problems which, in the authors' view, limit the widespread application of group technology. A group technology suitability checklist is presented and applied to three companies in a case-study format. The authors differentiate between the impacts of a group technology cell (cellular layout) and the flowline layout on these companies and conclude that group technology flowlines are highly efficient, but have limited application. A set of formulas developed show that it is erroneous to extrapolate the results obtained for group technology flowlines and assume that the same degree of net advantage will exist for group technology cells.

An early simulation study to investigate the effects of cellular grouping was carried out by Athersmith and Crookall [3]. They arranged twenty-eight machines of four different types into different number of cells to measure the effects of cellular layout on work-in-process levels, machine and labor utilization, and job throughput times. In most cases, the one cell or process layout environment appeared to out perform two or more cell (cellular) layout environments. This study's findings, in fact, conflict with almost all other studies which, at least, agree that the mean throughput time is shorter in cellular layouts. Shunk [91] combined simulation and layout techniques in measuring the effects of a hybrid shop with the usual production performance measures. Once the parts are grouped, the machines were assigned to the cells according to a simple machine fraction calculation. It was reported that the hybrid layout may be better than either a strict process layout or a total group technology layout. This study uses a due-date based rule for dispatching jobs on the shop floor and assigns machines to operations based on the available capacity and the average demand. The demand is taken as uniform over the entire year for all three environments compared. The author also experimented by varying set up times from hundred percent to sixty percent of normal and determined the average job completion time in each case.

In another simulation study by Willey and Ang [105] in 1980, the authors used the same twenty-eight machines of four different types as used by Athersmith and Crookall [3] and showed that a hybrid, and therefore non-pure group technology layout, may be economically justified as a means of mitigating some problems found in a pure group technology layout when inter-cell transfers are not permitted. Cellular production system was found superior to a functional one by Nisanci and Sury [75] who divided the machinery of a closing department of a shoe manufacturing factory into two big cells. Using only two cells and identical capacity, the authors presented the results of a simulation study which shows significant reductions in mean flow time and waiting times compared to functional system. An improvement was also reported for overall machine utilization. Steudel [96] described how SIMSHOP, a FORTRAN - based simulator, can be used in the design and analysis of a complex discrete parts manufacturing system involving a either cellular manufacturing layout or process layout configuration. This recent study (1986), reports on the results of the applications of SIMSHOP in the redesign of an existing job-shop facility into a cellular manufacturing layout. A sample of 350 part routings was selected as a typical part-mix and these parts were assigned to specialty cells. Without making the actual conversion at the plant site, this simulation study showed many advantages that could be gained by changing from process layout to cellular manufacturing layout. Unlike some studies, this study, as in early pro-group technology publications, promotes group technology as the better choice.

Cumming [20] used three milling, three drilling machines and three lathes in constructing simple forms of both process and cellular manufacturing layout. He simulated both layouts and reports that group technology layout has done much better with performance measures such as work-in-process, investment level, mean transit time, mean lateness, and the number of jobs completed per period. This study, however, utilizes a very small shop with no consideration for a material handling system and setup times. Ang and Willey [1] stated that while group technology overcomes some small-batch manufacturing problems, it lacks the necessary flexibility to cope effectively with work load variations. A simulation study was conducted to examine the effect of inter-cell workload transfer in improving overall performance of group technology shop. Thus, this study basically compared the pure group technology layout (inflexible cell) with the hybrid group technology layout (flexible cell) for measures such as the mean job flow time, lateness, tardiness, and the proportion of jobs not completed. The authors concluded that hybrid group technology shops can be superior to the corresponding pure group technology shop due to the better performance measures and the ease of the operation of the hybrid shops. They ignored the fact that there is little difference between a fairly hybrid group technology layout and a process layout. Furthermore, so called hybrid group technology layout violates some of the basic group technology principles and it is described as the "worst of two worlds " by Leonard and Rathmill [62]. This study, therefore, is really a comparison between process layout and group technology layout and the process layout seems to be in general preferable.

Flynn and Jacobs [35] and Flynn [31] [33] claimed that Cumming's study was not realistic because it compares an efficient group technology layout with an inefficient process layout. They simulated four different layouts, designed to emphasize the different features of both layouts, and used four distributions of demand for end items. Their experiments showed that group technology shops exhibit superior performance in terms of the average move and the set-up times while the process layout performs better in the queue related variables. Using batch sizes of one, this study considered six cells with multiple machines and used the CRAFT algorithm to ensure that both layouts are efficiently arranged before the simulation was carried out. The authors also assumed discrete demand distributions for six end items and used the end item demands in deriving the total load that pass through four layout types used in the simulation study. In 1987, Flynn and Jacobs [32] modified their previous article [35], but provided no new results. Their list of thirty-one references carefully and interestingly omits [35] which is ninety percent similar to [32]. Aneke and Carrie [107] proposed a unifying classification scheme for all varieties of flowlines. The authors compare and contrast group technology, process layout, and line layout for criteria such as the number of products, number of operations per product, sequence of operations and set-up requirements. However, this article does not recommend any of the three layouts considered because the article's goal is the discussion of the suitability of each layout under various conditions.

Lee [61] used SIMON simulation language in constructing a comprehensive simulation model to examine the effects of different numbers of tool set-up types or part families on the usual production related performance measures (flow-time, WIP, e.t.c.) of a manufacturing cell. Later in the study, the author compared a larger eighteen machine cell with three parallel six-machine cells. This comparison can be viewed as comparison between a functional or process layout, the eighteen machine cell, and cellular layout with three cells. This study's findings confirm the conclusions reached by Rathmill and Leonard [81] because the machines appear less utilized in cellular layout than the equivalent functional layout. A partial comparison of two production environments was presented by Lilly and Driscoll [64] who, in 1985, examined changing of an existing functional facility into a cellular one with three conventional and two FMS cells. The authors first reviewed methods of layout change of an existing facility and then provided a simulation approach using graphics and quantitative analysis including cost items such as material movement, relocation of machinery, production loss, and other overhead costs. This publication did not recommend either production environment as the preferred choice. The goal of the authors was to describe a simulation model in studying and comparing current and future production environments.

Considering only inventory related costs factors, Boucher and Muckstadt [10] recommended a conversion from functional layouts to GT layouts. The authors developed an analytical procedure to examine manufacturing costs in such a conversion using factors such as cycle stocks, safety stocks, and WIP inventory levels under normally distributed annual component demands. An example using ten different parts and deterministic annual demands showed GT layout cost performance superior over a functional one by 2.2. Finally, Askin and Subramanian [2] compared the two layouts as a part of their heuristic approach which determines machine groups and the corresponding component families by considering costs of work-in-processs and cycle inventory, intra-group material handling, set-up, variable and fixed machine costs. The authors used the twenty-four product, fourteen machine example of King [174,175] to show that cellular layout, in its extreme case (one product per cell), may be favorable over a functional layout when machine utilizations are fairly high. This paper actually promoted a new heuristic which shows that a hybrid layout gives a lower total cost than either alternative.

Fazakerley [30] was the first (1976) author who presented a solely human factors oriented comparison of these two environments. Using questionnaires, interviews, and participant observation, the author stated that cellular manufacturing itself does not create greater flexibility since many factors such as union contracts may prevent operators from changing jobs. The author also argued that the much publicized job variety benefit of cellular manufacturing over process layout was really not true because group technology operators work with components which are highly similar. Later, in 1985, Huber and Hyer [40] provided the first empirical human factor approach for the comparison of cellular and functional production environments. After statistically analyzing the perceptions of workers in both functionally and cellularly arranged sections of the same fabrication department of a medium size manufacturing company, the authors concluded that cellular manufacturing neither increased nor decreased worker performance or satisfaction over that achieved in the functionally designed unit.

This review has shown that the intended research has a potential to fill an important gap in the comparison of these two production environments. The previous work has not fully addressed the problem by not considering some real life situations such as random daily demand and other physical constraints. In addition, there is still no clear cut decision for either layout.

2.1.2 Group Technology

It is not the intent of this research to provide an extension or an improvement on any of the group technology areas. However, many of group technology concepts are needed to facilitate the intended comparison of two production environments. The literature on functional layout has not been reviewed herein since the massive job shop literature is generally attributable to functional layout. The literature on GT is rather voluminous too: there are over 700 publications which treat the overall group technology concept either as the main or the secondary topic. Although these texts cover many important areas of group technology, they do not include most of the newer analytical and simulation studies. Some segment of these studies are applicable to this research and they are reviewed in this chapter.

Articles by Greene and Sadoswki [156] , Greene and Cleary [155], and Mosier and Taube [73] provide a more recent descriptive coverage on group technology and its main components. Ham's [162] text is the only text which provides an analytical approach to various issues of group technology. This book appears as the group technology equivalent of Hitomi's text [167] which serves as a valuable reference in general production topics. Ham's text, similar to many of his articles, treats group technology in a quite different way by ignoring the cell concept and concentrating on scheduling and sequencing of jobs as if there were only one cell. Wemmerlov and Hyer [104], in 1987, described cellular manufacturing section of group technology as a highly researchable field spanning several academic disciplines. The authors discussed applicability, justification, design, and implementation of a cellular manufacturing system. Hyer and Wemmerlow [47] give some sixty references relevant to group technology and cellular manufacturing and discuss the joint applications/benefits of GT/MRP concepts.

The segment of group technology literature selected for review is discussed below under three, sometimes overlapping, areas:

1. General Discussions on Group Technology:

This section reviews the recent articles which provide discussions on group technology areas such as the lot sizing, capacity control, and layout design. The older articles are not reviewed here because the majority of these publications have already been thoroughly discussed in the review articles mentioned above.

Spencer [211] combined the concepts of material requirements planning and master scheduling with group technology for improved use of the available capacity. Koenig et al [57] showed how a General Electric Company production department has improved miscellaneous parts manufacturing productivity by taking advantage of group technology methods. The results indicated significant reductions in set-up times and manufacturing losses and improvements in the direct labor productivity. Boucher [118] claimed that there was a traceable relationship between the lot size and the work-in-progress inventory and developed an economic lot-sizing model appropriate for group technology. This model minimized the sum of the set-up, work-in-process and finished goods carrying cost. The empirical results indicated that his model performed better than the simple EOQ model especially when there was high demand and/or there was extensive machining time involved.

Greene and Sadowski [156] listed the variables affecting the control of a group technology system and discuss cell loading and cell scheduling with respect to system and job characteristics. They also described the advantages and disadvantages of cellular manufacturing, and the commonly implied assumptions in group technology. Sinha and Hollier [209] reviewed the areas of batch size selection, batch control, and scheduling of manufacturing cells. The authors identified and established some of the most significant and important features of cell scheduling by describing most of the simulation studies prior to 1984. They predicted that future manufacturing would be centered around computer systems which integrate CAD/CAM, part programming, group scheduling and FMS.

Chakravarty and Shtub [126] developed two design procedures which are capable of generating efficient layout of the machines in groups and establishing lot sizes of the components to match the layout. The first design is used when mutually independent machine-component groups can be found. The second procedure is for cases when no independent groups can be found. James [50] showed that the Computer Integrated Manufacturing (CIM) concept could be used in the creation of machine cell layouts from the information supplied by the CIM data base. The procedure starts with the process plan information for each job and determines the ideal layout for each cell. ALDEP layout is used as the reference in statistically testing the quality of the output. Baybars et al[115] presented two models for the supply of work to be processed in the cell and the removal of finished products. These models, the minimum waiting time model and the full load economic capacity model, help the planner in making capacity and batching decisions and carrying out a sensitivity analysis on the cell performance.

2. Part Family/Cell Formation:

The part family and resulting cell formation problems have been addressed using two different viewpoints: Production oriented grouping using information on part routings and the different machines required for each operation (forming cells first) and the design oriented grouping (forming families first) using the various codes available. When a new part is to be produced, only its geometrical or design information is known and this information can be used to find the closest family. The production family can then be located by taking the most similar parts as the key for the search process. Since this problem has received considerable attention in the literature, only 1980 and later publications are reviewed here. Several of the following articles also provide a review of the previous research in part family and cell formation areas.

Tarsuslugil and Bloor [98] described the available, simple grouping procedures and gave a numerical example for each procedure. Witte [223] presented a similarity coefficient based method by assuming that some machine types will be allocated to several cells. He defined three similarity coefficients and used the graph-theoretic approach for the clustering of the parts. King [175] reviewed the previous progress in the clustering area and then introduces a new method called Rank Order Clustering (ROC). He claimed that this method was well suited for machine-component group formation and it had special provisions to handle the exceptional elements and the bottleneck machines.

King and Nakornchai [174] provided a comprehensive review of the available methods for forming machines into groups. Later, they improved the ROC algorithm by making it more efficient and more capable in dealing with the bottleneck machines. Waghodekar and Sahu [218] used the similarity coefficient of the product types and developed a heuristic approach which yields a minimum number of exceptional elements after the grouping process is completed. Rodriguez and Adaniya [200] balanced the average set-up and the inventory holding costs by determining the number of cells and the machines to be allocated in each cell.

Chan and Milner [127] introduced a new and simple grouping technique which uses the machine component matrix as the only input. This method is based on progressive restructuring of the input matrix. The authors also showed that their method yields identical results compared to Burbidge's [122,123] manual method and handles the problems of exceptional elements and bottleneck machines as well as the Rank Order Clustering algorithm does. Stanfel [212] first gave a detailed review of the previous studies in clustering area and then proposed a divisive algorithm in which the machines are construed as beginning in a single, parent cell. The clusters are formed by selecting a machine at each iteration to leave the parent cell. This method attempts to optimize an objective function which contains inter-and intra-cell movements of the jobs.

Purcheck [193] stated that group formation was a hard combinatorial problem subject to exponential growth of complexity. He explained a heuristic solution method which searches the solution space of the problem in an efficient manner. The heuristic method uses set theory and boolean algebra. Chandrasekharan and Rajagopalan [128] discussed the weaknesses of the previous rank order clustering algorithm and improve it by providing an easy and objective identification of the bottleneck machines. Based on the association among the pairs of machine cells (already existing), they propose a hierarchical clustering method. Seifoddini [214] improved existing similarity coefficient methods by using special data storage and analysis techniques to simplify the machine-component grouping process. Dutta et al [138] developed a ratio called overall dissimilarity coefficient and used it in transferring parts between families. Their algorithm was illustrated with an example that has thirty parts. This method finds optimal grouping once the number of families has been specified.

Wu et al [225] applied the principles of syntactic pattern recognition for design of manufacturing cells by using formalized language theory. The comparison of their grouping results showed that the pattern recognition method has some distinct benefits. Han and Ham [163] used goal programming based computerized method in forming families. The input data for parts included the part and priority codes. Their optimal solution means that similar parts are close to each other in the sequence used to process jobs before a single processor. In one of several 1987 publications, Kusiak [58] explained the relationship between clustering models such as matrix and integer programming and classical group technology concept. Although he [49] basically reviewed two classes of clustering models, this paper is worth noting because it explains these rather confusing models in a concise manner. The main assumption used is that a number of process plans are available for each part. This author provided three examples on various clustering methods in a clear and easy to implement manner which is rarely found in the applicable literature. In another 1987 publication, Ballakur and Steudel[5] brought new considerations into the cellular system design problem. The authors proposed a part/family group formation heuristic which simultaneously considers practical criteria such as within-cell machine utilization, work load fractions, and percentage of operations of parts completed within a single cell. Another state-of-art review was provided by Chu and Pan [18] in 1988. The authors reviewed all available clustering methods in two groups : design oriented and product oriented approaches. Each method was evaluated with respect to performance measures such as consideration of operation sequences, level of computation requirement, handling of bottleneck machines, and grouping choice of the method between parts and/or machines.

3.Scheduling and/or Simulation Studies in Group Technology:

The third general publication area includes a vast array of articles and other publications that address to scheduling and sequencing of jobs in various forms of group technology environments. These studies use analytical or simulation methods in their approaches although few studies combine both methods.

Foo and Wager [37] examined sequence dependent set-up times through cyclic and acyclic group scheduling models by considering a single machine. Their dynamic programming procedure yields a lower total set-up time than four other methods listed for comparison purposes. Mosier et al [185] considered a group technology modified job shop with four machine centers and compared set-up time based group technology scheduling rules with non-group technology scheduling rules. The authors constructed seven hypotheses for testing the effects of various combinations of both types of rules which yield in conflicting results. Hitomi et al [45] (1977) constructed a simulation model for group production scheduling to investigate the effects of various flow pattern types (job shop to flow shop) and scheduling rules. This study assumes that the jobs to be processed are already classified into several set-up groups. The results show that set-up time plays a critical role in group scheduling only when the relative length of the set-up time to processing time is large. Otherwise, conventional scheduling rules such as FCFS and SPT display the best performance measures with respect to mean flow time for group scheduling indicating that the groups themselves do not have much impact.

Flynn [34] investigated the effect of average set-up time on the shop capacity. In this study, set-up times were lowered both by using family grouping methods and other sequence dependent set-up time based scheduling procedures. In 1983, Elgomayel and Nader [142] discussed the sequencing of similar parts with respect to set-up times and machine loading issues in group technology. The authors used a code named OPSSP optimization of set-up and scheduling of parts in sorting the components which require similar processing. Perng [190] in 1983 adopted general scheduling heuristics to group technology scheduling with emphasize on sequence dependent set-up times. This dissertation treated group technology in a cursory fashion and did not consider the cell system similar to Ham's approach of only concentrating on sequencing of groups of jobs as if there were only one processor. The author's simulation model showed that scheduling similar jobs will performed poorly with an increased number of machines. Thus, when a criterion other than the minimization of set-up times is concerned, a more traditional scheduling technique should be considered. The author also proposed a scheduling method which combines scheduling theory and group technology concepts. Sato et al [202] and Sato [201] integrated a group scheduling algorithm with material requirements planning techniques so as to take into account not only the part family concept for optimal sequencing but also the due dates, machine capacities, and material requirements.

Shtub [90] in 1988 presented a methodology for initial solution of the capacitated GT problem in similar direction to one of the stages of this research. This paper agrees with one of the assertion of this research that great majority of the previous work in GT field has conveniently ignored the capacitated nature of the problem. The author developed an efficient frontier in which the machine-operation cost for each of the possible layout choices is approximated. Selection criteria involves a trade off between the costs of inter-cell transfers and fixed cost of acquiring new machines to reduce or eliminate the need for such transfers.

2.1.3 Machine Requirements Planning

Although machine requirements planning and general capacity planning are not the same, they are usually combined together in the majority of publications. Therefore, all capacity related publications are examined here in the same section.

An early capacity decision model was presented by Fetter [143] who examined several types of available capacity and known requirements over a known planning horizon. The author assumed a discounted cost function to be minimized subject to production related constraints. An initial linear programming model was later modified in order to reflect the case which defines a probability that a specific value of demand occurs at each time period. Morris [184] considered a single work center and treated the production requirements, operation times, and machine effectiveness explicitly as random variables. Given a probability distribution for each of these parameters, Morris proposed a joint probability function for the number of machines required, but did not develop any of the distribution functions involved. This normative approach included a decision model based on a linear cost criterion and no constraints. Kalro and Arora [51] incorporated stochastic capacity requirements under fixed growth rate of aggregate demand. Capacity requirement classes were identified with known probability distributions of their demands at each stage in the planning horizon. A stochastic linear program was formulated and the effects of three probability distributions of capacity demands were discussed.

Reed [199] also considered machine requirements planning as a stochastic problem and used a multiple work center type production environment in which a serial work of flow occurs. His objective was to find the overall number of machines to meet a known demand mix. Based on assumed distributional input parameters, he developed an approximate normal distribution for the number of machines. Montgomery [182] defined capacity as a throughput rate and assumed that optimum capacities for the system should maximize the average periodic profit. The problem of determining optimal capacities in the face of a steady state arrival process was approached by three mathematical techniques. Goodman [153] used six distinct costs in developing an aggregate planning model which is formulated as a multi-stage decision problem with discrete opportunities for changes in capacity and the work force.

New [186] claimed that most of the existing literature was irrelevant to production operations of most manufacturing firms since the literature has paid too much attention to controlling the inventory of products which consisted of one component. His text provides guidance for inventory managers who face real world problems and includes a section on handling probabilistic demand levels. Plossl and Wight [184] compared the relative effectiveness and the implementability of infinite loading, finite loading, and input/output (I/O) control in an experimental manner. They concluded that finite loading is sophisticated but rather useless due to high computing costs. The authors recommended the I/O control as the only viable method for capacity planning and control. Eilon [140] reviewed five approaches to aggregate production planning. These forecast-based approaches are: 1) HMMS (Holt, Modigliani, Muth,Simon) linear decision rule, 2) DE (Diezel, Eilon) rule for production with time lag, 3) Management coefficients, 4) Linear programming methods, 5) Production switching method. Vollman [218] provided an interesting case study example on how a modest capacity planning can have a positive impact in smaller firms.

Miller and Davis [71] provided an overview of machine requirements planning up through 1977. The authors defined the problem and categorize the schemes with respect to systems scope, deterministic and probabilistic parameters, flow types, static versus dynamic formulation, objectives, constraints, and planning horizon. Next, they reviewed various general production planning publications dating to 1950 and explained how certain segments of these early publications could be applicable in machine requirements planning. In the area of long range capacity requirements planning, Miller and Davis [70] presented a linear programming solution to the generalized machine requirements planning problem. They considered floor space, capital budget, and the available overtime in the analysis of the resource allocation problem. A yearly minimum cost plan of machine requirements was produced by their models. The authors also perform a sensitivity analysis on the mathematical models solved.

Davis [22] used variational analysis to find a minimum cost machine choice for a continuous processing machine center and extended his results to establish an upper bound of the theoretical number of machines that can be installed. This publication included some probabilistic variables such as production and scrap rates, and machine efficiencies. Davis and Miller (1978) [23] solved the problem of defining the optimal number of machines and their operating rates for a serial multistage system with discretely distributed demand. They used linear programming and then modified the solution to meet the integer requirements. Fisk and Seagle [144] outlined a long range capacity planning method for evaluating a master schedule's feasibility by minimizing the capacity changing cost through a linear decision rule. Hayes [42] stated that machine requirements planning should normally be modeled as a mixed integer program, but he used a dynamic programming solution procedure with linear programming post-optimality techniques at each state of the machining process. This study combined the machine requirements planning with the machine cutting parameter optimization problem via an efficient dynamic programming method which was later compared with a mixed integer program for computation times.

Reasor [83] used simulation in his approach to machine requirements planning and examined the effects of varying the number, type, and the operating characteristics of the simulations in a production system. He also developed a normative mathematical model to identify the minimum cost production system design while finding integer results for the machine requirement decision. Solberg's CAN-Q [210] is a stochastic flow model for analyzing a capacity model and is related to a deterministic equivalent, the bottleneck model. CAN-Q neglects realities such as blocked servers, limited storage costs and assumes a constant number of units in the system.

Hayes et al [41] stated that mathematical model type techniques may prove to be incapable of reaching a solution in a feasible amount of time. They presented a dynamic programming approach to determine the optimum number of machines and the machine operating rates in a serial-flow system. Their model considered overtime, defective production, and discretely distributed machine operating rates. While yielding identical total production cost, the dynamic programming solution took much less computation time than the mixed integer program solution. Lunz [180] asserted that capacity requirements planning does not adequately represent the requirements needed because of the omission of what he calls an Additional Planning Factor (APF) which acts like a performance rating for capacity. The author suggested the modification of APF so that factors such as holidays, absenteeism, and efficiency ratings could be included for better determination of the "actual" capacity.

Sarper [86] presented (1982) an approach for solving the problem of determining a near optimal number of machines in order to minimize the total cost in a deterministic cellular manufacturing system. More specifically, a heuristic methodology was used in rounding the fractional number of machines assigned either up or down in their respective cells when a remainder cell was permitted with a fixed number of ordinary cells. Karni [52], in 1982, developed capacity requirements plan based on planeable work stations capacities and presented a method which analyses the flow of work through the work stations by relating the work flow to the nominal capacity of the stations. The same author [53] discussed the planning of the optimal steady capacity levels in 1981 by considering station environment in terms of internal and external constraints.

2.1.4 Production Planning and Control

This section includes publications in the areas of hierarchical production planning and loading of existing production systems such as job shops, flow shops, CM, and FMS. Some form of mathematical model is usually constructed by most authors in the statement and solution of the problem. Among many available publications which fall under this class, those relevant to this research are reviewed below.

Bitran et al [6] investigated determining a production schedule for style goods such as clothing under fixed capacity and stochastic demand constraints. The problem was formulated as a complex stochastic mixed integer program and solved by exploiting the hierarchical structure inherent in such problems. The authors assumed that changeover cost was negligible when two items are from the same family and high when the two families are different. Bitran and Ellenrieder [7] presented a production planning model for a large foundry with complex interrelationships among the various variables. A hierarchical approach was used to reduce the problem complexity by first solving an aggregate problem whose result was disaggregated through optimal sub-programs. Bitran and Hax [8] suggested optimum procedures to deal with resulting sub-problems when the overall decision problem was partitioned into a hierarchical framework.

There are other authors who combined hierarchical planning with mathematical modelling. Among them, Demmy [24], Meal [69], Stadtler [93], Dempster et al [25], Hax and Meal [43], and Morito and Salkin [72] provided good descriptions for general production planning problems. Erschler et al [28] focused on the consistency of decisions in a two-level structure and presented the necessary and the sufficient conditions for disaggregation procedure to be consistent. These authors examined the planning process of a manufacturing system in which the aggregation of products sharing similar characteristics leads to a hierarchical structure.

Lasserre et al [59] also suggested a hierarchical decomposition based approach to the planning of an electronic goods manufacturing setting.

Falk [29] provided a real life example of manufacturing hierarchy in production planning and control. The author used four integrated modules in addressing the problem. The modules used are; transportation, production planning, production scheduling, and distribution. Gunther also [40] described a hierarchical production model using four modules: 1) aggregate production planning, 2) detailed scheduling and sequencing, 3) determination of production orders for items, and 4) distribution and dispatching. While this article is not primarily an application of mathematical modelling to hierarchical planning, the author presents small mathematical models as solutions to various sub-problems encountered. Similar comments were made by Mangiamelli [67] who developed a methodology for solving a disaggregation problem in a multi-stage, multi-product production system.

Bruvold and Evans [11] modelled a production scheduling problem with multiple time periods. By redefining some of the sequence variables and adding a set of binary variables which can be relaxed later, the authors reduced the problem size considerably and made good, joint production assignments and sequencing decisions. Cai et al [12] presented a hierarchical machine load planning model which incorporates the bill of material, bill of tools, work center information, lot sizing, and the feasible machine-tool-part assignments. A combination of mathematical programming methods were used in the solution process. Chen et al [15] presented production problem formulations and solution techniques for two basic modules of an FMS : part tool-grouping and loading. The methodology developed receives set of jobs as input and provides set of decisions as output : batches of part types and required tools, assignment of tools to machines, and estimated aggregate production times. Chen [14] developed a hierarchical methodology for FMS design by addressing four levels of manufacturing problems. These levels are manufacturing system selection, shop loading, machine loading, and tool allocation. Then, the author tested the feasibility of the resulting schedule, determined in higher levels, by using the SIMAN simulation language.

Choobineh [17] first linked GT and MRP systems and presented a hierarchical planning procedure to utilize the potential advantages of the coexistence of these two concepts. Next, the author presented a multi-period linear programming model which determines the minimum cost loading schedule of manufacturing cells. The same author has recently proposed [16] a two-stage procedure for CM system design [16]. The first stage forms parts families and the second stage forms the machine cells via an integer programming model. In 1987, Mohanty and Kulharni [183] compared and contrasted hierarchical and monolithic production planning approaches. The authors provided a brief, but up to date, review of the hierarchical production planning area and propose a heuristic to minimize the backorders in a batch processing environment. Later, Tsubone and Sugawara [101] included human judgement between any two production planning levels of an hierarchical framework and used goal programming in developing a feasible production and scheduling plan for an electronic motor company.

Several authors model various production related problems without any explicit connection with hierarchical planning concept. Duran [26] formulated a large mathematical model for beverage production and distribution and then used a decomposition algorithm to reduce the problem complexity. Initial continuous solution was reoptimized for the final integer solution. The article states that the use of the model has resulted in a four percent reduction in total variable operating costs. Gonzales and Reeves [38] and Taylor and Anderson [99] demonstrated the use of goal programming in developing a master production schedule for manufacturing systems. The goals included minimizing total production cost, total inventory level, and over/under utilization of various manufacturing resources.

Kendall and Schniederjans [55] suggested that ordinary linear programming becomes insufficient in realistic multi-product production problems and recommended a linear goal programming model instead. It is shown that such a model is especially suitable when variable resource usage parameters and internal product flows, among the departments, must be considered. Similar ideas were also echoed by Lawrance and Burbridge [60] who argued that ordinary linear programming could not describe multiple goals that are often part of most production planning decisions. The authors formulated a multiple objective linear goal programming model to determine alternate production schedules for a group of products so that the best possible solution was found with respect to several conflicting objectives which include maximization of total sales revenue, minimization of total production and distribution costs, and maximization of certain item quantities at some locations. Hitomi and Ham [44] combined product-mix selection, capacity loading, and optimal machine cutting problems into a mathematical model to describe a multistage production system decision problem. As in their other publications, the authors attach their version of the group technology concept into the overall modelling process. The primary criterion of the mathematical models is the maximization of the production rate in a fixed amount of time. Ignoring part families and other set-up considerations that usually accompany cell loading decisions, Greene [39] developed two heuristics used in balancing machine loads between cells, balancing the load within each cell, and also balancing the ratio of large and small jobs between and within cells. The author assumes that job release times are preplanned and each job has multiple cells where it can be sent for processing. The loading problem is represented by a mixed integer program which is not attempted for solution. Instead, simulation, in SLAM, is used in validating the heuristics with respect to measures such as job tardiness and flow time. This research is among very few with respect to the explicit consideration of a remainder cell as a part of the total production facility.

Oliff and Burch [76] addressed production sequencing decisions at an Owens-Corning fiberglass plant. Implementation of lot size decisions, product line assignments, and other inventory level decisions determined by the aggregate planning process yields considerable savings compared to the previous operating policies. Another industrial application was reported by Osterfeld [77] who explained two capacity planning systems: the short term machine load planning system and the long term multi-plant allocation system. Major factors considered include overtime, transportation, other production costs, demand levels, and space requirements of the machines. Egbelu [27] stated that allocation of jobs to machines was not an independent decision from determining the machining conditions of the jobs on these machines. He advocated a simultaneous decision procedure for these two tasks. The author formulated a mathematical model with two segments: the machine process optimization problem and job allocation or scheduling subproblem. Heuristics are used in solving the model which turns out to be a mixed nonlinear integer program. Saul and Sadowski [87] described an intermediate resource planning methodology which produces implementable production plans. The authors created mathematical models with the objective of meeting due dates and limiting excess inventory.

Stecke [94] provided a valuable reference in the area of non-linear mixed integer mathematical models in production planning applications by formulating part grouping and FMS loading problems which are later solved using appropriate linearization techniques. Next, linearized mixed integer programs were applied to data from an existing FMS. The main loading objectives are to balance the assigned machine processing times and to minimize part movements under the constraints of assignment of each operation to at least one feasible machine and tool magazine capacity.

Leung and Tanchoco [63] presented an input/output model with operating profit maximization used as the criterion. A multi-machine, multi-product environment with an automated material handling device was considered. An illustrative example showing the effects of cost breakdowns and demand changes was provided. Each machine was capable of performing multiple operations and, thus, each part could have alternative routes through the system. Avonts et al [4] used LP models in allocating eleven job types between a FMS and a jobshop. The authors proposed five different objective functions with the same constraint set. A simulation model was used to test the feasibility of proposed solutions. Webster and Tyberghein [103] defined facility flexibility as the ability to respond to known and future demand, as opposed to stochastic and future, and presented an approach to design a machining facility in order to minimize annual material handling costs.

2.1.5 Chance Constrained Programming

Chance constrained programming is largely ignored in the texts on mathematical programming. It is possible to find some discussion on chance constrained programming in texts by Kolbin [176], Rao [80], and Sposito [92] as well as some other Operation Research texts. These three authors treat chance constrained programming in a straight forward manner which lends itself to easy understanding and application without requiring a strong mathematical background as is the case in some publications not mentioned here.

Articles by Hillier [165], Seppala [89], Hansotia [164], Hogan et al [169], and Seppala and Orpana [88] explain the various theoretical foundations and algorithms for chance constrained programming. This set of articles have been found applicable or supportive to the objectives of this research. The concept of chance constrained programming was first developed by Charness and Cooper in 1959 and later improved in 1963 [130] when the deterministic equivalency concept (see Appendix A) was proposed.

Review of some applications of chance constrained programming in general planning and production:

Bookbinder and H′ng [9] proposed a production planning procedure for probabilistic demands. They varied set-up cost, order cycle and the number of future periods for which demand forecast were available. Iwata et al [49] showed that the optimum cutting conditions were affected by the probabilistic nature of coefficients of the constraints such as maximum/minimum feed and speed of the machine, surface roughness of the part, and many others. The authors applied the chance constrained programming concept in proposing an analytical method to determine optimum cutting conditions under probabilistic constraints and objective function. This article is possibly the only one of its kind in actually rejecting the assumption that inputs to a machine cutting problem can be known with certainty.

Naslund (1966) [74] built risk into the existing model of investment behavior and used Kuhn-Tucker conditions in solving the resulting nonlinear programming problem. Goyali [154] computed the distribution of lot size for each product when demand is a stochastic variable with known distribution. Armstrong and Balintfy [109] applied chance constrained programming into nutrition requirements planning such that the joint realization probability of several constraints would not be less than a specified level. Noonan and Giglio [187] formulated a large scale chance constrained mixed integer program for optimal investment planning in electric utility industry. They used Bender's partitioning principle and a successive linearization procedure to handle the nonlinearities which always result after the problem is converted into the deterministic equivalent form.

Lingaraj and Wolfe [66] expanded their initial chance constrained model [65] for long range capacity planning of a tire plant. The new model determines process capacities and the time-phasing of the acquisition of capacity under probabilistic demand forecasts. The authors assumed future demands to be normally distributed and subject to growing uncertainty or risk level as the years get farther away in the planning horizon. The model assumes that there is only one product that has to visit all the production modules or departments in the facility. Thus, the authors optimized the bottleneck module first as a part of their overall decomposition method of solution.

Tabucanon et al [97] used chance constrained programming to find the optimum proportions of aggregates to meet the specific grading requirements which minimize the total cost consisting of the material cost and the expected penalty cost. De et al [135] applied chance constrained programming to solve a production related capital budgeting problem which was originally formulated as goal programming. Their example uses Naslund's [74] approximation and seeks to minimize the net present worth while meeting the various goals and a set of stochastic variable coefficients. Keown and Taylor [56] also combined goal programming and chance-constrained modelling concepts in selection of capital projects under multiple and conflicting goals and random demand. A good example of a chance constrained programming application in production was presented by Rakes et all [79] in 1984. The authors suggested a chance constrained goal programming approach to production planning by allowing the decision maker to specify the demand and the other production related parameters as stochastic variables. The hypothetical example was solved by assuming normal distribution for variables and using the MPSX package once an extensive linearization was completed. This publication presents how a decision maker can handle multiple objectives and the environmental uncertainties that affect production planning.

2.1.6 Other Allied Publication Areas

Simulation, facility design and planning, and scheduling are indispensable components of almost any research in the general area of production planning and control. Certain segments of these topics have already been reviewed here as parts of the other sections. It is not, however, necessary to review the literature which constitutes the gradual development in these three fundamental areas since these areas have already been extensively reported in many sources.

Rosenblatt and Lee's [85] article presented a heuristic for the single period plant layout problem under uncertain demand for various products that require processing in a job shop like environment. The demand levels, however, were assumed to follow some simple discrete distribution rather than continuous ones as is the case in most stochastic programming problems. Dale and Dewhurst [21] simulated a single group technology cell in an actual valve manufacturing company and conducted experiments on workflow, using only the SPT rule, by changing batch sizes, number of workers and the key machines. The article shows how throughput time and WIP levels change when each of the above factors are changed one at a time. Igel [171] explained the implementation of WASP, a computerized job shop planning program, and recommended that a single cell should exist separately from the rest of the job shop. According to the author, such a cell does not present any of the disadvantages of cellular manufacturing and serves in dealing with rush jobs. This publication also discusses ways of reorganizing the large capacity of entire jobshop into various product groups without mentioning regular cellular formation.

Using queuing theory and simulation, Kekre [54] investigated the impact of increasing the number of different parts assigned to a cell. The author increased the distinct members of the job-mix while maintaining the same machining load (excluding any set-up burden). The analysis showed, as expected, increased queuing delays and larger optimal batch sizes. Integration of Flexible Manufacturing Cells (FMC) into a functional production environment was recently (1986) discussed by Steudel and Berg [213] who provided an empirical study of the advantages to be gained by creating two automated cells within job shop. The authors considered the same industrial setting as in reference [214] and simulated, using SIMSHOP, two environments: current job shop and current job shop plus two FMC's. These FMC's were used to process only a specific subset of the total demand. Extensive statistical analysis indicated that such a capacity increase allows for increases in job arrivals to the shop without any significant changes in throughput times and work-in-process levels. The paper also shows how simulation and statistical experimentation may be used jointly in modelling complex manufacturing systems. This study does not serve as a comparison between the cellular and functional production environments since the cells are not only totally automated, but also have been added to the existing shop rather than being taken as alternatives to it.

The use of simulation as a planning tool was illustrated by Pegels and Narayan [78] who evaluated the effects of overtime, bottlenecks, WIP, and delays on an actual machine shop with sixty-nine work centers. Ring [84] developed a computer-based production planning and shop control system to deal with complexities of the manufacturing section of an actual foundry. Using SLAM, the author preloaded the system and scheduled arrivals. His thesis provides a good example of the use of simulation in making planning decisions with respect to resource utilization and delivery performances.

Summary:

This Chapter has provided review of the following areas :

1. Most relevant literature in comparison of the two production environments.
2. General GT and three major GT components.
3. Machine Requirements Planning.
4. Production Planning and Control.
5. Chance-Constrained Mathematical Programming.
6. Other Allied Fields.

3.0 Problem Statement and Research Objective

The problem may be described as a manufacturing cost based design and selection between the two layouts given both stochastic demand mix and machine operation times. The objectives of this research were twofold. The first objective was to develop a methodology which can be used by a manufacturing firm to design and compare the functional and cellular production environments in order to select the one which yields the lower overall cost. The second objective was to use this methodology to compare the two environments by varying external factors such as investment budget, plant space, demand mix, and machine capabilities in order to determine the range of input variables which favor a particular environment.

Input Requirements: Intended comparison required inputs in the following format.

- It is not realistic to assume identical or equally capable machines throughout the facilities. Therefore, investment cost, area requirement and other information are necessary for each available machine type.
- The set of operation classes (usually one to three) that each machine type can perform is needed.

- The variable cost and time (random) of each operation on each machine type are also needed since each machine performs its primary operation efficiently while taking longer time with other operations.
- Machines are not equally reliable, so the percentage of availability (random) of each machine per shift is necessary.
- Set of jobs to be machined that make up the daily demand mix with random demand level for each job needs to be known.
- Penalty or lost sales cost for each unmet job type.
- Information on the shape/size similarity of jobs which may be used in forming part families in case of cellular layout .
- Information as to how many of each job type can fit on each of the available material handling types and handling cost per job.
- Set-up cost and time information for each operation on each machine .
- Level of certainty desired in meeting the demand for each job.

3.1.1 Research Need

Once a production environment is selected, it is difficult, disruptive, and costly to later change or modify the material handling system and relocate the machines. Therefore, a sound method of before the fact production environment selection is necessary. Such a method should consider all inputs and pay special attention to machine requirements planning of overall manufacturing activity since the investment in machine tools is the largest single item of capital expenditure in most manufacturing firms [22,134].

The review of the most relevant literature in Chapter two clearly shows that there has been no previous study that compares the two production environments in the same way this research does. This research recognizes that it is unrealistic to assume deterministic values for demand levels, machine down times, and operation times and accounts for such uncertainties in an analytical manner. All previous research has either assumed deterministic input values in handling some portions of this problem or used simulation to account for any uncertainty [36,75].

Other researchers such as Shunk [91] have either avoided the concept of time-phased demand in their analysis (and assumed that demand is uniform over the entire planning horizon) or totally ignored demand based planning and machine/operation assignment concepts. If cellular manufacturing is expected to benefit low to mid-volume batch production, frequent demand changes should be considered in any realistic analysis. While static part families is a good assumption, an entire family, assigned to a cell, may not be required during every production period. It is desirable to: 1) allow randomness in the family membership, in terms of demand for a given job type, with predefined probabilities and, 2) define stochastic demand levels for each family member part once it is chosen.

Pure simulation studies tend to emphasize certain performance measures such as job flow times, machine utilizations, queue lengths, and tardiness. If the planner wants to include other monetary considerations into the decision process, simulation alone may not be sufficient. Then, a combined approach, analytical followed by simulation, should be able to capture both monetary and non-monetary performance measures. This research also was not based on the usual and rather convenient assumption that there is an one to one correspondance between each operation and each machine type. Here, machines were considered to be versatile and capable of performing multiple operations at varying levels of efficiency and cost.

3.1.2 Solution Method

This section overviews the steps utilized to solve the problem by capturing and reflecting as much reality as possible. Initially, a one step mathematical model was formulated to select optimal job-machine-operation assignments and determine the number of each machine type to be installed in each layout . This approach, however, resulted (after some experimentation) in large, and sometimes nonlinear, mixed integer programs which were highly intractable and costly to solve. Then, an hierarchical approach was developed as follows :

1. Using a simpler mathematical model, consider both production environments jointly and determine the total number of each machine type (in aggregate manner) that can be acquired under the imposed constraints.
2. Allocate selected machines to departments in case of the functional and to cells in case of the cellular layout .
3. If the constraints do not allow the daily demand to be completely satisfied, handle such infeasibilities later at lower decision levels by, e.g., incurring lost sales.
4. Use the chance-constrained programming concept of Stochastic Programming in dealing with the randomness of input variables.
5. Use normal distribution for the random variables not only for the general ease this distribution provides, but also for the fact that demand and operation times may well follow a distribution which can be approximated by normal distribution.
6. Develop codes which will be used in solving the non-linear mixed integer programs which result even after the deterministic equivalents have been written out for the chance-constrained mathematical models (linearization techniques or other approximations are used to avoid nonlinear terms).
7. Use CRAFT to determine an optimal or good arrangement of the machines within each cell and, in functional layout case, within each department or processing area.

8. Use SIMAN simulation package to simulate each environment by using the previously selected machines and layouts. The goal of simulation is to uncover some aspects of each manufacturing environment which can not be determined by the mathematical models. Note that this research is not primarily a simulation exercise and the limited use of simulation compliments the results of the mathematical models.
9. Utilize an overall performance index which combines the results both from the mathematical models and the simulation model.
10. Finally, through these steps, determine which manufacturing environment should be preferred under certain manufacturing requirements and the resources faced by a planner.

While there is only one functional environment performance index, there are several such indexes as the number of cells are altered. For example, equivalent functional environment can be represented as a two, three, or four-cell cellular environment. Figure 2 on page 56, Figure 3 on page 57, and Figure 4 on page 58 depict the flow and the connections of the hierarchical methodology.

The Goal: The goal is to develop a methodology which receives the data and recommends a solution after interacting with mathematical programming (MPSIII), layout (MICRO-CRAFT) [48], and simulation (SIMAN) [189] packages. Note that the development of a general purpose canned package was not a part of the objectives of the research. The input data consists of the input requirements mentioned earlier. A typical solution is of the following form :

" Based upon the input data, the daily cost of total production is \$....... for cellular facility with ...... cells and \$.......... for functional facility if the desired level of confidence to meet the daily demand is at least .. percent. According to the simulation results, mean job flow time, machine utilization, and percent of job completion is .....,....,..., and .... for the functional facility and ....,....,..., and .... for the cellular facility".

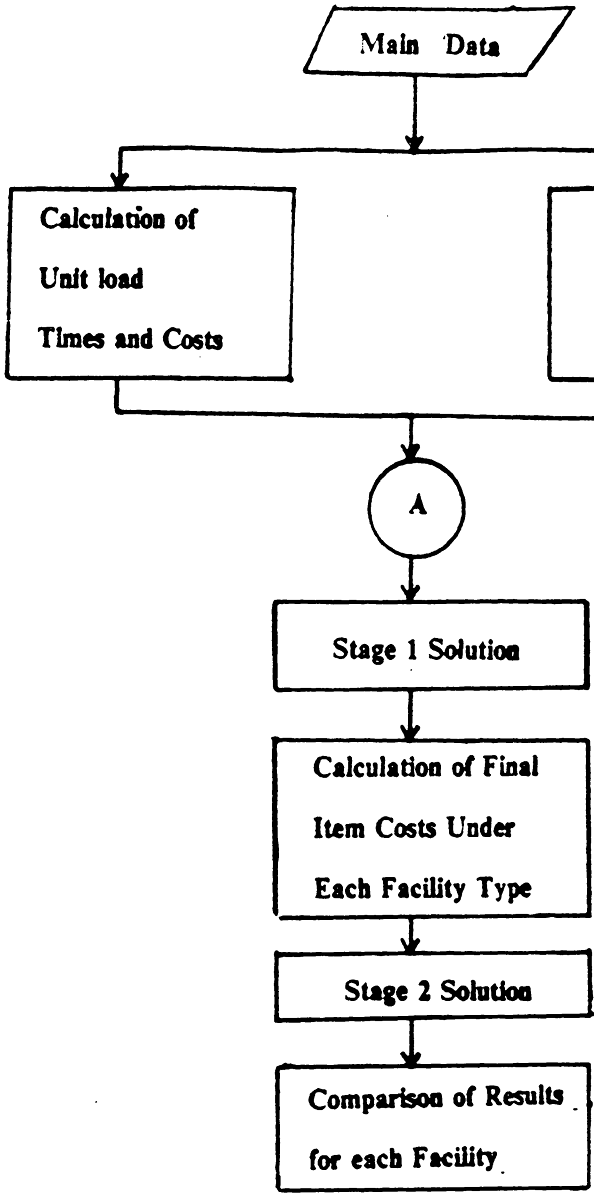


Figure 2. Major Blocks of the Hierarchical Methodology

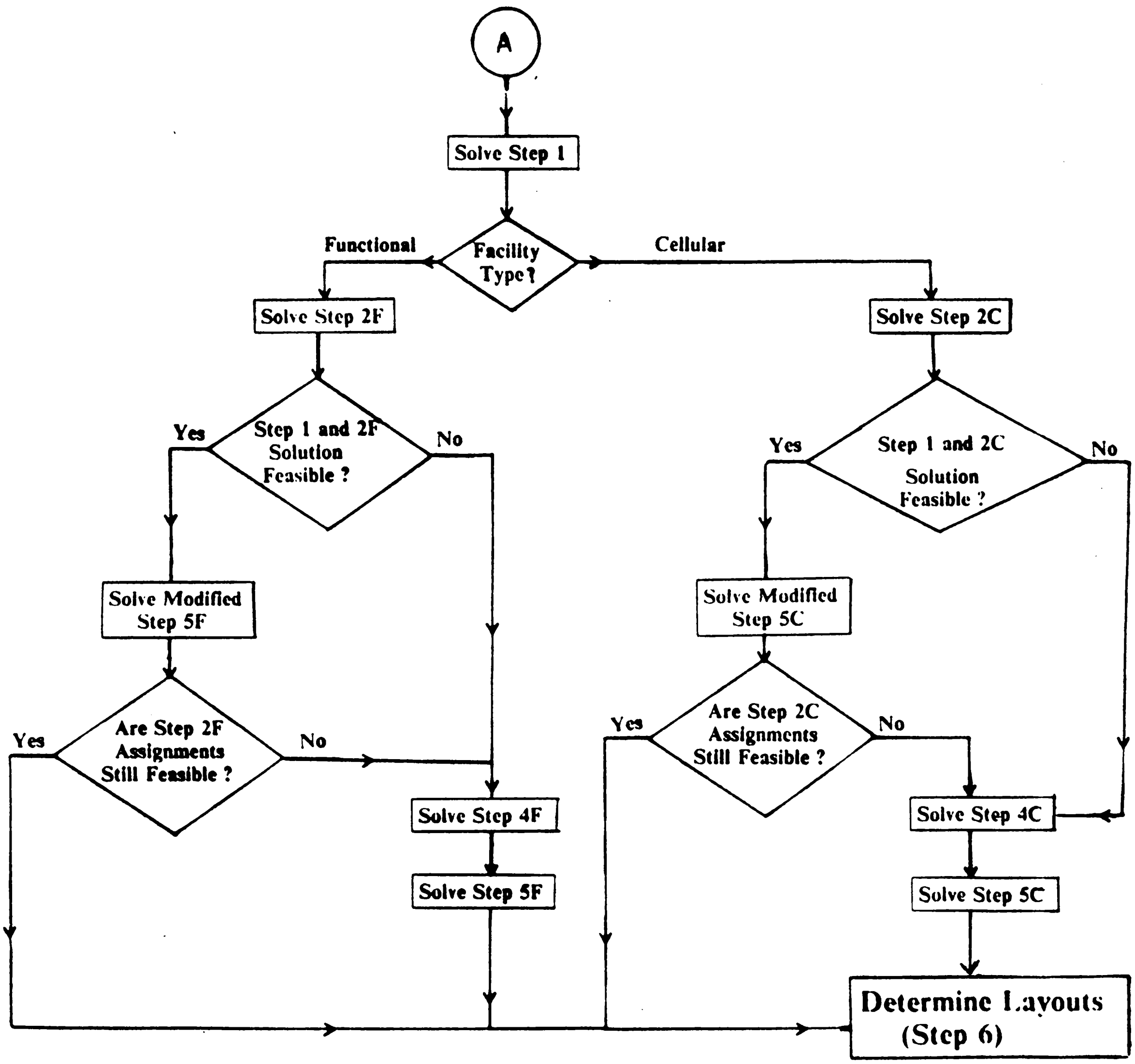


Figure 3. Stage One Procedures With Operating Constraints

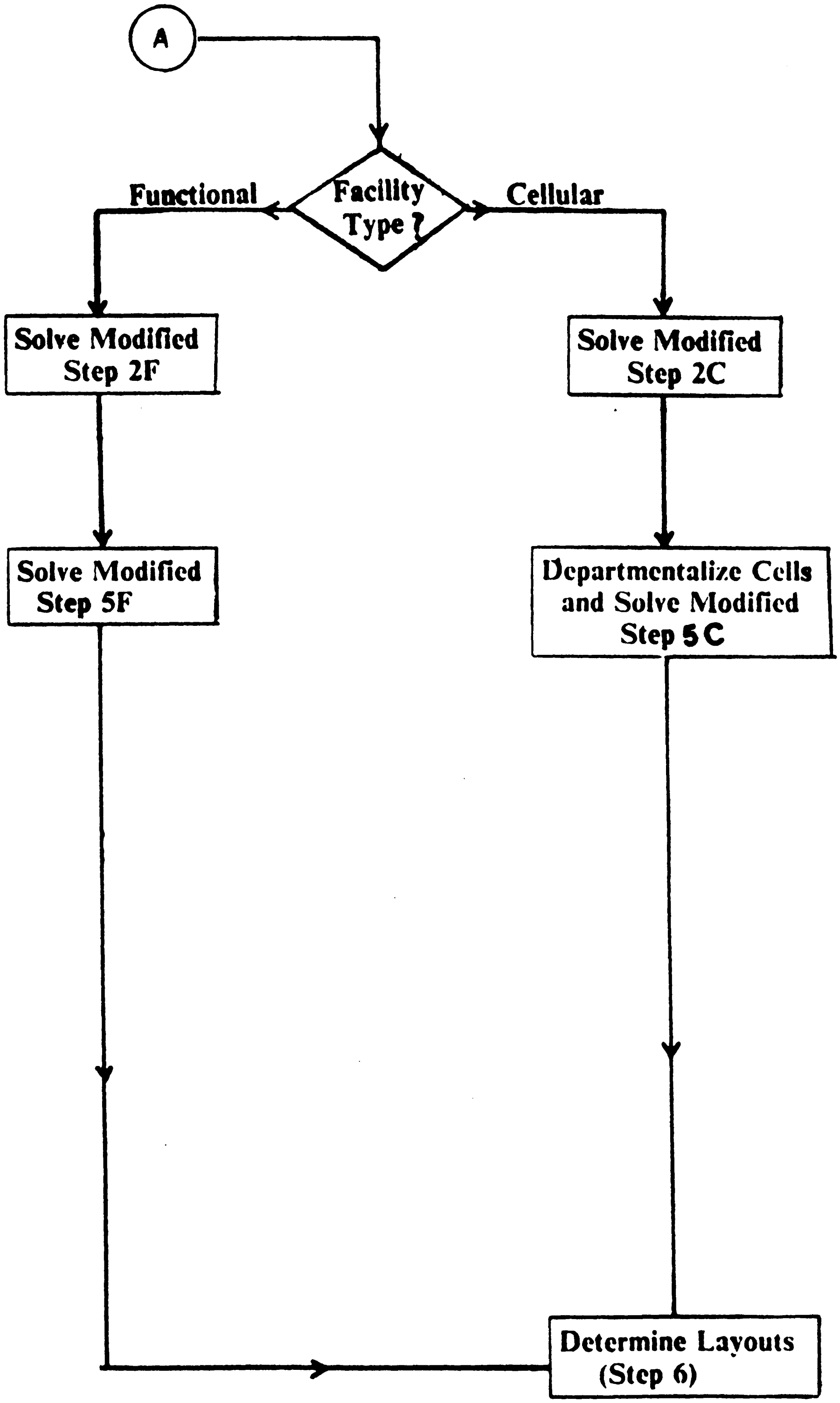


Figure 4. Stage One Procedures Without Operating Constraints

Capacity Planning Under Resource Constraints:

Stage one of this research seeks to determine a minimum cost machine requirements planning for both environments. A designer with the task of selecting among the available machines types to meet expected production requirements over a planning horizon faces one of the two following cases :

1) **Limited Resources:** The firm does not have enough resources such as investment funds and area to purchase and install machines which can provide the sufficient capacity. This case involves not only the selection of minimum cost machine mix, but also the subsequent decision pertaining to a set of choices to deal with insufficient capacity.

2) **Unlimited Resources:** The firm can meet the demand, and the goal of planning is the selection of those machines which yield a minimum production cost.

Steps of Cost Calculation When Resources are Limited:

In stage one, there is a six step (step 3 is implied) hierarchical solution process when there are such operating constraints.

<u>Step 1</u>

Determine how many of each type of machine should and/or could be acquired under the capital and area constraints. This step yields the minimum (initial) investment cost which is the same for both layouts and suggests a machine mix to purchase.

<u>Step 2 (2F and 2C)</u>

(F refers to functional and C refers to cellular environment) Determine Job-machine-operation assignments which also yield the total daily variable cost for each layout and any lack of capacity due to the investment constraints.

<u>Step 3</u>

Determine optimal sequencing of jobs at their assigned machines for various operations. This step would yield the total set-up cost for each layout as well as the additional capacity needed that will also result due to set-up needs. Optimal set-up costs and times, however, may not be realized in the actual operation of the facilities. This step would be applied if steps 1 and

2 are feasible. Appendix I presents a model which can be used for the functional case if an optimal sequencing of jobs for each machine is desired. Instead, a simpler method is used in step 5 to reflect the contribution of set-up requirements to the total cost and capacity planning.

Step 4F and 4C

Reduce the number of machines until both investment fund and plant space constraints are satisfied. This step is applied to get a feasible machine mixture if steps 1 and 2 are infeasible.

Step 5F and 5C

Determine the actual production level for each job using the revised machine mix found in step 4 above and account for major set-up and reset times while allocating the available capacity to jobs. Lost sales costs are incurred if the available capacity is not sufficient to meet the demand. Resulting production level decisions are examined next to calculate actual set-up costs by including the effect of similarity between jobs.

Step 6F and 6C

Determine a good layout for each facility. Next, calculate the material handling needs and the costs for each layout by considering the amounts of material flows between the various sections of the facilities.

Steps of Cost Calculation When Resources are not limited:

If the firm does not have to consider how much investment capital and plant space can be used (no operating constraints), lack of these constraints makes the solution of step 2 easier and step 1 is not needed. Steps 1 and 4 are skipped while steps 2 and 5 are modified.

Additivity of Hierarchical Evaluation Steps:

No effort was made to ensure that the cost amounts determined in each step are additive or of the same scale. Instead, each step reflects a different cost performance of each environment. For example, step 2 uses the result of step 1 and shows the ability of each environment to meet the total demand. Step 3 provides cost based comparison with respect to set-up requirements and step 5 uses step 4 results to provide lost sales comparison of the two choices. Finally, step 6 compares the two environments according to their material handling requirements and the costs after a good layout is found for each facility. Stage two uses the results of steps 2, 5, and 6 of stage one and simulates each environment for additional comparison of the environments using non-cost performance measures.

3.1.3 Description of the Complete Production Facility

The production activity can be best described as an **open shop** for this research. Figure 5 on page 63 shows only the in-plant segment of the final item (not to be associated with the term "final item" used in Chapter five) assembly requirements. The first area (marked within the trapezoid), the manufacturing or machining area, is the focus of this study, but the other two assembly areas affect the first area by imposing production levels and other requirements for the jobs or basic machined parts. The machining area, in functional or cellular formation, also receives orders from external customers who perform their own sub-and final assemblies. Let,

D_{fi}	Stochastic daily customer demand for final item fi.
D_s	Stochastic daily demand for subassembly s.
$D^e_{k,c}$	Stochastic daily demand of customer c for job type k (external demand).
D_k	Stochastic daily demand for job type k.
$F_{f,z}$	Number of type z subassemblies required to complete final item f.
$S_{z,k}$	Number of parts k required to complete subassembly z.
Q, R	Sets of all final items and subassemblies.

Then, the daily demand for each job type, D_k, may be found as follows :

$$D_k = \sum_{f \in Q} D_{fi} \sum_{z \in R} F_{f,z} \; S_{z,k} + \sum_{c \in C} D^e_{k,c} \quad \text{for all } k \qquad (3.0)$$

In equation 3.0, quantities $F_{f,z}$ and $S_{z,k}$ are both known constants from the design process and D_{fi} is a stochastic variable estimated by firm's marketing department. The first expression in equation 3.0 above refers to internal daily demand for job k as a result of all sub and final item assembly requirements. The second term represents the total daily demand for job type k from all external customers who, instead of the final item, happen to need job k for use in their own assembly or repair activities. Therefore, D_k is also a stochastic variable. In Figure 5 on page 63, only one subassembly level is used for illustration purposes. In different firms, there may be additional levels of subassembly requirements or other production related stages between the basic parts or jobs and the final items.

It is assumed that the distribution of each D_k has already been determined using the inputs of D_{fi}, $F_{f,z}$, and $S_{z,k}$ and available to the designer. In other words, $D_{fi} \rightarrow D_s \rightarrow D_k$. In this research D_k is assumed to follow a normal distribution. This assumption may or may not be proper for a given production environment.

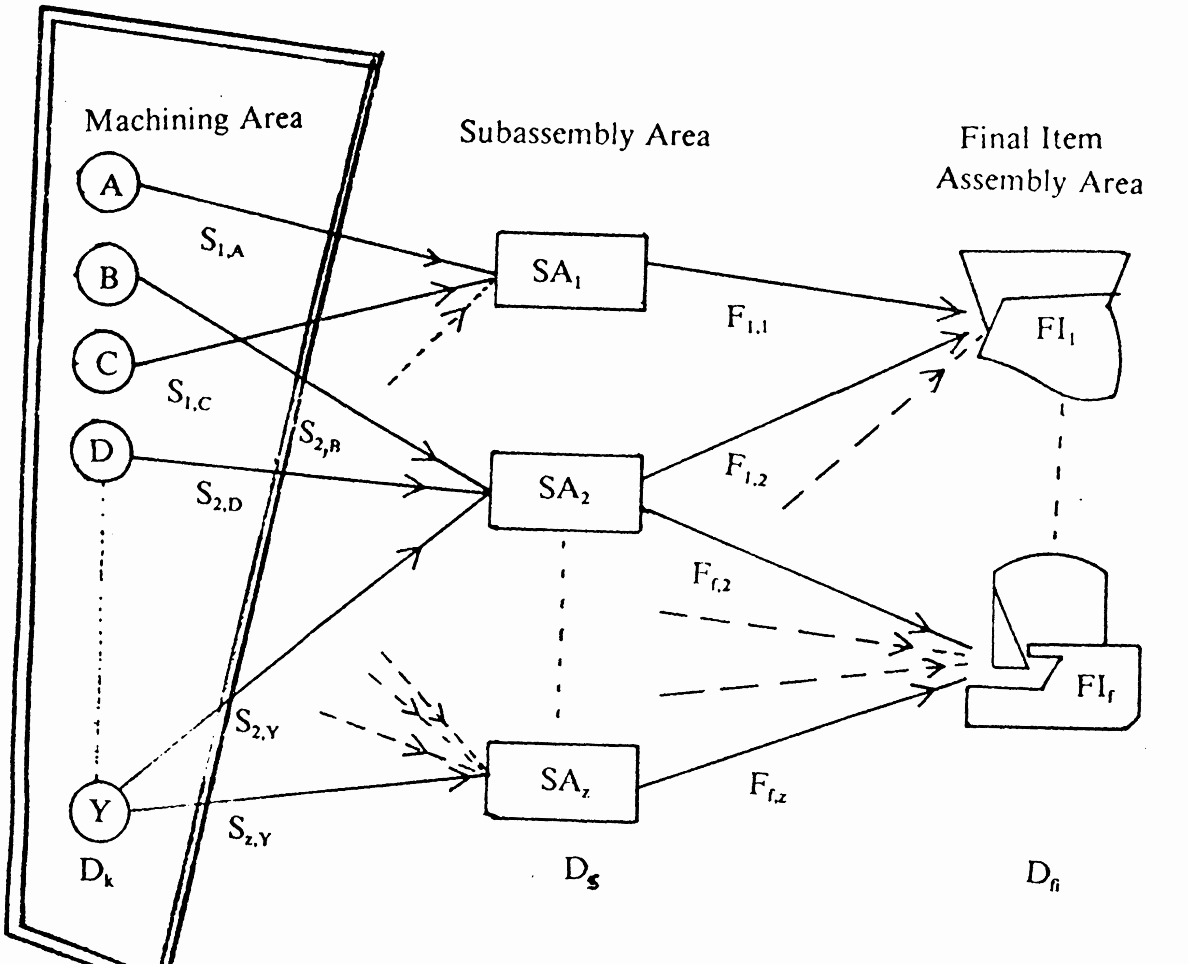


Figure 5. Three Production Areas of the Facility and the Associated Part Levels

3.1.4 General Assumptions

Some assumptions are necessary to limit the scope of the problem. Other assumptions, specific to the development of each segment, are stated as needed.

Assumptions for the Manufacturing Environment :

1. The prime goal of either facility is to meet the daily demand whenever possible within the operating constraints.
2. Altering customer service, influencing customer demand patterns, and changing product-mix demanded are not allowed in order to cope with fluctuating daily demands. In other words, the firm must strive to deliver the manufactured jobs as demanded.
3. For the cellular manufacturing layout, hybrid shops which combine the functional and the cellular manufacturing layouts are disregarded and no remainder cell is considered since the research goal is to compare two environments in their strictest definitions. Although, the use of the available capacity in another cell may be considered as an alternative to installing additional machines, this option is assumed too costly due to production planning problems.
4. For the cellular manufacturing layout, each job will be assigned to only one cell and all jobs are to be grouped based on their shape and/or design similarities and process plans.
5. Although the maximum number of cells can be the same as the number of distinct products or jobs demanded, number of cells vary only within a known range.
6. No interaction among the cells is allowed.
7. No facility exists beforehand, but it must be of rectangular shape to conform with the micro-computer layout package.

8. The facilities are intended for machining purposes only. Assembly work is neither necessary nor considered since a job, here, means the **simplest indivisible piece** that needs some machining operations.
9. The facility is only machine limited; that is, each machine is attended by one or sufficient number of workers.
10. No worker switching among the machines is considered, but workers can perform multiple operations if their assigned machine is capable of doing so.
11. Subcontracting and the use of overtime are not allowed.
12. Batch splitting is not allowed. Then, a decision must be made whether the entire batch, a portion of the total daily amount to be machined, should be rejected as lost sales or not.
13. Because the selection of the material handling system is not one of the research objectives, a generic material handling system such as a pallet with fixed carying capacity is assumed. Handling cost is proportional to flow amount, distance travelled and job handling difficulty.

Machine Assumptions :

1. Traditional machines are considered; that is, the machines do not operate in a highly automated fashion such as those found in a FMS and some stand-alone advanced CNC machines. Machines have not been purchased yet, but there is a finite set of available machines, with varying abilities and cost parameters, from which the machine-mix of any given facility must be chosen.
2. Some labor intensive operations, such as polishing and inspections, are considered ordinary operations available from some simpler machines just like any machining operation.
3. Most machines can perform more than one type of operation, but no machine can perform all operations. A machine may not always be utilized in a specific area, for example a department of a functional facility, compatible with the prime function of the machine. To

illustrate, A drill press can be used in an area where the primary operations are normally performed with lathes.

4. The same operation takes a different amount of time on different machine types, i.e. varying machine efficiencies.
5. Operation processing rate of a machine is inversely correlated to its ability to process increasing number of operations.
6. The reliability or uptime percentage of each machine is also inversely correlated to its ability to process increasing number of operations because simpler machines are assumed less prone to breakdowns.
7. Each machine can process only one operation on one job at a time.
8. The investment cost of each machine is correlated to its ability to perform increasing number of operations. Higher investment cost also implies lower variable cost for a given machine.
9. All cost and operation time information of each machine is available, but some randomness may be allowed for each operation time due to reasons such as labor skill level, machine maintainance record, and tool condition.
10. Salvage value of the machines and any other maintenance costs are disregarded.
11. Specific machine areas include allowances for additional area requirements due to operator movements, material handling requirements, tool and job queue areas, etc. The sum of the area requirements of all machines in a department or cell is equal to total area of the respective department or cell.
12. Each machine requires a set-up time before a different job type can be started. The duration of such set-up times are known with high certainty and can be treated as deterministic in the modelling stage. Also, each machine can only process a fixed number of parts before a minor set-up or adjustment is needed.
13. Machining parameters such as feed, speed, and depth of cut are not considered explicitly.

Job and Operation Assumptions :

1. In the cellular manufacturing layout case, each job type will be assigned to only one cell and each single operation of a job (for all the demand for that job) will be completed on the same machine or the machine group as selected by the mathematical model. Hence, a specific job operation assignment combinations may not be split between two different machines in the same cell (this assumption is relaxed later).
2. Jobs require machining operations with a known precedence.
3. Economic lot sizes are not considered explicitly. Literature provides various GT/CM lot sizing methods [118,209] in addition to the usual lot sizing methods for general (functional) production systems. But, for consistent comparison, lot sizes, in this research, are equal to the maximum number of jobs that can be carried on an available pallet.
4. The main function of both facilities is to supply an external assembly area with sufficient amount of jobs(parts) so that the final products can be assembled.
5. The daily demand for each job type follows a normal distribution with a known mean and a known variance.
6. Ideally all jobs must be finished within the fixed production period (day) and all jobs, in raw form, are available at the beginning of each period.
7. A given job-mix has already been derived from the information based on the demand level and the component requirements for each final product.
8. All job demand levels are independent of each other.
9. Down times due to machine failures will be accounted for in the mathematical models.
10. Scrap or rework is disregarded.
11. Precedence and routing requirements of all jobs are known in advance.
12. There are "c" general operation classes (distinct processes) such as drilling and milling.
13. Each general operation class has "OC" number of sub-operations. For example, if drilling is the general operation class, then suboperations would be drilling of holes whose depths fall into various ranges such as zero to one inch, one to to two inches, etc.

14. Each job needs only one, if any, operation from each class type.
15. No job requires any operation whose source machine would be very costly and impractical to provide in several cells. For example, heat treating, sand blasting, or heavy presswork can only be available at one location in the plant in accordance with functional layout design; hence, such large machines are not considered for any job.
16. A job can not require a multiple number of the same operation such as drilling the same size holes on all four sides of a casting. While not necessarily realistic, this assumption is needed to simplify the modelling process and the subsequent calculations.

3.1.5 Definition of the Variables for Mathematical Models

Input and decision (output) variables used in stage one are listed below.

Input Variables :

IC_i	Investment cost of machine i.
$C	Available budget for the purchase of all machines at planning time.
TM	Total number of movers or material handlers (unskilled operators with some mechanical means) available for either environment.
VC^c_{in}	Per unit variable cost of processing a class c operation n on machine i.
LSC_k	Lost sales cost for job type k.
D_k	Stochastic daily demand for job k.
α_{k1}	Desired level of insurance to meet the daily demand for job k in Step 1.
α_2	Desired level of insurance to meet the daily demand and, therefore, the machine capacity constraints in steps 2F and 2C.
BHC_k	Handling cost of each item k ($/ft).

MNK_k — Number of job k items that can be fitted on a fixed pallet (unit load size of job k).

t^c_{in} — Stochastic operation time of class c operation n on machine i.

MS_i — Maximum number of parts machine i can process before a minor set-up is needed.

RS_i — Duration of minor set-up or reset requirement on machine i.

ST^c_i — Set-up time of class c operation n on machine i.

SC_i — Set-up time for machine i.

u^{up}_i — Uptime percentage of machine i (stochastic).

MA_i — Floor area needed to install machine i (ft^2).

TA — Total area available in the plant for placing machines under either environment (ft^2).

BM — A high cost value used as a penalty in objective functions.

SM^d_{lm} — Design (d) similarity ratio between jobs l and m.

SM^o_{lm} — Operation similarity ratio between jobs l and m (calculated using input on operation requirements of the jobs).

I_c — Set of machines that can perform class c operations.

I_n — Set of machines that can perform operation n ($I_n = I_c$ if $n \in c$).

I_{jk} — Set of machines that can process at least one operation of any given job k assigned to cell j.

J — Index for cells.

K_j — Set of jobs assigned to cell j.

K_c — Set of jobs that need operation class c ($K_n = K_c$ if $n \in c$).

K_n — Set of jobs that need operation n.

N_{ck} — Set of class c operations needed by job k.

N_{nk} — Set of individual operations n needed by job k.

N_{in} — Set of individual operations,n , that machine i can perform.

N_{ik} — Set of operations needed by Job k and can be provided by machine i.

C_i Set of operation classes, c, that machine i can perform.

T Nominal number of minutes per shift for operation of the machines.

Input Variables for Step 5 (Output from Step 4 and code UNIT FORTRAN)

U_k Number of batches or unit loads of job k (found by dividing mean demand with maximum number of each job type that can be carried on the pallet).

$ULT_{k,i}^{u,c(n)}$ Sum of processing and set-up times of a class c operation n on machine i for u unit loads of job k.

r Index for machines of the same type in a department or cell.

R_i^c Set of machines of type i in department c (department c is same as class area c).

R_i^j Set of machines of type in cell j.

$I_c^{(4)}$ Set of same type of (cf, cn, and cm are used to replace c to denote some fixed c value) machines assigned to department or operation class area c in step 4F.

$I_j^{(4)}$ Set of same type of (jf, jn, and jm are used to replace c to denote some fixed c value) machines assigned to cell j in step 4C.

$T_{i,r}^c$ Number of minutes r^{th} machine i is available in department c (usually 480).

$T_{i,r}^j$ Number of minutes r^{th} machine i is available in cell j (usually 480).

cf indicates the very first operation class needed by a given job type. cn and cm indicate certain pairs found by the forward matching of operation classes needed by a given job type; for example, if a job needs one operation from each of the operation classes of 1, 2, 5, and 7, then the pairs are : 1 & 2, 2 & 5, and 5 & 7. The descriptions of jf, jn, and jm are the same.

Step 1 and 2 Decision Variables :

M_i	Number of type i machines that can be installed in either facility (Step 1).
M_{ikn}	Portion of the total machine i capacity devoted to operation n of job k in Step 1 (only a transition variable).
EC^x	Extra capital needed to prevent any unfeasible solution in Step 1.
AA^x	Extra area needed to prevent any unfeasible solution in Step 1.
M_{ic}	Number machines of type i to be installed in class c operation area (Step 2).
M_{ij}	Number of machines of type i to be installed in cell j (Step 2).
X_{ik}^{c}	Decision variable where : 1 if class c operation needed by job k is performed on machine i (functional case). 0 otherwise.
AC_i^p	Additional machine i capacity increase (as percentage over M_i) need coefficient for either shop (in step 2).
X_{ikn}^{j}	1 if operation n of job k is performed on machine i in cell j (cellular manufacturing layout case) 0 otherwise.

Step 5 Decision Variables :

$Q_{k,i,r}^{u,c}$	1 if u unit loads of job k are assigned to the r^{th} machine type i for operation class c. 0 otherwise.
$Q_{k,i,r}^{u,n,j}$	1 if u unit loads of job k, already assigned to cell j, are assigned to the r^{th} machine type i for operation n. 0 otherwise.
UD_k	Number of jobs of type k that will not be started and costed as lost-sales.

3.1.6 Steps 1, 2F, and 2C

The following models have been developed for capacity allocation segment of the hierarchical methodology used in designing of each facility. The overall modelling process is heavily based on the previously stated assumption that it is disruptive and undesirable to route batches to different machines for the same operation. Excess routing should be avoided although this results in, at times, unused capacity on a nearby machine while capacity shortage may also be present elsewhere. This seemingly sub-optimal action is justified by the assumption that the intangible cost of additional routing and its production planning is very high.

Initial Common Model for the Selection of Machines as First Step: The initial common model, shown in Figure 6 on page 74, considers both production environments together and determines the total number of each machine type that can be acquired under demand and other constraints such as the investment budget and the area available (Step 1). The main goal of this model is to inform the decision maker as to what the initial machine selection should be so that all constraints are met (determination of M_l 's). To provide flexibility, there should be at least one of each available machine type as a result of this model. Budget and/or the area constraints may not permit a feasible solution. Then, it will not be possible to meet a portion of the total daily demand. Such infeasibilities are handled later at lower levels by resorting to the option of incurring lost sales cost.

Mathematical Model for Functional Facility with Operation Class Areas:(Step 2F), The mathematical model for functional facility (MMFF) determines which of the available machines (M_l is an input now) should be purchased and placed in use so that the total daily cost of all operations is minimized. This model includes all operation class areas (Figure 7 on page 75) and assigns operation class needs of each job to a suitable machine.

Mathematical Model for Cellular Facility with Known Number of Cells: (Step 2C) The mathematical model for cellular facility with known number of cells, MMCF, assumes that all jobs have already been grouped and the desired number of cells and each M_i is now known. Then, this model considers all cells at once and assigns operations of jobs to a suitable machine to be included in the cell that the job is sent to. Unlike in MMPL, the best MMCL solution is dependent on the number of cells into which the initial job mix is divided. This model is shown in Figure 8 on page 76.

Capacity Allocation for Set-up Requirements: Models 2F and 2C force the use of all available machines resulting from Step 1. In the continuous solution, it is much less likely that additional capacity needs for various machine types, AC_i^p , variables will be non-zero, but the resulting machine allocations across the departments and the cells may still require excess capacity. Such excess capacity allocations should be regarded desirable because the models in Figure 7 on page 75 and Figure 8 on page 76 do not explicitly consider set-up times which are an essential part of most low-to mid-volume part manufacturing activities. Appendix I presents a model for a functional facility where jobs are optimally sequenced before each machine and additional capacity requirements, due to set-up, are determined. Incorporation of the sequencing model of Appendix I into the current hierarchical procedure is likely to increase the problem complexity without any significant benefit. Instead, the hierarchical procedure of Steps 2F and 2C reserves excess capacity in each department or cell by not including the capacity allocation variables, M_{ic} and M_{ij} , in the objective function with some cost coefficient. In other words, all available machines from Step 1 (conditional availability or not) are fully allocated to respective departments and cells while the actual capacity needed is generally lesser than the allocated capacity.

$$\text{Minimize} \sum_i IC_i \; M_i \; + \; BM\,(AA^x + EC^x)$$

Subject to :

$$T \sum_{i \in I_n} M_{ikn} \frac{1}{t_{in}^c} \geq D_k \qquad \text{for all } k,\ n \in N_{ik} \qquad [3.1.1]$$

$$\sum_k \sum_{n \in N_{ik}} M_{ikn} = u_i^{up} M_i \qquad \text{for all } i \qquad [3.1.2]$$

$$\sum_i M_i \; MA_i \leq TA + AA^x \qquad \text{for all } i \qquad [3.1.3]$$

$$\sum_i M_i \; IC_i \leq \$C + EC^x \qquad \text{for all } i \qquad [3.1.4]$$

$$M_{ikn} \geq 0 \qquad \text{for all } i, k, n \qquad [3.1.5]$$

$$M_i \geq 1 \text{ and integer} \qquad \text{for all } i \qquad [3.1.6]$$

$$D_k \sim N(\mu_k, \sigma_k^2) \qquad \text{for all } k \qquad [3.1.7]$$

$$t_{in}^c \sim N(\mu_t, \sigma_t^2) \qquad \text{for all } i, c, n \in c \qquad [3.1.8]$$

$$u_i^{up} \sim N(\mu_i, \sigma_i^2) \qquad \text{for all } i \qquad [3.1.9]$$

Figure 6. Initial Common Model for Machine Selection (Step 1)

$$\text{Minimize} \sum_{c} \left[\sum_{k \in K_c} D_k \sum_{i \in I_c} VC_{in}^{c\,'} X_{ik}^{c} + BM \sum_{i} AC_i^p \right]$$

Subject to :

$$\sum_{k \in K_c} D_k X_{ik}^c \sum_{n \in N_{ck}} t_{in}^c \leq T M_{ic} \qquad \text{for all } c, i \in I_c \qquad [3.2.1]$$

$$\sum_{i \in I_c} X_{ik}^c = 1 \qquad \text{for all } c, \; k \in K_c \qquad [3.2.2]$$

$$\sum_{c \in C_i} M_{ic} \leq M_i (1 + AC_i^p) \qquad \text{for all } i. \qquad [3.2.3]$$

$$X_{ik}^c = [0,1] \qquad \text{for all } c, i, k \qquad [3.2.4]$$

$$M_{ic} \geq 0 \text{ and integer} \qquad \text{for all } i, c \qquad [3.2.5]$$

$$D_k \sim N(\mu_k, \sigma_k^2) \qquad \text{for all } k \qquad [3.2.6]$$

$$t_{in}^c \sim N(\mu_t, \sigma_t^2) \qquad \text{for all } i, c, n \in c \qquad [3.2.7]$$

Figure 7. Mathematical Model for Functional Facility (MMFF, Step 2F)

$$\text{Minimize} \sum_{j} \left[\sum_{k \in K_j} D_k \sum_{n \in N_k} VC_{in}^{c} \, X_{ikn}^{j} + BM \sum_{i} AC_i^{p} \right]$$

Subject to :

$$\sum_{k \in K_j} D_k \sum_{n \in N_{nk}} X_{ikn}^{j} \, t_{in}^{c} \leq T \, M_{ij} \qquad \text{for all } j, \; i \in I_j \qquad [3.3.1]$$

$$\sum_{i \in I_n} X_{ikn}^{j} = 1 \qquad \text{for all } j, \; k \in K_j, \; n \in N_{nk} \qquad [3.3.2]$$

$$\sum_{j \in J} M_{ij} \leq M_i \, (1 + AC_i^{p}) \qquad \text{for all } k, \; i \in I_{jk} \qquad [3.3.3]$$

$$X_{ikn}^{j} = [0,1] \qquad \text{for all } j,i,k,n \qquad [3.3.4]$$

$$M_{ij} \geq 0 \text{ and integer} \qquad \text{for all } i,j \qquad [3.3.5]$$

$$D_k \sim N(\mu_k, \sigma_k^2) \qquad \text{for all } k \qquad [3.3.6]$$

$$t_{in}^{c} \sim N(\mu_t, \sigma_t^2) \qquad \text{for all } i, c, n \in c \qquad [3.3.7]$$

Figure 8. Mathematical Model for Cellular Facility (MMCF, Step 2C)

Explanation of the Objective Function and the Constraints for Steps 1 and 2

Step 1 (Figure 6):

1. [Objective function, Z] : Minimize total investment cost. If the solution is not feasible at first, variables AA and EC are added to get a solution at any cost.
2. [3.1.1] : Enough machine capacity is reserved for each operation of each job.
3. [3.1.2] : Portions of each machine i devoted to a particular job operation combination are summed to find the ideal number of machine type i needed.
4. [3.1.3] : Total number of machines is limited by total area available. AA, additional area at high cost of BM, is made available to avoid any infeasibility.
5. [3.1.4] : Total number of machines is limited by available investment budget. Similarly, extra capital is made available to avoid infeasibility.
6. [3.1.5] : A fraction of machine i may be allocated for each job k and operation n combination. For example, 1.3 of 2 machine P's may be assigned to perform operation No.2 of job A.
7. [3.1.6] : Step 1 must, however, yield at least one and integer number of machines of each kind to be installed.
8. [3.1.7. & 3.1.8] : Daily demand, operation times, and machine reliability are random variables.

Step 2F (Figure 7 on page 75):

1. Z : Minimizes total daily variable cost and the cost providing added capacity.

2. [3.2.1] : Using each M_i as input, a part or portion of machine type i assigned to department c [M_{ic}], Any department c must meet the total machining needed for class c operations for all demand.

3. [3.2.2] : Each job can only be assigned to one machine in each department c if the job k needs a class c operation.

4. [3.2.3] : Total number of type i machines, M_{ic}, assigned to all departments,c's, can not exceed the available number of machine i's from step 1. If some M_i's are not enough, the necessary amount of additional capacity [AC_i^p] , at the high penalty cost of BM, is determined for future use. Step 2F ends with all demands appearing satisfied pending a decision on how to create AC_i^p later on. A fractional value of 0.2 AC_k^p, for example, indicates that available number of machines of type k must be increased by 20 percent.

5. [3.2.4] : A job is assigned to one machine or machine group in each area c.

6. [3.2.5] : Machines assigned to each department must end up being integers.

7. [3.2.6. & 3.2.7] : Demand and operation times are still treated as random variables.

Step 2C (Figure 8 on page 76):

1. Z : Same as in Figure 2, but this Z references cells instead of departments.

2. [3.3.1] : Same as in 3.2.1 with M_{ij} replacing M_{ic} .

3. [3.3.2] : Jobs have already been assigned cells, then each operation of each job k is now assigned to one and only one machine or machine group in each cell.

4. [3.3.3. & 4 & 5] : Same as in 3.2.3. & 4 & 5.

5. [3.3.6. & 7] : Same as in 3.2.6 & 7.

Modification of Step 2 When Resources are not Limited:

If the firm wants to meet the daily demand for all job types and constraints 3.1.3 and 3.1.4 of step 1 do not matter, step 1 can be eliminated. Step 2 is solved with the goal of minimizing total daily variable cost while incurring the minimum initial investment cost. The following changes must be made to MMFF (Figure 7 on page 75) and MMCF (Figure 8 on page 76):

1. Term AC_i^p in both objective functions is replaced by term M_{lc} in MMFF and term M_{ij} in MMCF. Term AC_i^p is also deleted from constraints 3.2.3. and 3.3.3. of both models.
2. Constant M_i (input from step 1 when resources are limited) is replaced by some arbitrarily chosen value which estimates the maximum number of each machine type that may ever be needed for a given demand mix and level.

These changes convert MMFL and MMCF into models (not shown separately) which are highly related to the following three classical problems whose details are available in many sources:

1. Transportation Problem (TP).
2. Fixed Charge Warehouse Location Problem (FCWLP).
3. Generalized Assignment Problem (GAP).

The relationships between the models developed in this research and the aforementioned problems are as follows:

- The VC_{in}^c term of the modified step 2 models is equivalent to the cost term, c_{ij}, of the above three problems.
- The term, BM, of the objective functions and the fixed cost term of FCWLP are identical.
- Binary assignment variables X_{in}^c and X_{ij}^l of modified MMFL and MMCF are analogous to the binary assignment variables of X_{ij} of GAP and X_i of FCWLP.

- Operation class c of MMFF and operation n of MMCF are equivalent to the item i of GAP, the customer j of FCWLP, and the destination j of TP.
- The three classical problems also have constraints similar to 3.2.1. and 3.3.1 of the modified MMFF and MMCF.
- Decision variables M_{ic} and M_{ij} of modified MMFF and MMCF serve a role similar to the binary decision variable X_i of FCWLP.

Solution Method for Modified Step 2 Models:

Optimal job, operation, and machine assignments can be obtained by solving the deterministic equivalent of the modified forms of MMFF and MMCM as ordinary LP's rather than as mixed integer problems. This heuristic claim, also validated by actual MPSIII runs (but not shown here), is based on the following assertion : FCWLP, GAP, and indirectly TP are all 0/1 type models that yield 0/1 results when restricted as such. If the modified step 2 models, when solved as LP's, yield 0/1 assignments, without such restrictions, then these models can always be expected to yield 0/1 assignments because of the relationships with these three classical problems. In summary, modified step 2 models can be solved as LP's and the results (fractional M_{ic} and M_{ij} values and 0/1 assignment variables) can be used as inputs to a modified step 5.

3.1.7 Step 4 (Reintroduction of Operating Constraints)

This step is skipped if step 1 and 2 yield a feasible machine mix and job-operation-machine assignment set for each department and cell. This step also serves as refinement of suggested machine assignments at steps 2F and 2C as constraints 3.2.3. and 3.3.3 of Figure 7 on page 75 and Figure 8 on page 76 may, at times, result in excessive assignments of some machines due to integer machine requirements. Constraints 3.2.3 and 3.3.3 of steps 2F and 2C require that the suggested machine mix of step 1 be fully used even if that results in assignment of more machines than necessary in some cases.

Reduction Process for Functional Facility (Step 4F) :

- Find, if any integer M_{ic} assignment has no associated X^{c}_{ik} assignment. If there is none, eliminate that machine.
- Compare, for each class, the number of X^{c}_{ik} assignments against number of machines. If there appears to be excessive machine assignments, calculate actual capacity needed for each machine k. After rounding up the capacity requirement just calculated, eliminate excess machines, if any, from the machine mix found in Step 2F for that class.
- Reduce the number of machines across all departments using the difference between the integer and continuous machine requirement amounts as priority in descending order.
- If the continuous assignment is higher, then skip to the next machine type in the same or different department unless there are no other machine assignments to reduce and the investment and/or area constraints have not been met.
- Also, skip to the next machine type if the current integer machine count is one.
- As the reduction process continues, keep reducing the necessary investment and area requirements by the amounts required for the machines just eliminated.
- Update the differences between integer and continuous machine assignments.
- After the first pass, keep removing machines from each department sequentially.

- Stop whenever resource constraints are both satisfied or current shortage(s) of capital and/or area is less than the additional reduction that could be achieved if a machine with the least resource requirements is further eliminated.

The above reduction process insures that each department has at least one machine (of any type) left.

Reduction Process for Cellular Facility (Step 4C):

This process is very similar to the one presented in the previous section and is to be applied to each cell by considering a cell as a miniature functional facility in which a group of one or more machines may be thought of as one of the departments. Reduction of target machines, determined by calculation of slacks as in above, is carried out by rotating among the cells and reducing one machine at a time from a given cell in order to maintain some degree of equality in cell capacities. Then, the next most suitable machine or the one with the largest slack may not be removed if the reduction turn is at some other cell. Excess machines are removed first regardless of the order.

The above priority rules may be relaxed in the very last iteration so that a machine with a lower priority can be eliminated (higher priority machines are first eliminated) if this elimination can prevent eliminating another one.

3.1.8 Step 5F and 5C (Determination of Actual Production levels)

The purpose of this step is to determine the portion of the daily demand for each job type, D_k, which must be set aside as lost sales without any operations performed. Such a decision becomes necessary as a consequence of the overall capacity revision of step 4. In accordance with the previous assumption that partially completed jobs are not acceptable, there must be enough machining capacity for each required operation as the jobs flow through the facilities. The stochastic nature of the demand and the operation times make it necessary to maintain what may be to be an over capacity in most cases. Also, the rejection of some of the demand may appear as a sub-optimal action. It must be kept in mind that one of the goals of the overall planning process is to ensure that all capacity constraints hold at least with the prespecified probabilities. To account for uncertain manufacturing conditions, it is essential to keep some excess capacity as a part of the business of manufacturing.

If, for example, department No.3 of a functional facility has sufficient capacity to machine all the demand for job A's operation No.6 (a class 3 operation) while the next department to be visited (department No.4 for operation No.11) only has enough capacity to machine 92 job A's (8 or 9 unit loads of job A at 11 A jobs per pallet), then no more than 92 of 104 (total mean daily demand) job A's can be machined to completion subject to capacity availability in other departments. It is also assumed that cost of idle machine capacity is negligible compared to the cost of handling incomplete jobs. This step insures that the portion of the total demand started should have a high probability of being completed regardless of the amount by which some machines may stay idle due to insufficient work. Job splitting is now allowed in the form of partitioning of batches of jobs and not the batch itself among two or more same or similar machines (i.e. seven batches of job A may visit machine P for operation No.2 and 2 batches of the same job A may visit machine J for the same operation in the same department or cell) thus increasing set-up requirements while relaxing strict binary assignments made in step 2.

Mathematical Model for Step 5:

Step 5 contains two different models: one for the functional and one for the cellular facility to determine exact production levels of each job type when resources are limited.

1. Mathematical Model for Functional Facility (Figure 9 on page 86).
2. Mathematical Model for Cellular Facility (Figure 10 on page 87).

In both models, demand is shown as a stochastic input variable to express the problem in more exact detail, but it is no longer necessary to treat demand as a stochastic variable. Steps 1 and 2 have fully considered the effects of stochastic demand and operation times. The inputs of this step already include necessary insurance or assurance factors to account for the stochastic input. Figure 10 on page 87 is roughly the same as Figure 9 on page 86 except for its size. It is constructed and solved separately for each cell since cells are considered independent. The index j used as a superscript in constraints 3.5.1. and 3.5.6. refers to the particular cell being considered. Binary assignment variable Q and input variable ULT actually have only two superscripts and two subscripts each as index j is not used in the actual expansion of MMCF. Using the machine mix found in step 4C and the unit load time amounts, following heuristic procedure allows each cell to be modified into a miniature functional facility so that the code, STEP5 FORTRAN, can still be used to generate necessary MPSIII input file for both facility types.

Departmentalization of Cells:

The operation class capability domain for each cell should be compared with operation class needs of the job mix assigned. Step 2C assures that each cell has all necessary operation class capabilities, but such capability may be lost as a result of step 4C elimination process. Following checks should be made :

- Compare operation class needs of cell's job mix with operation class capability domain of the remaining machines in the cell.

- If all operation class needs of a given cell are not fully covered, exchange machines among the cells if such an exchange does not critically decrease operation class capability of the lending cell.
- If all operation class needs of a cell are covered by the capability domain of the remaining machines, but there are not enough machines to devote at least one machine for each operation class, then machines must be shared for some operation classes.
- Operation classes needed the least should be considered for sharing machines.
- Any extra unassigned machine should be assigned by giving priority to those operation classes needed most frequently by cell's job mix.
- If there is a tie for the most frequently needed operation class selection, extra machine(s) should be shared by most frequently needed two or more mini-departments.
- Sharing of one machine by two mini-departments is equivalent to having two machines, one in each mini-department, with 240 minutes of daily capacity for each machine.
- Step 4C decisions may be altered if such an alteration does not violate any of the operating constraints. For example, a machine from the remaining machine mix may be exchanged for a machine which was eliminated if such an exchange makes the departmentalization easier.
- Resulting mini-departments are not absolutely dedicated to a given operation class as in the functional case. Extra capacity of a machine in a given mini-department may be used to perform other feasible department operations. For example, if mini-department No.1 of cell No.1 has two type P machines with only 600 minutes of work assigned (960 minutes is the capacity of two machines) while mini-department No.7, with a single type T machine, has 540 minutes of work assigned, then 60 minutes of class 7 work can be performed in mini-department No.1 because machine P is able to perform operation classes 1, 2 and 7.

$$\text{Minimize} \sum_{k} LSC_k \, UD_k$$

Subject to :

$$\sum_{u=1}^{U_k} Q_{k,i,r}^{u,c} \leq 1 \qquad \text{for all } c,\ k \in K_c,\ i \in I_c^{(4)},\ r \in R_i^c \qquad [3.4.1]$$

$$D_k Q_{k,i,r}^{U_k,cf} + \sum_{i \in I_{cf}^{(4)}} \sum_{r \in R_i^{cf}} \sum_{u=1}^{U_k - 1} u\, MNK_k\, Q_{k,i,r}^{u,cf} + UD_k = D_k \qquad [3.4.2]$$

$$\text{for all } k,\ cf(k)$$

$$D_k Q_{k,i,r}^{U_k,cn} + \sum_{i \in I_{cn}^{(4)}} \sum_{r \in R_{cm}^{i}} \sum_{u=1}^{U_k - 1} u\, MNK_k\, Q_{k,i,r}^{u,cn} = D_k Q_{k,i,r}^{U_k,cm} + \sum_{i \in I_{cm}^{(4)}} \sum_{r \in R_i^{cm}} \sum_{u=1}^{U_k - 1} u\, MNK_k\, Q_{k,i,r}^{u,cm}$$

$$\text{for all } k,\ cn,\ cm \qquad [3.4.3]$$

$$\sum_{k \in K_c} \sum_{u=1}^{U_k} ULT_{k,i}^{u,c(n)}\, Q_{k,i,r}^{u,c} \leq T_{i,r}^{c} \qquad \text{for all } c,\ i \in I_c^4,\ r \in R_i^c \qquad [3.4.4]$$

$$D_k \sim N(\mu_k, \sigma_k^2) \qquad \text{for all } k \qquad [3.4.5]$$

$$Q_{k,i,r}^{u,c} = [0,1]\ ,\ UD_k \geq 0 \qquad \text{for all } u, c, i, k, r \qquad [3.4.6]$$

Figure 9. Mathematical Model for Functional Facility (Step 5F)

$$\text{Minimize} \sum_{k \in K_j} LSC_k \; UD_k$$

Subject to :

$$\sum_{u=1}^{U_k} Q_{k,i,r}^{u,n,j} \leq 1 \qquad \text{for all } n,\ k \in K_j,\ i \in I_j^{(4)},\ r \in R_i^j \qquad [3.5.1]$$

$$D_k \, Q_{k,i,r}^{U_k, jf} + \sum_{l \in I_{jf}^{(4)}} \sum_{r \in R_i^{jf}} \sum_{u=1}^{U_k - 1} u \; MNK_k \; Q_{k,i,r}^{u,jf} + UD_k = D_k \qquad [3.5.2]$$

$$\text{for all } k,\ jf(k)$$

$$D_k \, Q_{k,i,r}^{U_k, jn} + \sum_{l \in I_{jn}^{(4)}} \sum_{r \in R_{jm}^{i}} \sum_{u=1}^{U_k - 1} u \; MNK_k \; Q_{k,i,r}^{u,jn} = D_k \, Q_{k,i,r}^{U_k, jm} + \sum_{l \in I_{cm}^{(4)}} \sum_{r \in R_i^{jm}} \sum_{u=1}^{U_k - 1} u \; MNK_k \; Q_{k,l,r}^{u,cm}$$

$$\text{for all } k,\ jn,\ jm \qquad [3.5.3]$$

$$\sum_{k \in K_j} \sum_{u=1}^{U_k} ULT_{k,i}^{u,n,j} \; Q_{k,i,r}^{u,n,j} \leq T_{i,r}^{j} \qquad \text{for all } n,\ i \in I_j^4,\ r \in R_i^j \qquad [3.5.4]$$

$$D_k \sim N(\mu_k, \sigma_k^2) \qquad \text{for all } k \qquad [3.5.5]$$

$$Q_{k,i,r}^{u,n,j} = [0,1] \;,\; UD_k \geq 0 \qquad \text{for all } u,\ i,n,\ k,\ r \qquad [3.5.6]$$

Figure 10. Mathematical Model for Cellular Facility (Step 5C)

Explanation of the Objective Function and the Constraints of Model for Step 5F

1. Objective Function [Z] : Minimize total daily lost sales costs over all jobs demanded from the functional facility.
2. [3.4.1] : Only a single unit load amount of a feasible job type can be assigned to any given machine. Example : if there are two machine P's left in department No.1, then only one of the possible unit load amounts can be assigned to each one. If a feasible job, such as job A, is to be produced at the amount of eight unit loads (two unit loads not being produced), the first machine P may assigned, for instance, three unit loads while the second machine P is assigned the rest (five unit loads). This constraint insures that the model does not make multiple assignments such as assigning two and three unit loads of job A to the same machine while it should assign five unit loads.
3. [3.4.2] : The sum of the produced jobs and the unmet amount (lost sales) must equal the demand for all jobs. The first term of this constraint indicates a possible decision to meet total demand since the last unit load is always equal to the demand level as discussed later in this Chapter. This constraint is only written for the very first operation class needed by each job type considered, but constraint 3.4.3 provides the necessary coupling effect to implicitly impose constraint 3.4.2 for all operation class needs of all jobs without increasing the problem size.
4. [3.4.3] : The number of unit loads jobs must receive an equal number of all necessary operations from each department (no partially completed jobs allowed). To illustrate using job A which requires operations from departments 1, 3, 4, and 5, this constraint sets the number of operations performed in each class equal to each other by successively equating number of operations. For example;

   - Number operations performed on job A in department No.1 equal those performed in department No.3 (88 operation No.2 in department No.1 and 88 operation No.8 in department No.3).

- Number operations performed on job A in department No.3 equal those performed in department No.4.

- Number operations performed on job A in department No.4 equal those performed in department No.5.

5. [3.4.4] : Sum of the unit load times assigned to a given machine can not exceed the available capacity of that machine.

Explanation of the Objective Function and the Constraints of Model for Step 5C:

Each cell is thought of as a miniature functional facility with its own mimi-departments, defined in step 4C, with machine and job mixes. The objective function and the constraints of this model are the same as those discussed previously for the functional case, but each cell and its job mix are considered instead of the complete job mix. The mathematical model for step 5C, shown in Figure 10 on page 87, is to be set-up and solved, one at a time, for each of the cell structures considered.

Complexity of Step 5 Models:

Any given Step 5 (F or C) model has two types of variables: integer variables for unmet daily demand of each job and binary assignment variables. The total number of variables for MMFF can be expressed as :

$$K + \left[\sum_{c} I_c \left(\sum_{k \in K_c} MNK_k \right) \right] \tag{3.6}$$

Where K is the number of jobs in the job mix and I_c is the total number of machines remaining in each department c. Using problem set No.1, one can quickly realize that an ordinary solution of Step 5 can involve too many variables and become very hard even with efficient methods and powerful packages such as MPSIII. The mainframe used was an IBM 3090 Model

200/VF computer. In Table 2 on page 90, The first three attempts show the results of a brute-force attempt to get an integer solution when there are 2^{468} possibilities. In the fourth attempt, unit loads were temporarily doubled (halving MNK_k values) to reduce the problem size, but an integer solution was still not found as in the first three attempts.

Table 2. Solution Attempts for Step 5F of Problem Set No.1

Attempt No.	Number of Binary Variables	Number of Nodes Examined	Exit Time (CPU + I/O)
1	468	500	3.374 minutes
2	468	1500	11.762 minutes
3	468	6527	59.10 minutes
4	241	987	5.534 minutes
4A	241	1218	6.257 minutes
5	405	2000	19.00 minutes
6	182	2	0.051 minutes

The following heuristic solution method was developed and implemented in attempts No.5 and 6 :

Heuristic Solution of Step 5 (F and C) Models :The procedure described below is applicable for either facility, the entire functional or one cell of a cellular facility. The term "zone" refers to a department or a mini-department.

1. Compare the machine mix and the production capacity of each zone with the set of jobs that need to visit the same zone in order to identify any clear factors which limit the production level of one single job in all departments to be visited by that job. Bottlenecks are identified easily when the number of job types visiting a zone is equal to the number of machines in the zone considered. Therefore, such departments should be considered first. For example, if department No.7 has machine P as the only machine and it is to be visited only by Job B. Then, a maximum of 11 unit loads of job B which require 478 minutes for class No.7 operation on machine P can be produced. All binary combinations that

include job B with unit load amounts higher than 11 may now be deleted from the input file STEP5 CNTL before submitting to MPSIII package for solution.

2. If no clear limiting factors can be determined, match the jobs and the machines of a given zone one to one. The maximum number of unit loads, or upper bound on the amount of production of each job type, is the maximum amount found in the matching process.
3. Once all redundant binary variables are deleted from input file STEP5 CNTL, run the MPSIII package and keep the continuous solution. For example, deletion of obviously redundant binary variables has reduced the total number of binary variables from 468 to 405 as shown in the fifth attempt row of Table 2 on page 90.
4. Examine the continuous solution for assignments at or around the values of 1.0 and 0. Adapt some such assignments as temporary production level decisions.
5. Double the unit load sizes for each job type to reduce number of binary variables and determine a new integer solution for use in approximation later.

Post-Step 5 Analysis for Functional Facility:

The functional facility is under a rigid assumption that excess capacity in a given department can not be used for any other feasible operation's class of work. Any machine left idle in a department should be transferred to another feasible department in order to increase the production of at least one job type. The mathematical model for Step 5F may, at times, assign no load to some machine(s) as a consequence of constraint 3.4.3 which requires that no incomplete jobs are allowed. The step 5F solution should be further examined for possible exchanges between the machine load assignments in order to free some machines for transfer to other departments utilize any unloaded or underloaded machines elsewhere in the facility.

Preferred Solution Method for Step 5C When The Problem Size is Small:

If the number of cells is high and/or cell's job/machine mixes are small, it becomes possible to find an exact integer solution by allocating a sufficient amount of CPU time and number of nodes for the MPSIII package to work with. Experimentation has shown that an integer solution was easily obtained when the number of binary variables was under 200. Problem size of 200 binary variables corresponds to a functional facility with four departments and four jobs. Figure 11 on page 93 shows the procedures used in step 5.

Post Step 5 Analysis for Cellular Facility:

Amounts set aside as lost sales can be reduced in some cells by rerouting some jobs to other mini-departments where excess capacity exists at one or more feasible machines which can also perform the needed class of operations. Such transfers are not considered possible in a functional facility due to longer distances among, and the rigid specialization of, the departments. It is assumed that the cell's teamwork environment and additional expertise of cell workers enable such transactions.

Solution of a Modified Step 5 (When Resources are not Limited):

Since all daily demands can now be met, there is no need to use mathematical models such as those shown in Figure 9 on page 86 and Figure 10 on page 87. In this step, set-up factors need to be incorporated to the binary assignments received from the modified step 2 along with fractional number of machines of each type. In other words, the models of step 5 are not used

- Examine each X^c_{ik} (functional) and X^l_{ikn} (cellular) determined in modified step 2 and use them as guides in loading type i machines with sufficient unit loads of type k jobs for operation class c (functional or cellular).
- Round up fractional M_{ij} or M_{ij} variables as needed.
- In the case of the cellular facility, cell departmentalization is still necessary and it may result in rounding down a few of the M_{ij}'s found in modified step 2.

This modified form of step 5 must be performed since feasible step 2 solution may become infeasible with the inclusion of set-up times.

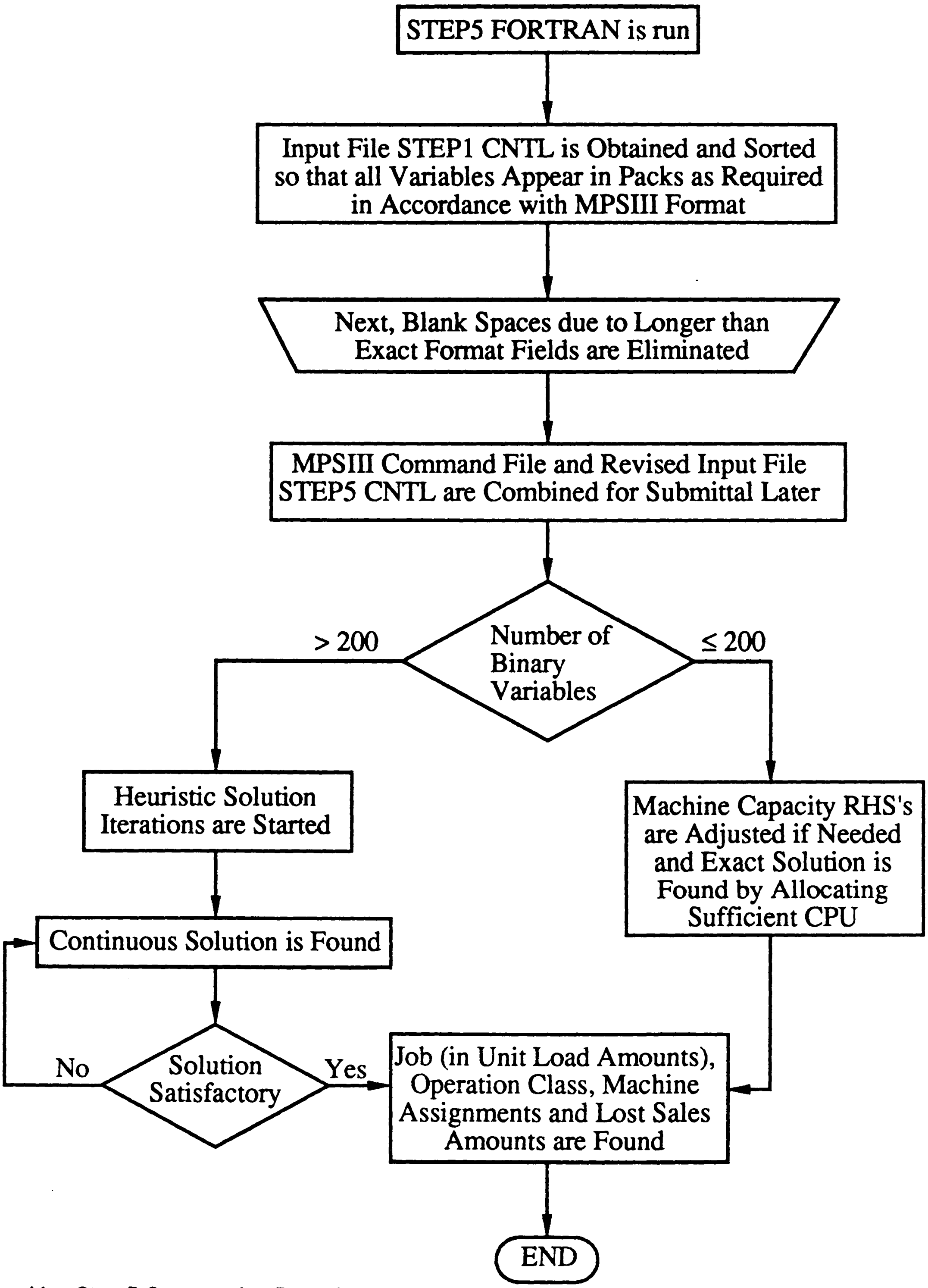


Figure 11. Step 5 Computation Procedures

3.1.9 Job/Cell Grouping Methodology

Although the development of a job grouping heuristic is not one of the goals of this research, it is essential that any grouping be carried out carefully in order to provide as fair of a comparison as possible. The structure of the input data in Appendix D and some of the assumptions do not allow adopting a pre-grouped example from earlier literature. Major benefits attributed to the cellular manufacturing environment are based on the grouping of similar jobs so that certain set-up time reductions and savings in planning effort may be realized. Randomly constructed groups are likely to be inefficient with respect to such objectives. While optimal grouping is a difficult enumerative task especially with a large number of jobs, the following guidelines can be used in constructing good job/cell assignment decisions :

- It is desirable to balance the production load, in terms of hours of machining per period, among all cells in addition to satisfying other similarity objectives, but, here, the primary emphasize will be on assigning roughly the same number of job types to each cell.
- The process similarity of each job with other jobs can be found using one of the well-known similarity index formulas often cited in the literature [98,224]. The formula shown below considers common operation classes needed by both jobs in the pair l and m, CO_{lm}, and the number of operation classes needed by each job: (O_l and O_m) :

$$SM^{p}_{lm} = CO_{lm} / (O_l + O_m - CO_{lm}) \qquad (3.7)$$

Considered independently, each of these similarity measures, SM^{d}_{lm} (directly inputted from Table 68 on page 253 in Appendix D) and SM^{p}_{lm} may result in different job/cell assignments because each promotes job grouping based on a different objective (process and shape/design similarities). Then, a linear combination of the above similarity indices can serve as a compromise measure :

$$AS_{lm} = V_1\, SM^p_{lm} + V_2\, SM^d_{lm} \tag{3.8}$$

where V_1 and V_2 range from 0 to 1 and be defined by management in accordance with some firm policy. Jobs are assigned to cells by beginning with the first cell and selecting the job set which yields a fairly high AS_{lm} sum. This process is repeated until there are no unassigned jobs. Assignments are limited by a predetermined number of jobs each cell may have. This process may yield some job/cell assignments with relatively high or low total AS_{lm} scores. It should be noted that :

- The above procedure is by no means an optimal one; instead, it is an alternative to random job/cell assignments or complicated near-optimal methods found in literature [127,174,175,193].
- Rather than using a job/operation need matrix as above, the literature suggests the use of a job/machine visit matrix as the basis for calculating job similarities due to the common assumption of an one to one correspondance between machines and operations. This assumption was considered too simplistic for this research because most real-life machines are able to perform two or more different operation classes. Example problem set No.2 is used in illustrating the grouping process. Values shown Table 3 on page 96 below are unitless similarity measures calculated via equation (3.7) and Table 66 on page 252 in Appendix D.

Table 3. Job Similarity Data Based on Process Plans

	Job A	Job B	Job C	Job D	Job E	Job F	Job H
A	1.00	0.33	0.33	0.17	0.40	0.50	0.50
B		1.00	0.33	0.17	0.17	0.50	0.50
C			1.00	0.40	0.40	0.29	0.80
D				1.00	0.50	0.33	0.33
E					1.00	0.60	0.33
F						1.00	0.43
H							1.00

Jobs A and B need operations 2, 8, 11, 14 and 1, 13, 20, 14 or general operation class sets of 1, 3, 4, 5 and 1, 2, 5, 7. Then, jobs A and B have two operation classes in common (1 and 5):

$$SM^{o}_{A,B} = \frac{2}{(4+4-2)} = 0.33$$

Table 4. Weighted Job Similarity Data.

	Job A	Job B	Job C	Job D	Job E	Job F	Job H
A	1.00	0.47	0.37	0.24	0.31	0.58	0.61
B		1.00	0.36	0.26	0.29	0.54	0.57
C			1.00	0.58	0.61	0.34	0.61
D				1.00	0.62	0.38	0.31
E					1.00	0.48	0.32
F						1.00	0.50
H							1.00

If $V_1 = V_2 = 0.50$, then $AS_{A,B} = 0.50\,(0.33) + 0.50\,(0.60) = 0.47$.

A SM^{d}_{AB} of 0.60 is an input and taken from Table 68 on page 253 of Appendix D where another weighted similarity data table which includes all four problem sets is given.

3.1.10 Data and Problem Sets

Four example sets are considered. These sets represent batch production of four to twelve job types at various daily demand levels. These jobs require three to five distinct operations. There are eight different machines (P, J, K, N, W, Z, S, T), twelve distinct job types (A, B, C, D, E, F, H, Q, R, S, U, V), seven distinct operation classes or departments in the functional case, and twenty operations which belong to these seven major operation classes. Appendix D contains the details. The number of machines and the jobs considered are gradually increased in the following four problem sets :

Problem Sets With Operating Constraints:

In the first two problem sets, setting up of the facilities is under area and budget constraints.

1. **Set No.1:** Machines P, J, K, N and jobs A, B, C, D with two cells in the case of the cellular manufacturing layout. TA = 1350 ft^2 and \$C = \$1,100,000.
2. **Set No.2:** Six machines, P, J, K, N, W, Z, and seven jobs A, B, C, D, E, F, H with the number of cells being two and three. TA = 1425 ft^2 and \$C = \$1,510,000.

Problem Sets Without Operating Constraints:

It is assumed that there are sufficient amounts of investment funds and plant area so that the daily demand for all job types can be met in full with the minimum predefined probabilities. Therefore, the following two problem sets are defined:

1. **Set No.3:** The same six machines as in problem set No.2 and three additional jobs : Q,R,S. Number of cells is also equal to two and three.

2. **Set No.4:** Two additional machines, S and T, and two additional jobs, U and V, with three and four cells in case of the cellular manufacturing layout.

Problem set No.1 is used for illustrating the expansion of the modelling steps. The expansion of other problem sets for illustration would be too long to present in a detailed manner. In the cellular case, jobs A and B and C and D are assigned to cells one and two without using the job/cell assignment method discussed previously (job/cell assignments of other example sets were determined in accordance with aforementioned job/cell grouping methodology). Weighted similarity values as in Table 4 on page 96 must be reconstructed whenever a new job type is added to the current job-mix. Table 4 on page 96 is also used below to illustrate the job/cell grouping process for problem set No.2 with two cells:

- Since there are seven job types to be assigned to or divided into two cells, four job types will be assigned to the first cell and the remaining three to the second cell.
- Table 4 on page 96 shows that job pairs CE, DE, CH, AF, and AH have fairly high similarities of 0.61, 0.62, 0.61, 0.58, and 0.61 respectively.
- By inspection, job mix subsets A,F,H and C,E,D are grouped and assigned to the first and second cells to yield a total AS_{lm} of 1.69 (0.58 + 0.50 + 0.61) for cell one and 1.81 (0.58 + 0.61 + 0.62) for cell two.
- The remaining job, B, is assigned to cell one since job B is more similar to members of cell one's job mix.

Table 5 on page 99 summarizes the job/cell assignments for all problem sets.

Table 5. Problem Sets and Job/Cell Assignments for Cellular Environment

Problem Set	Number of Cells	Job/Cell Assignment
No.1	2	Cell No.1 : A,B Cell No.2 : C,D
No.2C-2	2	Cell No.1 : A,B,F,H Cell No.2 : C,D,E
No.2C-3	3	Cell No.1 : A,B,F Cell No.2 : C,H Cell No.3 : D,E
No.3C-2	2	Cell No.1 : A,B,F,H,R Cell No.2 : C,D,E,Q,S
No.3C-3	3	Cell No.1 : A,B,F,Q Cell No.2 : C,H,S Cell No.3 : D,E,R (*)
No.4C-3	3	Cell No.1 : A,B,D,H Cell No.2 : C,E,S,V Cell No.3 : F,Q,R,U
No.4C-4	4	Cell No.1 : A,B,H Cell No.2 : C,S,V Cell No.3 : D,E,R (*) Cell No.4 : F,Q,U

(*): Same job mix in cells No.3C3-3 and 4C4-3.

There are always seven departments in the functional environment cases.

3.1.11 Calculation of Unit Load Times

Once the job-machine-operation class and job-cell-machine-operation assignments are known, major and minor set-up times and unit load considerations must be introduced into the hierarchical planning process. The MNK_k value, unit load size for job k, is a fixed character of each job type and is used in calculation of unit load times.

Determination of the Number Batches Per Day for Each Job Type:

If daily demand variances are ignored, the number of unit loads or batches of each job type is found via,

$$U_k = [\frac{\overline{D}_k}{MNK_k}]^+ \tag{3.9}$$

The last batch may not be a full one if the above division is not an integer. Then, upward rounding off must be made.

Average Set-up Factor for Functional Facility:

In a real world functional facility, typically there is no attempt to sequence the batches of similar job types together in order to realize reductions in set-up times, so it is reasonable to expect randomness in similarities of the jobs that follow and precede each other on a given machine. Methodology presented in Appendix I seeks optimal sequencing with respect to set-up times, but it is too cumbersome to implement here. Instead, the following heuristic based on expected randomness in job type arrivals to a machine is used. Let $(ASF)^f$ be the average set-up factor for functional facility, then:

$$(ASF)^f = 1 - \frac{\left[\sum_{p=1}^{K-1} \sum_{q=p+1}^{K} SM^d_{p,q} \right]}{\binom{K}{2}} \tag{3.10}$$

where K is the total number of jobs considered and p refers to the first job and $q = p + 1$ refers to the next job in order. The numerator sums the similarity values between all possible pairs of the jobs in the facility. Denominator determines the number of the pairs. The division results in an average similarity value among all job types. The compliment of the average similarity value is the average dissimilarity. Using problem set No.1 to illustrate ($K = 4$),

$$(ASF)^f = 1 - \frac{SM^d_{A,B} + SM^d_{A,C} + SM^d_{A,D} + SM^d_{B,C} + SM^d_{B,D} + SM^d_{C,D}}{6}$$

$$= 1 - \frac{0.60 + 0.41 + 0.30 + 0.38 + 0.34 + 0.75}{6} = 0.54$$

The $(ASF)^f$ of 0.54 reflects an average measure of dissimilarity between all job types that will flow through the departments of the functional facility. If a given machine and operation class combination takes 24 minutes for a full set-up, then $24 * 0.54 = 13$ minutes of average set-up time must be considered at the start of each job type.

Average Set-up Factor for each Cell of a Cellular Facility:

Since each cell is expected to function like a miniature functional facility, the same randomness in job similarities on a given machine is also assumed here. Then, $(ASF)^{cl}_j$ is the average set-up factor for cell j and can be calculated as in above by considering only those jobs assigned to a given cell. Problem set No.2 is used to illustrate since problem set No.1 is a trivial case for cellular formation.

$$(ASF)_1^{cl} = 1 - (0.60 + 0.65 + 0.71 + 0.58 + 0.63 + 0.57)/6 = 0.38 \text{ and}$$

$$(ASF)_2^{cl} = 1 - (0.82 + 0.75 + 0.74)/3 = 0.23.$$

For comparison, $(ASF)^f$ is calculated as 0.51 for problem set No.2 and is greater than both 0.38 and 0.23. Any good job grouping heuristic should ensure that :

$$(ASF)^f \geq (ASF)_j^{cl} \quad j \in J \tag{3.11}$$

holds for any given total job-mix.

Table 6. Average Set-up Factors for both Environments.

Problem Set	Functional	Cellular
No.1	0.54	Cell No.1 : 0.40 Cell No.2 : 0.25
No.2C-2	0.51	Cell No.1 : 0.38 Cell No.2 : 0.23
No.2C-3	0.51	Cell No.1 : 0.39 Cell No.2 : 0.59 Cell No.3 : 0.26
No.3C-2	0.52	Cell No.1 : 0.45 Cell No.2 : 0.39
No.3C-3	0.52	Cell No.1 : 0.35 Cell No.2 : 0.47 Cell No.3 : 0.46
No.4C-3	0.53	Cell No.1 : 0.52 Cell No.2 : 0.22 Cell No.3 : 0.46
No.4C-4	0.53	Cell No.1 : 0.35 Cell No.2 : 0.22 Cell No.3 : 0.46 Cell No.4 : 0.49

Table 6 on page 102 shows that, as expected, the cellular average set-up factors are generally lower than the functional ones, but the differences are not significant in all cases. This could be explained by the fact that average set-up factors are calculated by using design similarity data while jobs are grouped based on a weighted similarity data. Moreover, it is obvious that job cell assignments of Table 5 on page 99 could be improved by using more precise grouping methods. This would cause a direct reduction in average cellular set-up factors.

Unit Load Times Expression:

The unit load processing time on a given machine is calculated via equation (3.12) shown below and is consisted of three parts :

1. Initial set-up of the machine,
2. Actual operation time on the machine for each of the jobs in the unit load, and
3. A periodic machine reset or minor set-up times.

$$ULT_{k,l}^{u,c(n)} = [\,(ASF)^{f}\ ST_{l}^{c}\,] + [\,u\,MNK_{k} \times \bar{t}_{in}^{c}\,] + ASF^{f}[\,(\frac{u\,MNK_{k}}{RS_{\ l}})\,] \times MS_{l} \quad (3.12)$$

This equation is also applicable when unit load times are calculated for the cellular facilities. UNIT FORTRAN code determines all feasible combinations in equation (3.12) above by following the steps outlined in Figure 13 on page 113. Figure 12 on page 105 shows the flowchart for this code. Using three batches of job A on machine P for class 1 operation (No.2) to illustrate,

$(ASF)^{f} = 0.54$, $ST_{P}^{1} = 30$, $u = 3$, $\bar{t}_{P,2}^{1} = 2.3$ minutes, $MNK_{A} = 11$ parts, $RS_{p} = 20$ parts , and $MS_{p} = 2$ minutes. If three batches of job A (3 X 11 = 33 individual items) are assigned to machine P for a class 1 operation, machine P will be set-up once and reset after the first 20 of the 33 parts are processed. Using equation 3.12 ;

$$ULT_{A,P}^{3,1(2)} = [\,0.54 * 30\,] + [\,3 * 11 * 2.3\,] + [\,0.54\,\{\,int(\,(3 * 11)/20\,)\,\} * 2\,] = 93.18 \text{ minutes}$$

which is the amount of time machine P must be allocated for above operation including the set-up requirements. Table 7 on page 104 shows the number of batches for all twelve job types considered in problem set No.4. Jobs B, H, and Q have full last batches (indicated with f). The number of batches of Job A, for example, is found by dividing the mean daily demand by the maximum number of job A's that can be carried using a standard pallet (104/11). Fractional division result of 9.46 indicates that the first nine batches are full (9 x 11 = 99) and the tenth batch has five jobs (104 - 99).

Table 7. Batch Information of all Twelve Jobs

	Job A	Job B	Job C	Job D	Job E	Job F	Job H	Job Q	Job R	Job S	Job U	Job V
Number of Batches	10	15	18	19	28	13	24	19	17	9	17	15
Number of Items in Last Batch	5	12(f)	4	7	3	6	5(f)	5(f)	1	2	10	7

Appendix K contains a partial list of the total required machine times for all possible combinations. A full list of these combination is used as one of the input requirements of code STEP5 FORTRAN.

Summary

This Chapter has described the problem and explained the assumptions. Mathematical models for steps 1,2, and 5 were developed. Heuristic methods, when needed, were developed and explained along with secondary topics such as unit load parameters and job/cell grouping.

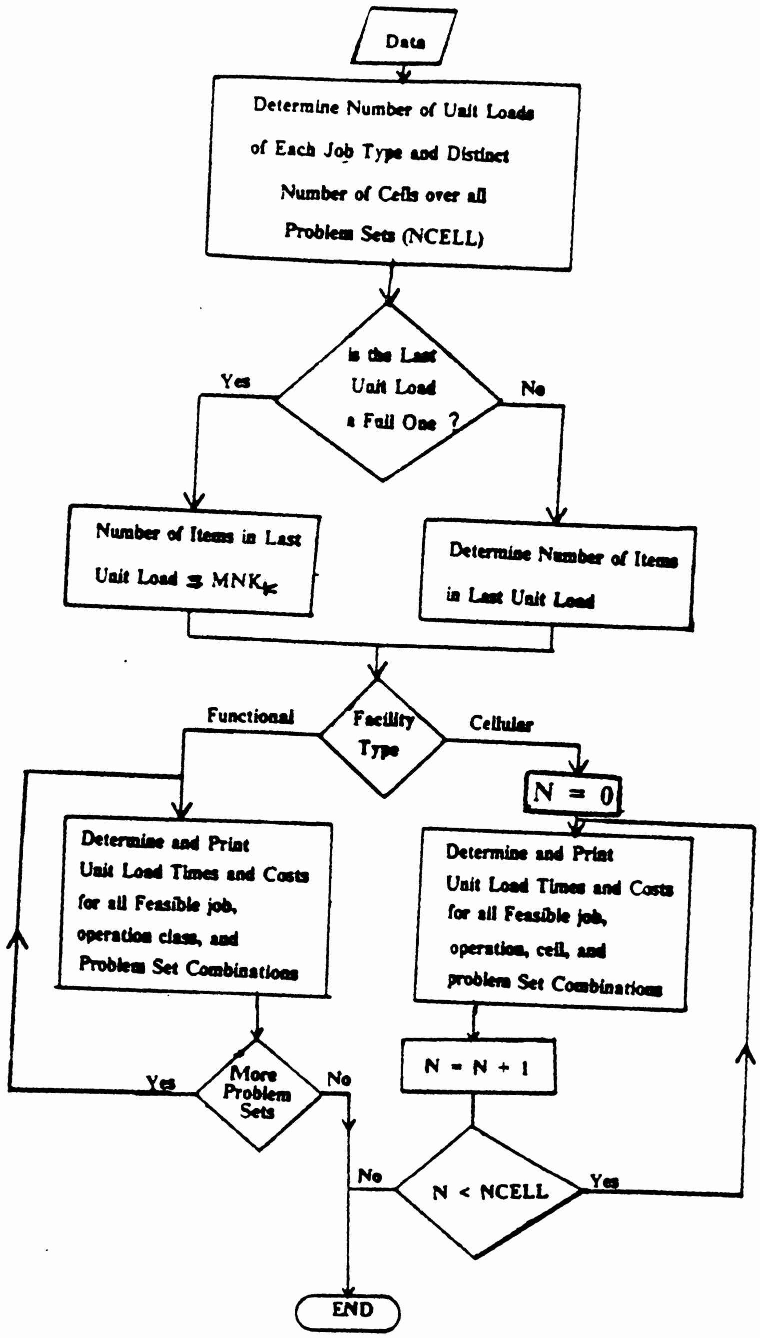


Figure 12. Flow Chart of UNIT FORTRAN Code

4.0 Solution of Hierarchical Mathematical Models (Stage One) and Examples

Four example problem sets are solved in this Chapter following discussions on how data sets are created for the steps in stage one.

4.1.1 Solution of Step 1

The model of step 1, Figure 6 on page 74, contains a stochastic right hand side and two stochastic coefficients: D_k, $1/t^c_{in}$, and, u_i^{up}. The objective function has no stochastic coefficients. As explained in Appendix F, this model corresponds to stochastic right hand side and constraint coefficient case (due to constraints 3.1.1. and 3.1.2) after term $u_i^{up} M_i$ is carried over to the left of the equality with a minus sign. Major difficulty arises with using a normal distribution for both operation times and daily demands in constraint 3.1.1 since it involves taking an inverse of a normal distribution. Appendix N contains the derivations of closed form expressions for both the inverse of a normal distribution and the product of two independent normal distributions (for steps 2F and 2C) which was accomplished after a lengthy search of various statistics and probability sources proved to be of little help. Even if the results of Appendix N is correct, they must still be applied to modify the chance constrained programming methodology of Charness and Cooper [130] for the case of non-normal (both normal x normal and 1/normal are not normal) technology coefficients. These tasks are rather complicated research areas which have not been investigated so far. To avoid such complications, it is necessary that operation times be treated as deterministic in stage one. In the simulation stage, stage two, both operation times and daily demands are treated as stochastic variables. Machine uptime ratios, u_i^{up}'s, can also be taken as deterministic (equal to their means) in step 1 of stage one since their variances are assumed to be small. If both t_{in}^{c} and u_i^{up} can be taken equal to their means, then only the constraints of type 3.2.1. need chance-constrained formulation. For example, consider operation No.2 of job A and machines P,J,K, and N from the data tables in Appendix D:

Only machines P and J can perform operation No.2 which belongs to a general operation class of 1. $D_A \sim N(104,18)$ and α_{k1} of ninety-nine percent corresponds to e_{a1} of 2.33.

$$\Pr\left[\, 480\left(M_{p,a,2}\frac{1}{2.3} + M_{j,a,2}\frac{1}{2.1}\right) \geq D_A \right] \geq 0.99 \tag{4.1}$$

This constraint is then converted into its deterministic equivalent as shown in Appendices A and F. Here, only the right hand side (RHS) or b_i element is stochastic and the resulting equivalent form, below, is still linear :

$$208.7\, M_{p,a,2} + 228.57\, M_{j,a,2} \geq 113.89 \tag{4.2}$$

Figure 41 on page 264 in Appendix F shows the complete step 1 expansion for this very small example.

4.1.2 Solution of Step 2F

Step 2F is more complicated than Step 1. This model determines the number of each of the available machine types to be allocated to each operation class area or department and, simultaneously, assigns each operation of each job to a machine type. In constraint 3.2.1 (capacity constraint), normally distributed terms, D_k and t^c_{in} are in product form causing difficulties as discussed above. If the operation time can be taken as deterministic, the product term will still be normally distributed with a mean of [$\overline{D}_k t^c_{in}$] and a variance expressed as [$(D_k)\,(t^c_{in})^2$]. The objective function of Step 2F has stochastic coefficients due to multiplication of stochastic daily demand with constant variable cost. Each such objective function coefficient is still normally distributed with a mean of [$\overline{D}_k VC^c_{in}$] and a variance term expressed as [$Var(D_k)\,(VC^c_{in})^2$]. The remaining part of the objective function is linear.

Stochastic Expansion of Step 2F

Only the objective function, Z, and the capacity constraints of Figure 7 on page 75 need to be formulated in the chance-constrained format because they contain stochastic coefficients which make the usual, absolute constraints and objective function optimization impossible. Instead, as discussed in Chapter one, the decision maker specifies a desired probability, α_k, of meeting a given machine capacity constraint. To illustrate the expansion of Step 2F, only operation class 1 (C1) of problem set No.1 (four job, four machine case) will be used :

- Jobs that need C1 operations: Job A for operation No.2, Job B for operation No.1, and Job C for operation No.3.
- Machines that can perform any C1 operation : Machines P and J.
- Stochastic objective function coefficients for above combinations: N(249.6,103.68) for (C1,P,A) [104 x 2.4 = 249.6 and 18 x 2.4 x 2.4 = 103.68], N(360,96) for (C1,P,B), N(378,123.93) for (C1,P,C), and N(406,142.97) for (C1,J,C).

- Stochastic coefficients of capacity constraints: N(239.2,95.22), N(306,69.36), N(434,163.37), N(218.4,79.38), N(270,54), and N(392,133.28) for the same combinations as above.
- α_k : Ninety-nine percent.
- T : 480 minutes since time losses due to machine failures have been accounted for in step 1.

This small example results in twenty-two zero-one assignment variables, X^c_{ik}'s, which appear both in capacity and assignment constraints, and the objective function Z. Using $k_1 = 1$ and $k_2 = 1$ as discussed in Appendix A, the objective function row, Z, would be as follows :

$$N(249.6,103.68)\, X^1_{p,b} + N(360,96)\, X^1_{p,b} + \ldots\ldots + N(161.2,43.24)\, X^5_{n,a} + \ldots\ldots +$$

$$\ldots\, N(518,232.73)\, X^6_{n,c} + \ldots\ldots + N(486,174.96)\, X^7_{n,c} \tag{4.3}$$

Similarly, the very first row of the constraints of type 3.2.1 is :

$$N(239.2,95.22)\, X^1_{p,a} + N(306,69.36)\, X^1_{p,b} + N(434,163.37)\, X^1_{p,b} \leq 480\, M_{P,1} \tag{4.4}$$

Each coefficient above is now stochastic.

Chance-constrained Formulation of Step 2F:

The objective function, Z, is not subject to chance-constrained format. It is desired that each type 3.2.1 constraint holds with at least a probability of α_k:

$$\Pr\left[\, \sum_{k\in K_c} D_k\, X^c_{ik} \sum_{n\in N_{ck}} t^c_{in} \leq T\, M_{ic} \qquad \text{for all } c, i \in I_c \,\right] \geq \alpha_k \tag{4.5}$$

Deterministic Equivalent of Step 2F:

Appendix A contains the formulas needed to transform a chance-constrained model with stochastic coefficients both in objective function and the constraints into deterministic equivalent format. Figure 42 on page 265 in Appendix F shows the deterministic equivalent form of the limited problem size described above. As seen in Figure 42 on page 265, both Z and type 3.2.1 constraints become nonlinear making the direct application of any currently available LP/MIP package infeasible. Also, an average problem size would be too large to use any of few available nonlinear programming packages although the nonlinear terms have a particular structure (square root of the sum of the zero-one variables) which may be exploited in conjuction with some nonlinear programming solution techniques. Then, linearization of all nonlinear terms may be a good way to solve the deterministic equivalent form of Step 2F.

Linearization of the Deterministic Equivalent of Step 2F:

The literature (Appendix B) shows that there is only one formal algorithm (CHAPS) developed to linearize and solve the deterministic equivalent of chance-constrained programs with normally distributed coefficients. The literature also provides only very small examples solved by some general nonlinear programming methods. In Appendix C, the CHAPS algorithm is compared against a much simpler to apply alternative which involves only an one step linearization of all nonlinear portions of both the objective and constraints via Naslund's approximation (Appendix B). Appendix C justifies the use of Naslund's approximation in this research because of the enormous savings in programming effort and computation. Appendices B and C show the details of the linearization procedure which involves the conversion of nonlinear expressions such as those that result when expressions like (4.4) are written in deterministic equivalent form. Equation (4.4) above is converted into the following form :

$$245.85\, X^1_{p,a} + 310.75\, X^1_{p,b} + 446.3\, X^1_{p,c} - 480\, M_{P,1} \leq -18.51 \tag{4.6}$$

Figure 44 on page 267 in Appendix F shows linearized segments of the deterministic equivalent of step 2F for the small example considered. Once linearized, it then becomes a matter of using a mixed integer package to solve all steps of the hierarchical procedure. The MPSIII package was used in this research since this package is available in VPI's mainframe, and it is efficient and capable of handling very large problems with hundreds of decision variables. Appendix G gives a brief description for this package. A similar expansion, chance-constrained formulation, deterministic equivalent, and linearization steps are performed for step 2C (not shown). Notation is different between steps 2F and 2C as step 2C is written with respect to operations which belong to one of the general operation classes, c's, used in step 2F.

4.1.3 Input Generation For Steps 1 and 2 (2F and 2C)

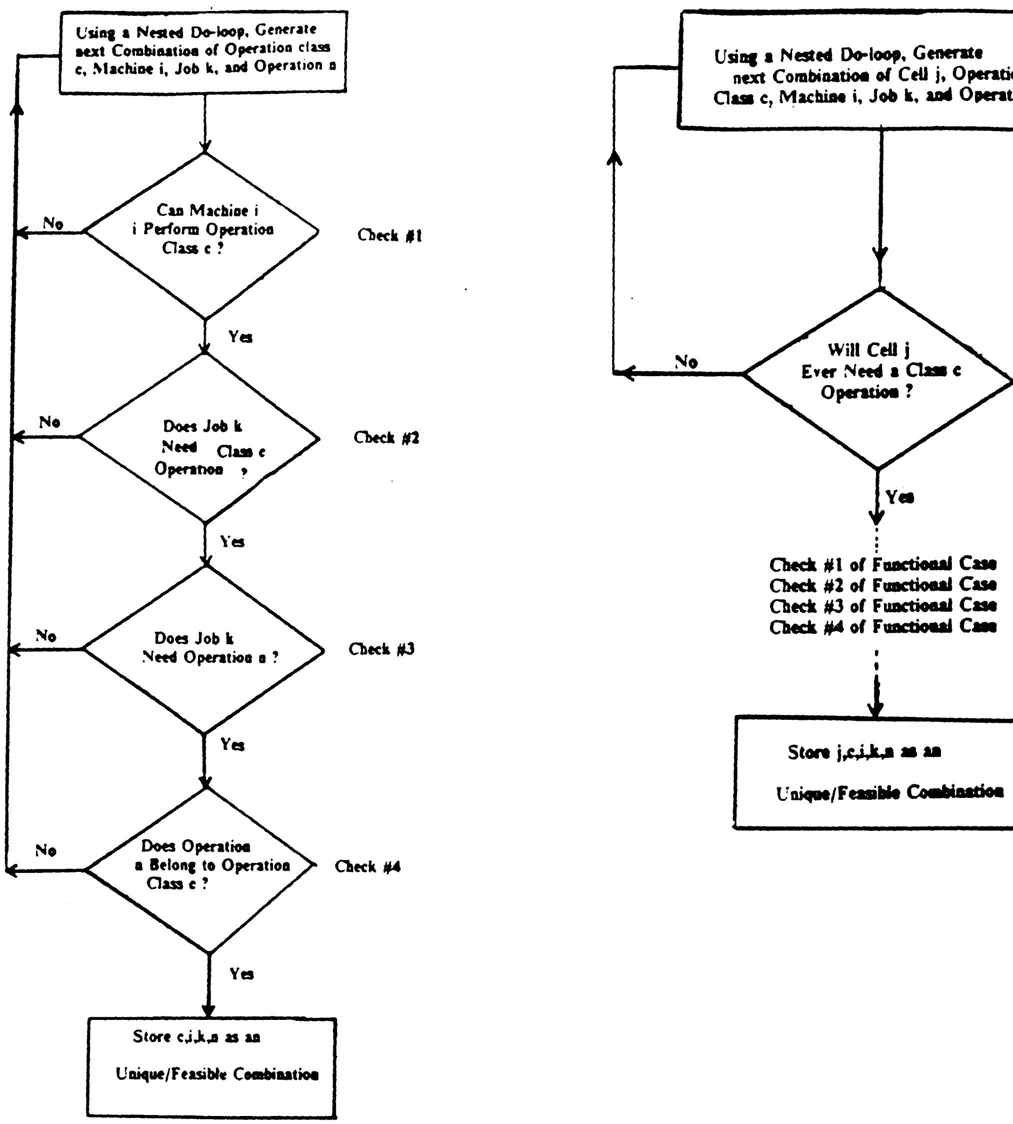
Fortran codes Step1 FORTRAN and Step2 FORTRAN (Appendix J) are used to facilitate the expansion of the first three models of Chapter three so that mixed integer solution package could be applied. Initially, smaller problems (see Appendix F) were written out manually and then used to verify the results obtained from the codes. Manual input generation would be not only unreliable, but also very time consuming even with problems of moderate sizes. Since most realistic problems can easily involve dozens of different jobs and available machine types, the use of computer code in input generation is justified for accuracy and ability to alter the data for new runs.

Input Generation :

1. Read all data.
2. Determine all feasible job, operation, class, and machine (step 2F) and job, operation, cell, machine (step 2C) combinations as outlined in Figure 13 on page 113.
3. Determine number of capacity and assignment constraints.
4. Calculate objective function and constraint coefficients for above combinations.

5. Linearize all nonlinear portions of any row or objective function which result from conversion into deterministic equivalent form.
6. Determine total number of rows and their right hand side values.
7. Finally, write out variable, row, coefficient, right hand side, integer, zero-one, and nonnegativity information in a format acceptable to MPSIII package.

Figure 14 on page 114, Figure 15 on page 115, and Figure 16 on page 116 show how input is generated via FORTRAN programming. Appendix K shows segments of the resulting outputs for each of the four problem sets using the FORTRAN codes given in Appendix J.



Functional **Cellular**

Figure 13. Selection of Feasible Combinations

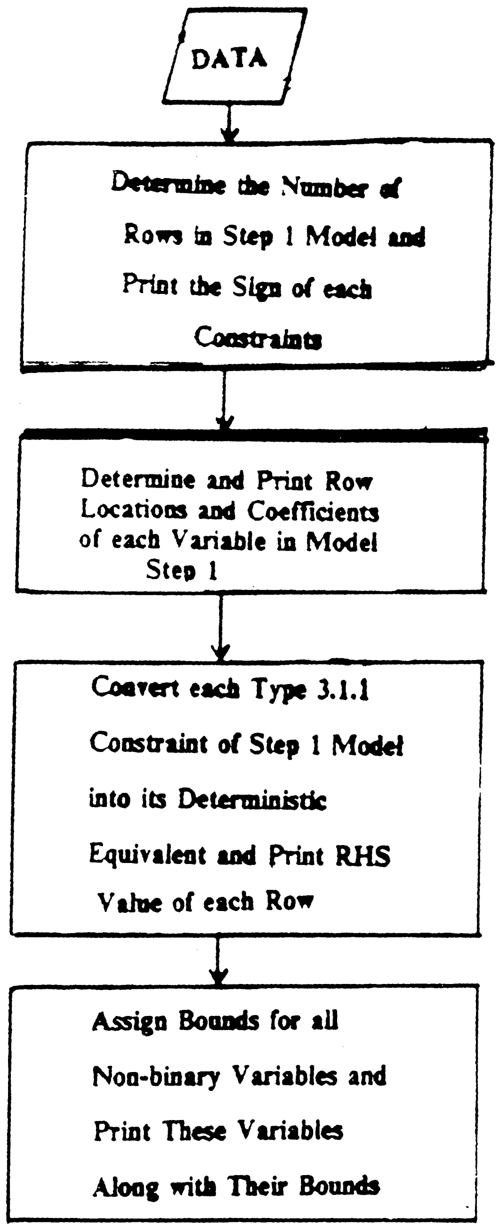


Figure 14. Main Tasks Performed by STEP1 FORTRAN Code

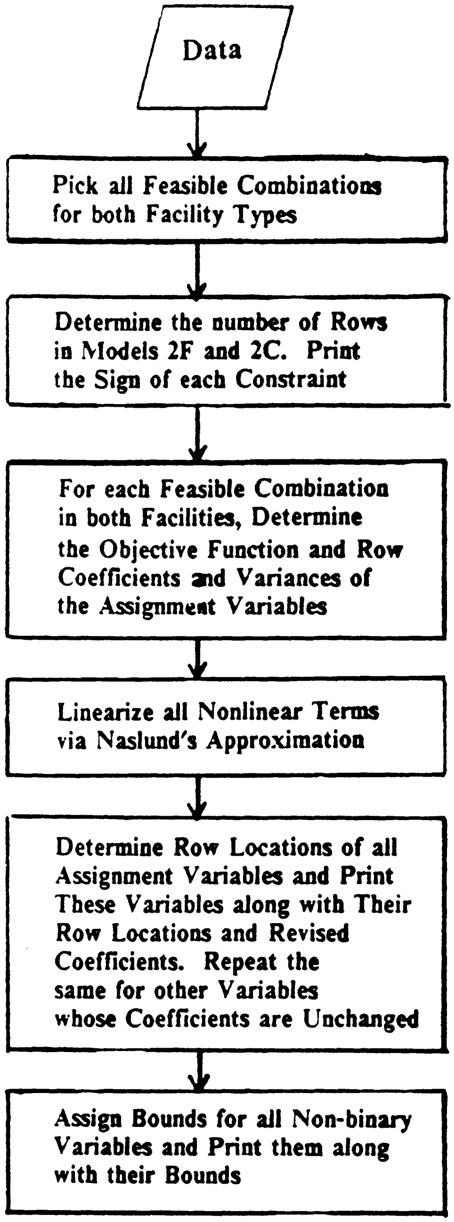


Figure 15. Main Tasks Performed by STEP2 FORTRAN Code

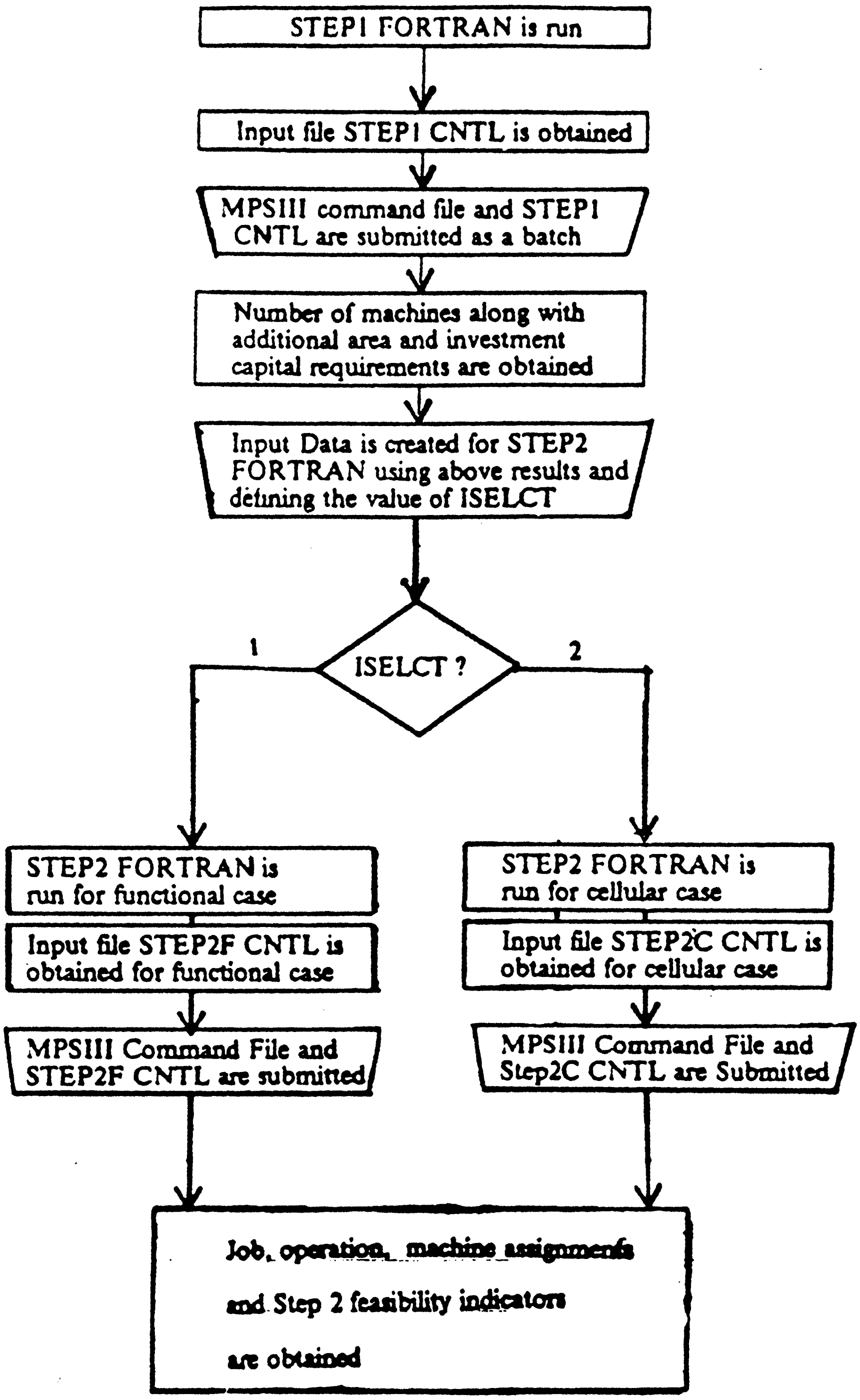


Figure 16. Input/Output for Steps 1 and 2

4.1.4 Solution of Step 5 (5F and 5C)

Mathematical Models of 5F and 5C are shown in Figure 9 on page 86 and Figure 10 on page 87 in the previous Chapter. As stated earlier, it is no longer necessary to consider demand as a stochastic variable. Fortran code of STEP5 FORTRAN is used in creating the necessary input file needed by the MPSIII package. Figure 17 on page 118 shows the flowchart of this code. Appendix E contains partial input for this step.

4.1.5 Numerical Examples

Four problem sets are used, but each problem set can be enlarged without the basic data limits which consists of seven operation classes in the functional case, machine and job specifications, operation time and variable cost matrix, and loss sales cost data as shown in Appendix D. Input variables which may be altered are available resources, fixed in this research, and the insurance level of α_k for each job k.

Feasibility Check For All Solutions:

The solution of step 2F or step 2C is feasible if:

1) if all AC_i^p, additional capacity requirement indicators, are zero in the Step 2 solution, and

2) additional resource requirements of Step 1, EC and AA, are also zero.

Whenever an infeasible solution is found, Steps 4 and 5 must be used. Otherwise, step 3 (implied) is followed by modified step 5. It is possible that step 2 can result in some non-zero AC_i^p values even though both EC and AA may be zero in step 1.

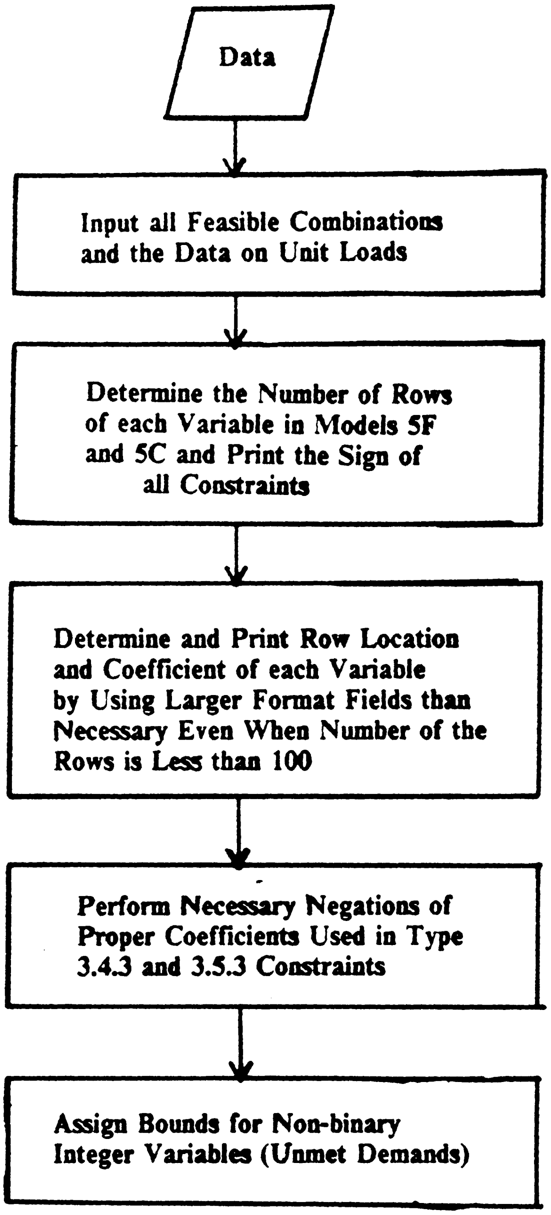


Figure 17. Main Tasks Performed by STEP5 FORTRAN Code

4.1.6 Problem Set No.1

Step 1 solution of problem set No.1 is shown in Table 8 on page 119.

Table 8. Step 1 Solution of Problem Set No.1

EC : $333K	AA : 0
MP : 5.0	MJ : 3.0
MK : 7.0	MN : 3.0

This solution shows that additional investment capital of $333,000 is needed to meet the expected demand by purchasing the machine mix shown in Table 8. For example, MP of 5 indicates the that number of type P machines, M_P, is suggested as 5 by step 1 solution. AA of zero indicates that the available plant space is sufficient. This machine mix is to be distributed to seven departments in functional and two cells in cellular formation cases. Step 1 solution, however, does not consider unique job, operation, machine assignment requirements and the capacity defined above may be insufficient in steps 2F and 2C when machines are not fully utilized because of this requirement.

Table 9 on page 120 shows step 2F solution for this set in three parts:

1. Objective function values for continuous and integer solutions.
2. Machine assignment values for continuous and integer solutions.
3. Job, operation, machine assignments.

Table 9. Step 2F Solution for Problem Set No.1

	Integer Solution :	Continuous Solution:	
Z:	$17316.33	$5267.80	
Machine Allocation Variables :			
MPC1	: 1	1.42	Department No.1
MJC1	: 2	0.68	
MPC2	: 3	2.30	Department No.2
MKC3	: 2	1.67	Department No.3
MNC3	: 1	0.88	
MJC4	: 2	2.32	Department No.4
MKC5	: 5	5.33	Department No.5
MNC5	: 1	0.09	
MNC6	: 3	2.03	Department No.6
MPC7	: 2	1.28	Department No.7
Job/Operation-Class/Machine Assignment Variables:			
XC1PA	: 0	n.a.	Department No.1
XC1PC	: 1	n.a.	
XC1JA	: 1	n.a.	
XC1JB	: 1	n.a.	
XC2PB	: 1	n.a.	Department No.2
XC2PC	: 1	n.a.	
XC2PD	: 1	n.a.	
XC3KA	: 0	n.a.	Department No.3
XC3KD	: 1	n.a.	
XC3NA	: 1	n.a.	
XC4JA	: 1	n.a.	Department No.4
XC4JC	: 1	n.a.	
XC5KA	: 1	n.a.	Department No.5
XC5KB	: 1	n.a.	
XC5NA	: 0	n.a.	
XC5NB	: 0	n.a.	
XC6NC	: 1	n.a.	Department No.6
XC6ND	: 1	n.a.	
XC7PB	: 1	n.a.	Department No.7
Additional Capacity Requirement Indicator Variables:			
ACP	: 20 %	0 %	
ACJ	: 33 %	0 %	
ACK	: 0 %	0 %	
ACN	: 67 %	0 %	

n.a. : Not applicable.

Table 9 on page 120 shows that, according to the optimal continuous solution, department No.1 should receive 1.42 of P type and 0.68 of J type machines (MPC1 and MJC1), but the integer solution requires that these assignment be 1 and 2. XC1JA or $X^1_{j,a}$ of 1 indicates that job A is assigned to machine J in department 1 for class 1 operation job A needs (No.2). The increase in the objective value from \$5267.80 to \$17316.33 is largely due to penalty factors associated with the non-zero AC_i^p values. Using a BM of \$10000, the actual total variable cost of the integer solution is :

$$\$17316.33 - \$10000\,(0.20 + 0.33 + 0.67) = \$5316.33/\text{Day}.$$

The integer solution is infeasible due to the non-zero AC_i^p values which require the use of steps 4F and 5F to remain within the resource constraint bounds. For example, ACJ, (AC_J^p) of 33 percent indicates that the number of type J machines should be 33 percent more than the step 1 solution shown in Table 8 on page 119 if unique job, operation, machine assignments are to be maintained to provide a savings in set-up and production control. Then, the number machine J's should increase to four from the step 1 value of three. These four type J machines are assigned to departments 1 and 4 (two each). Similarly, ACP of twenty percent indicates that the number of type P machines should be twenty percent higher than what step 1 solution indicates: (1 + 0.2) 5 = 6 which is the sum of the number of type P machines assigned to departments 1, 2, and 7 as shown in Table 9 on page 120.

Table 10 on page 122 shows step 2C solution with two cells in problem set No.1. Interpretation of Table 10 on page 122 is similar to that discussed above.

Table 10. Step 2C Solution for Problem Set No.1

	Integer Solution :	Continuous Solution:	
Z:	$ 8623.53	$5265.49	
Machine Allocation Variables :			
MPC1	3	2.69	Cell No.1
MJC1	1	0.97	
MKC1	5	5.38	
MNC1	1	0.91	
MPC2	2	2.31	Cell No.2
MJC2	2	2.03	
MKC2	2	1.62	
MNC2	3	2.09	
Job/operation-cell/machine Assignment Variables:			
X1PA2	0	n.a.	Cell No.1
X1PB1	1	n.a.	
X1PB4	1	n.a.	
X1PB20	1	n.a	
X1JA2	1	n.a.	
X1JA11	1	n.a.	
X1JB1	0	n.a.	
X1KA8	0	n.a.	
X1KA14	0	n.a.	
X1KB13	1	n.a.	
X1NA8	1	n.a.	
X1NA14	1	n.a.	
X1NB13	0	n.a.	
X2PC3	0	n.a.	Cell No.2
X2PD5	1	n.a.	
X2JC3	1	n.a.	
X2JC12	1	n.a.	
X2KD9	1	n.a.	
X2NC18	1	n.a.	
X2ND9	0	n.a.	
X2ND17	1	n.a.	
Additional Capacity Requirement Indicator Variables:			
ACP	0	0	
ACJ	0	0	
ACK	0	0	
ACN	33 %	0	

MPC1 = M_p^1 (Number of type P machines in cell 1),

X2NC18 = $X^2_{n,c,18}$ (Operation No.18 of job C, pre-assigned to cell 2, is assigned to machine N).

Actual total variable cost = $8623.53 - 0.33 (10000) = $ 5323.53/Day.

Step 4F Solution for Problem Set No.1:

Step 1 solution as shown in Table 8 on page 119 indicates that available capital is not sufficient to purchase all the machines. The step 2F solution requires additional machines (Table 9 on page 120) for all machine types except machine K. Since step 2F has increased the required machine mix, total investment and area requirements must be recalculated.

Table 11. Determination of Shortages in Set No.1 (4F)

Machine Type	Step 2F Requirement	Total Capital Required	Total Area Required
P	6	\$582K	336 ft^2
J	4	\$245K	160 ft^2
K	7	\$525K	336 ft^2
N	5	\$400K	275 ft^2
Total Need	22	\$1751K	1107 ft^2
Available	n.a.	\$1100K	1350 ft^2
Shortage	n.a.	\$651K	0 ft^2

Legend : For machine P, 6 x \$97 = \$582K and 6 x 56 = 336 ft^2 .

Table 11 shows that the EC of \$333,000 of step 1 has now increased to \$651,000 due to unique job operation machine assignments and integral machine assignment requirements. Plant space is still sufficient in this case. The total number of machines will be reduced until \$651,000 worth of machines have been removed from the machine mix suggested in Table 9 on page 120. Step 4 reduction procedure outlined in Chapter three is used below. The slack machine amounts are found by taking the difference between the integer and fractional machine assignments when integer assignments is larger than the fractional or continuous assignment. These slack amounts are tabulated next and used in construction of Table 12 on page 124.

Machine P :	0.70, and 0.72	in departments 2, and 7.
Machine J :	1.32,	in department 1.
Machine K :	0.33	in department 3.
Machine N :	0.12, 0.91, 0.97	in departments 3, 5, and 6.

Table 12. Elimination of Machines to Meet Constraints (Set No.1 Step 4F).

Iteration Number	Machine Type	Taken From Department	Current Assignment	Reduced to Assignment	Cumulative Savings
1	N	No.5	1	0	$ 80K
2	K	No.5	5	4	$155K
3	J	No.1	2	1	$235K
4	N	No.6	3	2	$296K
5	P	No.7	2	1	$393K
6	P	No.2	3	2	$490K
7	K	No.3	2	1	$565K
8	K	No.5	4	3	$662K

Actual capacity needed for machine K in department No.5 is found to be 1774 minutes or 3.69 machines. Then, at least one of the five machine K's assigned to department No.5 is redundant. The next five iterations are carried out by selecting slacks in decreasing order. Once there are no more slacks, iteration No.8 is performed by reducing another type K machine from department No.5 since other departments only have two or less machines of any kind remaining. After iteration No.7, cumulative cost reduction in investment requirement amounts to only $565,000 and falls short of $651,000 by $86,000. Since $86,000 is more than the cost of the lowest cost machine (J with $61,000), the elimination process continues. The final machine mix of the functional facility is shown in Table 13 on page 125.

Table 13. Final Functional Machine Mix of Problem Set No.1

	Department Number						
Machine	**1**	**2**	**3**	**4**	**5**	**6**	**7**
P	1	2					1
J	1			2			
K			1		3		
N			1			2	

Step 4C Solution of Set No.1:

As in step 4F, resource shortages are calculated below.

Table 14. Determination of Shortages in Set No.1 (4C)

Machine Type	Step 2C Requirement	Total Capital Required	Total Area Required
P	5	$ 485K	280 ft^2
J	3	$ 183K	120 ft^2
K	7	$ 525K	336 ft^2
N	4	$ 320K	220 ft^2
Total Need	19	$1513K	956 ft^2
Available	n.a.	$1100K	1350 ft^2
Shortage	n.a.	$ 413K	0 ft^2

The plant area constraint is not binding, but $413,000 worth of machines must be removed from the machine mix suggested in step 2C. To do so, qualified machine capacity slack amounts are determined first. It is noted that the actual capacity needed for machine K in cell No.1 is 2.4 machines.

Machine P :	0.31	in cell No.1.
Machine J :	0.03	in cell No.1.
Machine K :	0.38	in cell No.2
Machine N :	0.09 and 0.91	in cells No.1 and 2. .

Table 15. Elimination of Machines to Meet Constraints (Set No.1 Step 4C).

Iteration Number	Machine Type	Taken From Cell	Current Assignment	Reduced to Assignment	Cumulative Savings
1	K	No.1	5	3	$150K
2	N	No.2	3	2	$230K
3	P	No.1	3	2	$327K
4	K	No.2	2	1	$402K

At the end of iteration No.4, $402,000 worth of machines have been removed with $9000 worth of machines remaining to be reduced. Since the machine with the lowest cost (J) is more expensive than this amount, the elimination process ends.

Table 16. Cellular Machine Mix of Problem Set No.1

	Cell Number	
Machine	**1**	**2**
P	2	2
J	1	2
K	3	1
N	1	2

Departmentalization of Cells:

Any time operating constraints prevent installation of a sufficient number of machines, operation machine assignments of step 2C shown in Table 10 on page 122 can not be realized. To determine the amount of production level of each job in a given cell, first remaining machines in each cell should be divided into necessary number of mini-departments.

Table 17. Job Operation Need and Cell Operation Capability Analysis for Problem Set No.1

Cell No.	Job Type	Operation Class Needs in Cell	Least Needed Operation Classes	Operation Class Capability of Cell
1	A,B	1,2,3,4,5,7	2,3,4,7	1,2,3,4,5,6,7
2	C,D	1,2,3,4,6	1,3,4	1,2,3,4,5,6,7

Table 17 shows that while available machines cover all necessary operation classes in both cells, there are not enough machines to allocate at least one machine to each class or mini-department area. For example, Cell No.1 has only one type J machine and two type P machines. These machines are the only ones that can cover operation class needs of 1, 2,4, and 7. Machine J is the only machine type that is capable of performing class 4 operations, then the two type P machines must be allocated to class areas of 1, 2, and 7. Since operation classes of 2 and 7 are both needed less often than operation class 1, one of the two type P machines must be either shared for operation classes of 2 and 7 or one of the machines, N or K, should be exchanged for a machine P eliminated in iteration No.3 above. Exchange of machine N for machine P reduces cumulative savings amount to $385000 leaving $28000 worth of machines to be reduced. Since $28000 is also less than the cost of the least expensive machine, the exchange can be easily made. Table 18 shows the departmentalization of cell's machine mix for this small example.

Table 18. Departmentilization of Cellular Machine Mix in Problem Set No.1

Mini-Department	Cell No.1	Cell No.2
1	P	P, 1/2 J (*)
2	P	P
3	2K	K
4	J	J, 1/2 J (*)
5	2K,N	-
6	-	2 N
7	P	-

After the first assignment pass, machine types N in both cells are left over and are assigned to class areas or mini-departments 5 in cell No.1 and 6 in cell No.2 since these are feasible operation classes for type N machines and are not on the least needed operation class column in Table 17 on page 126. In cell No.2, the remaining machine J is divided between mini-departments 1 and 4 since both of these departments are on the least needed column and machine J can only perform operation classes of 1 and 4.

* **Note :** Exact mixed integer solution of step 5C (later) shows that this machine J is left entirely idle. Then, this machine can be removed from the machine mix reducing amount of fixed cost portion of the final item cost for cell No.2.

Step 5F Solution of Problem Set No.1:

It is now necessary to determine how many unit loads of each of the jobs (A,B,C,D) can be fully machined using the machine mix shown in Table 13 on page 125. The current problem was used as example in Chapter three, so the details of the solution will not be repeated here. Instead, the solution of step 5F for Problem set No.2 is discussed later. MPSIII took 0.08 minutes of CPU time in finding the continuous optimum solution for the reduced form of the input file Step5 CNTL with 407 binary variables and 468 rows. Table 19 below shows the results.

Table 19. Step 5F Solution of Problem Set No.1

Department No.	Assignment Decisions
1	16C to P(1)/ 8A and 10B to J(1)
2	4B and 13D to P(1)/ 6B and 16C to P(2)
3	8A and 3D to K(1)/ 10D to K(2)
4	8A to J(1) / 16C to J(2)
5	6B to K(1)/ 6A to K(2) 2A and 4B to K(3)
6	16C to N(1) / 13D to N(2)
7	10B to P(1)

Notation : P(1) refers to the first machine P in the department.

According to Table 19, the functional facility is able to fully machine eight unit loads of Job A (Job A visits departments 1, 3, 4, and 5) or 8 X 11 = 88 Job A items, ten unit loads of Job B (120 items), sixteen unit loads of of job C (128 items), and thirteen unit loads of Job D; thus, leaving sixteen (104-80) items of Job A, sixty items of Job B (180 - 10 x 12), twelve items of Job C, and fifty-seven items of Job D as lost sales. This results in total daily production of 466 combined items and daily lost sales cost of :

$$16 * \$34/A + 60 * \$56/B + 12 * \$23/C + 57 * \$28/D = \$5776/day.$$

Final Job-machine assignments:

Table 19 on page 128 also indicates, for example, that :

- Machine P in department No.1 is assigned to process all job C's to be produced while machine J of the same department is assigned to perform the class No.1 operation needs of jobs A and B.
- Assignments at department No.5 show how step 5 solution may, at times, partitions total number of unit loads of jobs among the machines of a department.
- Job B is the only job type that needs to visit mini-department No.7 or it is the only job needing a class No.7 operation. Machine P is the only available machine in this mini-department as a result of step 4F and all type B jobs are assigned to machine P in mini-department No.7.

Other assignments shown in Table 19 on page 128 can be interpreted similarly.

Step 5C Solution of Problem Set No.1:

Table 20 below shows the resulting assignments if two cells are used.

Table 20. Step 5C Solution of Problem Set No.1

Mini-Department No.	Cell No.1	Cell No.2
1	5A to P(1) and 14B to P(1)	13C to P(1)
2	14B to P(1) 2B to P(1) for Class No.7 op.	13C to P(1) and 11D to P(1)
3	7A to K(1) 2B to K(2) for class No.5 op. 2A to K(2) for class No.5 op.	11D to K(1)
4	7A to J(1) 2A to J(1) for class No.1 op.	13C to J(1)
5	6B to K(1) and 1B to K(2) 5A to K(2) and 5B to K(3)	n/a
6	n/a	13C to N(1) and 11D to N(2)
7	12B to P(1)	n/a

Table 20 indicates that the cellular facility with two cells is not able to produce as many fully machined job items (459) as the functional facility, but the cellular facility incurs less total daily lost sales cost by producing more of Job B which has the highest lost sales cost value (14 vs 10 unit loads under functional facility). The production levels of each item are 77 (A), 168 (B), 104 (C), and 110 (D). Using the amount of unmet demand for each job, total daily lost sales cost is found as

$$27 * \$34/A + 12 * \$56/B + 36 * \$23/C + 77 * \$28/D = \$4574/day.$$

In cell No.1 above, post step 5 analysis increases the production level of job A from five to seven unit loads and job B from tvelwe to fourteen unit loads by transferring two unit loads of job A to mini-department No.4 for class No.1 operation as mini-department No.1 can only process five unit loads of job A and fourteen unit loads of job B (extra two unit loads of job B is able to stay with the original tvelwe unit loads). Similarly, two unit loads of job B is transferred to mini-department No.2 for class No.7 operation work (in short notation : 2B to No.2 for No.7). Other transfers, in short notation, are 2A to No.3 for No.5, 2B to No.3 for No.5, and 2A to No.4 for No.1. Post step 5C analysis does not result in any increases in the production levels of jobs C and D of Cell No.2.

4.1.7 Problem Set No.2

Table 21. Step 1 Solution of Problem Set No.2

EC :	\$775K	AA :	71 ft^2
MP :	2.0	MJ :	6.0
MK :	13.0	MN :	5.0
MW :	3.0	MZ :	1.0

For this problem set, step 1 indicates that neither of the two resources, investment capital and area, is sufficient to acquire all the machines shown in Table 21. As in problem set No.1, infeasible step 1 solution assures that step 2 solutions will be infeasible for both functional and cellular environments and therefore require higher amounts of both resources. The revised (reduced) form of the current step 1 machine mix will be distributed to seven departments and two or three cells at the end of step 4. Next, machine allocations to departments and cells and job operation machine assignments are given using a different format than that used for problem set No.1. Table 22 shows integer and continuous machine assignments in step 2F.

Table 22. Step 2F Solution for Problem Set No.2.

	Machines					
	P	**J**	**K**	**N**	**W**	**Z**
Department 1 :	1 (0.06)	3 (3.28)				1 (0.52)
Department 2 :	2 (0.25)				2 (2.88)	
Department 3 :			4 (4.06)	1 (0.53)	1 (0.08)	
Department 4 :		3 (2.72)			1 (0.05)	
Department 5 :			9 (8.94)	1 (0.14)		
Department 6 :				5 (4.33)		1 (0.06)
Department 7 :	2 (1.69)					1 (0.42)
Total Need :	5	6	13	7	4	3
Available :	2	6	13	5	3	1
Additional Need :	150 %	0 %	0 %	40 %	33 %	200 %

Total Variable Costs and Job Machine Assignments for Step 2F:

Variable cost is the objective function value in models 2F and 2C and is based on the 0/1 assignments shown below.

Continuous Solution : $9448.43 (Machine allocations shown in parenthesis above)

Integer Solution : $51665.13, but actual (infeasible) integer solution has the objective function value of $9365.13 ($51665.13 - $10000 (1.50 + 0.4 + 0.33 + 2.0)). The difference in variable costs between the integer and continuous solutions is due to shifting a small portion of the job operation assignments from the optimal machines to others.

Assignment Variables for each department in Problem Set No.2F.

Job A :	XC1JA	XC3WA	XC4WA	XC5KA	
Job B :	XC1ZB	XC2PB	XC5KB	XC7PB	
Job C :	XC1PC	XC2WC	XC4JC	XC6ZC	
Job D :	XC2WD	XC3KD	XC6ND		
Job E :	XC1JE	XC3KE	XC6NE		
Job F :	XC1JF	XC3NF	XC5KF	XC6NF	XC7ZF
Job H :	XC1JH	XC2PH	XC4JH	XC5KH	XC6NH

XC3WA indicates that $X^3_{w,a} = 1$ is chosen by the mathematical model, and the class 3 operation need of job A (No.8) is assigned to machine W in department No.3. Table 23 shows machine amounts in step 2C-2 solution.

Table 23. Step 2C Solution for Problem Set No.2 with 2 Cells (2C-2).

Machine	**Cell 1**	**Cell 2**	**Total Need**	**Available**	**Additional Need**
P	2 (1.96)	1 (0.04)	3	2	50 %
J	3 (3.64)	3 (2.36)	6	6	0 %
K	11 (10.11)	2 (2.88)	13	13	0 %
N	2 (2.22)	4 (2.78)	6	5	20 %
W	2 (1.33)	1 (1.67)	3	3	0 %
Z	1 (0.94)	1 (0.06)	2	1	100 %

Total Variable Costs and Job Machine Assignments for Step 2C-2:

Continuous Solution : $9428.74 (Machine allocations shown in parenthesis above)

Integer Solution : $26459.27, but actual (infeasible) integer solution has the objective function value of $9459.27 ($26459.27 - $10000 (0.50 + 0.2 + 1.0)). The difference in variable costs between the integer and continuous solutions is due to shifting a small portion of the job operation assignments from the optimal machines to others.

Assignment Variables for Cell No.1 Problem Set No.2C-2

Job A :	X1PA2	X1JA11	X1KA8	X1KA14	
Job B :	X1PB20	X1JB1	X1KB13	X1WB4	
Job F :	X1JF3	X1KF8	X1KF13	X1NF18	X1ZF20
Job H :	X1JH2	X1JH11	X1KH14	X1NH18	X1WH5

For example, operation No.11 of job H is assigned to a group of type J machines in cell 1 (X1J11).

Assignment Variables for Cell No.2 Problem Set No.2C-2

Job C :	X2JC3	X2JC12	X2NC18	X2WC4
Job D :	X2PD5	X2KD9	X2ND17	
Job E :	X2JE1	X2NE8	X2ZE16	

Table 24. Step2C Solution for Problem Set No.2 with 3 Cells (2C-3).

Machine	Cell 1	Cell 2	Cell 3	Total Need	Available	Additional Need
P	3 (1.92)	1 (0.05)	1 (0.03)	3	2	150 %
J	3 (1.82)	3 (3.62)	0 (0.56)	6	6	0 %
K	6 (8.35)	5 (1.77)	2 (2.89)	13	13	0 %
N	3 (1.37)	2 (1.77)	3 (1.86)	8	5	60 %
W	2 (0.65)	1 (1.31)	2 (1.04)	5	3	67 %
Z	1 (0.90)	1 (0.06)	2 (0.04)	4	1	300 %

Total Variable Costs and Job Machine Assignments for Step 2C-3

Continuous Solution : \$9441.71 (Machine allocations shown in parenthesis above)

Integer Solution : \$66879.97. Actual (infeasible) integer solution has the objective function value of \$9179.97 (\$66879.97 - \$10000 (1.50 + 0.6 + 0.67 + 3.0))

Assignment Variables for Cell No.1 Problem Set No.2C-3:

Job A :	X1JA2	X1KA8	X1JA11	X1KA14	
Job B :	X1PB20	X1PB1	X1KB13	X1WB4	
Job F :	X1PF3	X1WF8	X1NF13	X1NF18	X1ZF20

Assignment Variables for Cell No.2 Problem Set No.2C-3

Job C :	X2JC3	X2JC12	X2ZC18	X2WC4	
Job H :	X2PH5	X2JH2	X2JH11	X2KH14	X2NH18

Assignment Variables for Cell No.3 Problem Set No.2C-3

Job D :	X3WD5	X3ND9	X3ZD17
Job E :	X3ZE1	X3KE8	X3NE16

Step 4F Solution for Problem Set No.2:

Table 21 on page 131 shows that the EC is \$775000 and AA is 71 ft². Calculation of resource shortages (not shown) indicate that these amounts increase to \$1,511,000 and 539 ft² over the available amounts listed in Chapter three. The elimination process for this case is given for the last time and only the resulting machine mixes are tabulated after this case. Further analysis of capacity allocations and job machine assignments indicate that step 2F has resulted in some redundant machines and these machines are first eliminated before slacks are considered. Table 25 on page 135 shows step 4F solution process for problem set No.2.

Table 25. Elimination of Machines to Meet Constraints (Set No.2 Step 4F).

Iteration Number	Machine Type	From Department	Current Assignment	Reduced to Assignment	Cumulative Savings in Capital	in Area
1	K	No.3	4	3	$ 75K	48 ft²
2	K	No.5	9	5	$ 375K	240 ft²
3	N	No.6	5	2	$ 615K	405 ft²
4	J	No.4	3	2	$ 676K	445 ft²
5	K	No.5	5	4	$ 751K	493 ft²
6	K	No.5	4	3	$ 826K	ENDED
7	J	No.1	3	2	$ 887K	
8	K	No.3	3	2	$ 962K	
9	K	No.5	3	2	$1037K	
10	W	No.2	2	1	$1120K	
11	J	No.1	2	1	$1181K	
12	N	No.6	2	1	$1261K	
13	P	No.2	2	1	$1358K	
14	J	No.1	2	1	$1419K	
15	P	No.7	2	1	$1455K	ENDED

Enough machines are removed at the 6^{th} iteration to satisfy the area constraint. It takes additional iterations to be within the $56,000 ($1,511,000 - $1,455,000) of the investment constraint where elimination stops since $56,000 is less than the cost of the lowest priced machine. Step 4C is not shown. Table 26 on page 136 shows the final machine allocations in functional departments. For example, department No.1 is allocated three machines (P, J, and Z) to perform class 1 operations of operation No.1, 2, and 3. These machines take 1.7, 1.5, and 1.8 minutes to perform, e.g., operations No.1, 2, and 3 at the variable cost of $2.0, $2.3, and $1.7 as shown in Table 64 on page 249 of Appendix D. Tables from Table 27 on page 136 through Table 30 on page 138 show applications of steps 2C and 4C to subsets 2C-2 and 2C-3 of problem set No.2.

Table 26. Final Functional Machine Mix of Problem Set No.2

	Department Number						
Machine	1	2	3	4	5	6	7
P	1	1					1
J	1			2			
K			2		2		
N			1		1	1	
W		1	1	1			
Z	1					1	1

Table 27 shows that both cells in problem No.2C-2 are assigned the same machine mix.

Table 27. Cellular Machine Mix of Problem Set No.2C-2

	Cell Number	
Machine	1	2
P	1	1
J	2	2
K	2	2
N	2	2
W	1	1
Z	1	1

Next, each cell was departmentalized by dedicating group of machines to perform a specific operation class in each cell. Class area refers to such mini-departments in Table 28 on page 137.

Table 28. Departmentilization of Cellular Machine Mix in Problem Set No.2C-2

Mini Department	Cell No.1 (*)	Cell No.2
1	2 J	Z,J
2	P	P
3	K	2 K, W
4	W	J
5	N,2 K	-
6	N	2 N
7	Z	-

(*) An extra machine K is added to cell No.1 in Table 28 since total investment cost of the machine mix shown above is only $1,426,000 while available budget is at $1,510,000.

Table 29 and Table 30 on page 138 show the results of above procedures for problem set No.2 with three cells.

Table 29. Cellular Machine Mix of Problem Set No.2C-3

	Cell Number		
Machine	1	2	3
P	1	1	1
J	1	2	0
K	3	1	0
N	1	1	1
W	1	1	1
Z	1	1	1

Table 30. Departmentilization of Cellular Machine Mix in Problem Set No.2C-3

Mini Department	Cell No.1	Cell No.2	Cell No.3
1	J	J,Z	P
2	P	P	W
3	K	-	N
4	W	J,W	-
5	2K	K	-
6	N	N	Z
7	Z	-	-

Step 5F Solution Steps of Problem Set No.2:

Functional facility of problem set No.2 is used in illustrating step 5F outlined in Chapter three.

- Identify the departments in which the number of machines left after step 4F is equal to the number of jobs that visit: department No.4 (machines J(1), J(2), W(1) and jobs A,C,H) ; department No.7 (machines P(1), Z(1) and jobs B,F ; department No.3 (machines K(1), K(2), N(1), W(1) and jobs A,D,E,F).
- Examine initial capacity availability which determines the maximum production level of jobs B, D, and E as 12, 11, and 22 unit loads (based on department No.7)
- Perform a similar analysis of department No.2. The production limits of jobs C and H are found as 16 unit loads out of 18 and 24 possible unit loads respectively.
- After reducing the problem size down to 777 decision variables, continuous solution recommendation is found as tvelwe unit loads of job B and fourteen unit loads of job E.
- Fixing the high lost sales cost jobs B and D at levels of 12 and 11 and re-running of MPSIII package shows that machine W of department No.4 and machine N of department No.4 are left idle.
- Switching machines to increase production levels produces: machine W of department No.4 to department No.3, machine N of department No.3 to department No.5, machine K

of department No.3 to department 5 (because department No.3 and department No.5 require much higher capacity than the other departments).

- Additional loading of available machine capacities in various departments, and performing new MPSIII runs after each assignment arrangements results in the final assignment decisions shown in Table 31.
- It becomes necessary to exclude one of the two machine J's in department No.4 from the machine mix as its inclusion does not increase daily production. Such exclusions reduce fixed cost components of final item costs.

Table 31. Step 5F Solution of Problem Set No.2

Department No.	Assignment Decisions
1	10E and 8F to P(1) 6A, and 10C to J(1)/ 15B to Z(1)
2	15B to P(1)/ 10C and 11D to W(1)
3	5A, 10E, and 1D to K(1)/ 10D to W(1) 1A and 8F to W(2)
4	6A and 10C to J(1)
5	6B to K(1)/ 6B to K(2)/ 7F to K(3) 5A to N(1)/ 1F, 3B, and 1A to N(2)
6	10C and 7F to N(1)/ 11D, 10E, and 1F to Z(1)
7	12B to P(1)/ 8F and 3B to Z(1)

According to Table 31, functional facility, under its operating constraints and rules, is able to fully process six unit loads of job A (66 items), and fifteen unit loads of job B (180 items or full daily demand). Production levels of other jobs in this problem set are 10C (80 items), 11D (110), 10E (60), 8F (72), and zero H. Amounts of unmet daily demands are 104-66 = 38 items of job A, and 0, 60, 77, 105, 42, and 120 for jobs B, C, D, E, F, and H respectively. Total number of items produced and rejected as lost sales are 568 and 442. Multiplication of these unmet daily demands with proper LSC_k values (lost sales cost per job type) result in a total daily lost sales cost of $8881.

Step 5C Solution With Two Cells:

Table 32 shows that the cellular facility with two cells can fully process seven unit loads of job A (77 items), twelfve of job B (144), eighteen of C (140 items or full demand), fourteen of D (140), twenty-four of E (144), five of F (45), and just one unit load of job H (5). It must be remembered that these production levels are just one of the many feasible combinations determined by the heuristic methodology based on the continuous solution of large mixed-integer problem. The amount of unmet daily demands, then, are: 27, 36, 0, 47, 21, 69, and 115 for 7 jobs of this problem set. Number of total items produced and rejected as lost sales are 695 and 315. Resulting daily lost sales cost is $7789.

Once again, a mini-department refers to a group of machines dedicated to a specific operation class work in a cell.

Table 32. Step 5C Solution of Problem Set No.2C-2

Mini-Department	Cell No.1	Cell No.2
1	7A and 1H to J(1) 1A to J(1) for Class No.4 op. 12B and 5F to J(2)	18C to J(1) 24E to Z(1) 16E to Z(1) for Class No.6 op.
2	12B and 1H to P(1) 5F to P(1) for Class No.7	14D and 8C to P(1)
3	1B to K(1) for Class No.5 op. 1F to K(1) for Class No.5 op. 5F to K(1)/ 1A to K(1) 1A to K(1) for Class No.5	11D to K(1)/13E to W(1) 3D and 11E to K(2) 10C to W(1) for class No.2 op.
4	6A to W(1)/1H to W(1) 6A to W(1) for class No.3 op.	18C to J(1)
5	6B to K(1)/5B to N(1) 1H to N(1)/6A to K(2)	n/a
6	1H and 5F to N(1) 4F to N(1) for Class No.5 op.	14D and 6E to N(1) 18C and 2E to N(2)
7	12B to Z(1)	n/a

Step 5C Solution With Three Cells:

Machine K of mini-department No.3, shown in Table 30 on page 138, in cell No.1 is switched to mini-department No.5. Table 33 shows that the cellular facility with three cells can fully process jobs in the following quantities : A (66), B (144), C (136), D (100), E (60), F (0), and H (70) with 38, 36, 87, 105, 114, and 50 items of unmet demand for each job type. Term "for No.3" in mini-department of cell No.1 above stands for "for class No.3 operation". This facility produces a total of 576 and rejects 434 items. Daily lost sales cost is $10637.

Table 33. Step 5C Solution of Problem Set No.2C-3

Mini-Department Number	Cell No.1	Cell No.2	Cell No.3
1	12B to J(1)	14H to J(1) 13C to J(1) 4C to Z(1) 14H to Z(1) for No.6	10E to P(1)
2	12B to P(1) 6A to P(1) for No.1	14H to P(1) 17C to P(1)	10D to W(1) 10E to W(1) for No.3
3	n/a	n/a	10D to N(1)
4	6A to W(1)	14H to J(1) 2C to J(1) 15C to W(1)	n/a
5	6B to K(1) 6B to K(2) 6A to K(3)	14H to K(1)	n/a
6	6A to N(1) for No.3	17C to N(1)	10E to Z(1) 10D to Z(1)
7	12B to Z(1)	n/a	n/a

4.1.8 Problem Set No.3

All daily demands must be met in problem sets No.3 and 4.

Functional Facility:

- Department No.1 : 5J (4.33) Department No.2 : 4P (3.38)
- Department No.3 : 6K (5.64) Department No.4 : 3J (2.34)
- Department No.5 : 10K (9.38) Department No.6 : 6Z (4.81)
- Department No.7 : 4Z (2.93)

Machine amounts in parenthesis above show the continuous machine requirements of each type. These amounts, found after solving the modified step 2, are rounded up to next whole number (sometimes to one more than the next whole number) at modified step 5F as shown above. Department No.4 is used for illustration: jobs A, C, H, and S need to visit department No.4 for their class No.4 operation requirements. According to pre-calculated unit load times tables, partially shown in Appendix K, a full load of job A (10 unit loads) takes 235 minutes on machine J including set-up times leaving 245 minutes of capacity. Among the remaining jobs, this capacity best fits to fulfil job S′s demand of 9 unit loads which require 208 minutes on machine J. Next, job C requires 466 minutes on machine J for its 18 unit loads, so job C alone is assigned to the second machine J with only (480-466) 16 minutes of the machine capacity remaining idle. The last job, H with 24 unit loads, requires 268 minutes on machine J. Since idle capacities of the first two machines are not sufficient for this requirement, a third machine J must be used. In fact, continuous value for number machine J′s, 2.34, indicates that the job mix of department No.4 will require more than two whole machines and the use of an additional machine is necessary even before set-up time factors are included.

Inclusion of set-up time factor may, sometimes, require two additional machines over the rounded down continuous value. Table 34 on page 143 summarizes the solution for functional facility.

Table 34. Step 5F Solution of Problem Set No.3

Department No.	Assignment Decisions
1	8A and 28E to J(1)/ 2A and 13F to J(2) 15B and 17R to J(3)/ 18C to J(4) 24H and 19Q to J(5)
2	15B to P(1)/ 19D to P(2) 24H and 17R to P(3)/ 18C and 9S to P(4)
3	11D to K(1)/ 8D, 5E, and 1E(*) to K(2) 22E to K(3)/ 13F and 3R to K(4) 10A and 5R to K(5)/ 19Q and 9R to K(6)
4	10A and 9S to J(1) / 24H to J(2) 18C to J(3)
5	6A and 1H to K(1)/ 4A and 2B to K(2) 6B to K(3)/ 6B to K(4)/ 8F to K(5) 5F, 1B, and 3H to K(6)/ 14H to K(7) 6H and 8Q to K(8)/ 11Q and 3R to K(9) 14R to K(10)
6	18C to Z(1)/ 18D to Z(2) 28E and 1D to Z(3)/ 13F and 6H to Z(4) 18H and 14R to Z(5)/ 3R and 9S to Z(6)
7	12B to Z(1)/ 3B and 19Q to Z(2) 13F to Z(3)/ 9S to Z(4)

(*) Last unit load has only three job E items and the load of 8D and 5E leave only 18.8 minutes of available time on machine K. Three job E items take 3 * 3.4 = 10.2 minutes. 18.8 - 10.2 = 8.6 minutes is assumed sufficient to meet additional, if any, set-up time requirements.

Step 5C Solution With Two Cells:

Ten job types, pre-assigned to one of the cells, are further assigned to machines in mini-departments for various operations. Each cell has already been departmentalized as a part of modified step 5C solution method. All demands are met by sometimes making use of the available capacity in another mini-department instead of installing another machine to the original mini-department. For example, 18 of 24 unit loads of job H stay in mini-department No.5 for job H's required class No.5 operation, but six unit loads of job H are to be sent to mini-department No.3 for using the available capacities of the 2nd and 3rd machine K as machine K is able provide both operation class No.3 and No.5. The final machine mix for each cell along with the continuous amounts, results of the modified step 2C, are given below :

- In cell No.1 : 2P (1.69), 4J (3.59), 11K (10.13), and 4Z (3.92).
- In cell No.2 : 2P (1.76), 4J (3.12), 5K (4.81), and 5Z (3.85).

Table 35 shows the results for both cells.

Table 35. Step 5C Solution of Problem Set No.3C-2

Mini-Department No.	Cell No.1	Cell No.2
1	10A and 17R to J(1) 2H to J(1) for Class No.4 op. 15B and 17H to J(2) 13F and 7H to J(3)	18C to J(1) 28E and 19Q to J(2)
2	15B to P(1) 24H and 17R to P(2) 2B to P(1) for No.7 1B to P(2) for No.7	18C and 9S to P(1) 19D to P(2)
3	10A to K(1)/ 13F to K(2) 2H to K(2) for Class No.5 op. 17R to K(3) 4H to K(3) for Class No.5 op.	11D to K(1) 8D and 6E to K(2) 22E to K(3) 19Q to K(4) 5Q to K(4) for Class No.5 op.
4	10A and 22H to J(1)	18C to J(1)/ 9S to J(2)
5	6A and 1H to K(1) 4A and 2B to K(2) 6B to K(3)/ 6B to K(4) 8F to K(5) 5F, 1B, and 3H to K(6) 14H to K(7)/ 17R to K(8)	14Q to K(1)
6	13F and 8R to Z(1) 24H and 7R to Z(2)	18C and 1D to Z(1) 28E to Z(3)/ 9S to Z(4) 18D to Z(2)
7	12B to Z(1)/ 13F to Z(2) 2R to Z(2) for Class No.6 op.	19Q and 9S to Z(1)

Step 5C Solution With Three Cells:

The same ten jobs are now in three groups which result in the following machine mix requirement after steps 2C and 5C are implemented.

- In cell No.1 : 1P (0.83), 3J (2.66), 10K (8.87), and 4Z (3.36)
- In cell No.2 : 2P (1.44), 4J (3.25), 2K (1.77), and 3Z (2.31)
- In cell No.3 : 2P (1.21), 5K (4.40), and 3Z (2.78)

Table 36 shows the solution for all three cells.

Table 36. Step 5C Solution of Problem Set No.3C-3

Mini-Department No.	Cell No.1	Cell No.2	Cell No.3
1	10A to J(1) 19Q to J(1) 15B to J(2) 8A to J(2) for No.4	18C to J(1) 24H to J(2)	n/a
2	15B to P(1)	18C to P(1) 24H to P(2) 9S to P(2)	19D to P(1) 17R to P(2) 28E to P(2) for No.1
3	10A to K(1) 13F to K(2) 19Q to K(3)	n/a	11D to K(1) 8D to K(2) 6E to K(2) 22E to K(3) 17R to K(4) 2R to K(4) for No.5
4	2A to J(1) 13F to J(1) for No.1	18C to J(1) 24H to J(2) 9S to J(2)	n/a
5	6A and 1Q to K(1) 4A and 3B to K(2) 6B to K(3) 6B to K(4) 8F to K(5) 5F and 4Q to K(6) 14Q to K(7)	12H to K(1) 12H to K(2)	15R to K(1)
6	13F to Z(1)	18C to Z(1) 24H to Z(2)	18D to Z(1) 28E and 1D to Z(2) 17R to Z(3) 17R to Z(3) for No.1
7	15B to Z(1) 13F and 2B to Z(2) 19Q to Z(3)	9S to Z(1) 9S to Z(1) for No.6	n/a

4.1.9 Problem Set No.4

Step 5F Solution for Functional Facility:

The modified step 5F solution results in the following machine mix amounts (continuous modified step 2F amounts are shown in parenthesis). Table 37 shows the solution for the functional facility.

- Department No.1 : 5J (4.37) Department No.2 : 7P (5.90)
- Department No.3 : 9K (7.81) Department No.4 : 6J (5.01)
- Department No.5 : 10T (8.89) Department No.6 : 7Z (6.21)
- Department No.7 : 5T (4.00)

Table 37. Step 5F Solution of Problem Set No.4

Department No.	Assignment Decisions
1	10A and 25E to J(1)/ 15B, 3E, and 17R to J(2) 18C to J(3)/ 13F to J(4) 24H and 19Q to J(5)
2	15B and 6S to P(1)/ 18C, and 17R to P(2) 19D to P(3)/ 24H and 4V to P(4) 11V to P(5)/ 11U to P(6) 6U and 3S to P(7)
3	10A and 1E to K(1)/ 11D to K(2) 8D and 5E to K(3)/ 22E to K(4) 13F to K(5)/ 19Q and 9R to K(6) 6V to K(7)/ 6V to K(8) 3V and 8R to K(9)
4	10A and 1U to J(1) / 16U to J(2) 18C to J(3)/ 8V to J(4) 7V to J(5)/ 24H and 9S to J(6)
5	6A to T(1)/ 4A to T(2)/ 6B to T(3) 6B to T(4)/ 3B and 4F to T(5)/ 9F to T(6) 14H to T(7)/ 14Q to T(8) 17R to T(9)/ 5Q and 10H to T(10)
6	18C to Z(1)/ 18D to Z(2) 28E, 1D and 3S to Z(3)/ 13F and 6S to Z(4) 24H to Z(5)/ 17R to Z(6) 17U to Z(7)
7	14B to T(1)/ 13F and 1B to T(2) 19Q to T(3)/ 9V to T(4) 6V and 9S to T(5)

Step 5C Solution With Three Cells:

Twelve jobs are now in three cells which result the following machine mix requirements and assignments shown below in Table 38.

- In cell No.1 : 3P (2.31), 3J (2.62), 3K (2.47), 2Z (1.81), and 6T (6.33)
- In cell No.2 : 3P (2.08), 5J (4.40), 4K (3.45), 2Z (1.92) and 2T (1.72)
- In cell No.3 : 2P (1.65), 3J (2.43), 3K (2.09), 3Z (2.62) and 6T (4.88)

Table 38. Step 5C Solution of Problem Set No.4C-3

Mini-Department Number	Cell No.1	Cell No.2	Cell No.3
1	10A to J(1) 21H to J(1) 15B to J(2) 3H to J(2) 3H to J(2) for No.4	18C to J(1) 28E to J(2) 9S to J(2) for No.4	13F to J(1) 19Q to J(2) 1U to J(1) for No.4 17R to J(2)
2	15B to P(1) 19D to P(2) 24H to P(3)	18C to P(1) 12V to P(2) 9S to P(3) 3V to P(3)	17R to P(1) 5U to P(1) 12U to P(2)
3	10A to K(1) 11D to K(2) 8D to K(3)	23E to K(1) 6V to K(2) 6V to K(3) 3V to K(4) 5E to K(4)	13F to K(1) 19Q to K(2) 17R to K(3)
4	10A to J(1) 21H to J(1)	18C to J(1) 8V to J(2) 7V to J(3)	16U to J(1)
5	6A to T(1) 4A and 2H to T(2) 6B to T(3) 1B to T(3) for No.7 6B to T(4) 3B and 8H to T(5) 14H to T(6)	n/a	9F to T(1) 4F and 8Q to T(2) 11Q and 3R to T(3) 14R to T(4)
6	18D to Z(1) 24H and 1D to Z(2)	18C and 2S to Z(1) 28E and 7S to Z(2)	13F and 1U to Z(1) 17R and 5U to Z(2) 11U to Z(3)
7	14B to T(1)	10V to T(1) 5V and 9S to T(2)	13F to T(1) 19Q to T(2)

Step 5C Solution With Four Cells:

Initial (modified step 2F) and final (modified step 5F) machine mix requirements are :

- cell No.1 : 2P (1.41), 3J (2.62), 1K (0.86), 1Z (0.83), and 7T (6.33)
- cell No.2 : 2P (2.08), 4J (3.88), 3W (2.44), 2Z (1.22), and 2T (1.77)
- cell No.3 : 2P (1.21), 5K (4.40), and 4Z (2.78)
- cell No.4 : 2P (1.38), 3J (2.14), 2K (1.53), 3Z (2.21), and 4T (3.75)

Table 39 and Table 40 on page 149 show the solution for the first two and and the last two cells.

Table 39. Step 5C Solution of Problem Set No.4C-4 (Cell No.1 and 2)

Mini-Department No.	Cell No.1	Cell No.2
1	10A and 23H to J(1) 15B and 1H to J(2) 2H to J(2) for No.4	18C to J(1)
2	15B to P(1) 24H to P(2)	18C to P(1)/ 12V to P(2) 9S and 2V to P(1)
3	10A to K(1)	6V to W(1)/ 6V to W(2) 3V to W(3) 1V to W(3) for No.2 3S to W(3) for No.4
4	10A and 22H to J(1)	18C and 1S to J(1) 8V and 1S to J(2) 7V and 4S to J(3)
5	6A to T(1) 4A and 4H to T(2) 6B to T(3)/ 6B to T(4) 3B and 6H to T(5) 1B to T(5) for No.7 14H to T(6)	n/a
6	24H to Z(1)	18C to Z(1)/ 9S to Z(2)
7	14B to T(1)	10V to T(1)/ 5V and 9S to T(2)

Table 41 on page 149 compares all four problem sets with respect to problem size, total number of required machines, and the computation times on an IBM 3090 Model 200/VF mainframe computer.

Table 40. Step 5C Solution of Problem Set No.4C-4 (Cell No.3 and 4)

Mini-Department No.	Cell No.3	Cell No.4
1	28E and 14R to Z(1)	13F to J(1)/ 19Q to J(2)
2	19D to P(1)/ 17R to P(2)	12U to P(1)/ 5U to P(2)
3	11D to K(1)/ 8D to K(2) 22E to K(3) 17R and 6E to K(4)	13F to K(1) 19Q to K(2)
4	n/a	17U to J(1)
5	17R to K(1)	9F to T(1)/ 14Q to T(2) 4F and 5Q to T(3)
6	18D to Z(1) 28E and 1D to Z(2) 3R to Z(2) for No.1 17R to Z(3)	13F to Z(1) 6Q to Z(1) for No.7 11U to Z(2)/ 6U to Z(3) 13Q to Z(3) for No.7
7	n/a	13F to T(1)

Table 41. Comparison of Problem Sizes and Computation Times of Step 2.

	Set No.1		Set No.2			Set No.3			Set No.4		
Problem No. :	1F	1C	2F	2C-2	2C-3	3F	3C-2	3C-3	4F	4C-3	4C-4
Number of Rows	29	27	50	46	52	63	60	66	76	80	88
Integer Variables	10	8	16	12	18	-	-	-	-	-	-
Binary Variables	22	22	66	66	66	96	96	96	130	130	130
Continuous Variables	4	4	6	6	6	16	12	18	19	24	32
Total Variables	36	34	88	84	90	112	108	114	149	154	162
Total Machines Needed	22	19	38	33	39	*	*	*	*	*	*
Exit Time (Minutes) (I/O + CPU)	0.195	0.127	0.436	0.386	0.407	0.018	0.019	0.021	0.025	0.026	0.029

(*) **Note** : Resulting machine numbers are fractional and converted to integers later in modified step 5 which usually rounds up fractions to next integer, but, in some cases of cellular facility, fractional amounts may be rounded down. On occasion, rounding up in both cases may require an additional machine over the rounded up value if set-up factors are significant.

Summary

Four example problems were solved by implementing the first five steps of the hierarchical methodology. Results found in this Chapter are used as raw data in final item calculations performed in Chapter five.

5.0 Layout Design of Facilities and Final Item Cost Calculations

This Chapter concludes stage one of the hierarchical methodology by determining a good layout for each facility (Step 6). Next, final item cost of each job type is calculated for each facility in all problem sets.

5.1.1 Determination of a Good Layout for Each Facility

Previous chapters have determined, for each facility, the production load per period using the fixed number of machines. There are no interactions among the cells and the only layout related considerations are as follows :

1. **Flow of jobs within the cell:** Each cell should be laid out so as to minimize total material handling cost and transportation times. Since a cell is considered a small independent facility with a group of machines, mini-departments, dedicated to perform pre-specified

operations of the cell's job mix, the arrangement of the cells with respect to each other does not matter. But, the total area occupied by all cells plus the receiving/shipping areas, common to all cells, can not exceed the available plant space.

2. **Flow of jobs among various departments:** The departments of the functional layout should be arranged such that the total material handling cost of the facility and the amount of transportation times for a batch or unit load of job, as it flows through the facility, is minimum.

Effect of the shared machines between the mini-departments of cellular facility, a rare possibility, should be given the first priority in placing those mini-departments adjacent to each other. The layout of machines within each functional department or class area does not need to be examined because each job batch normally visits only one of the usually identical, otherwise. similar, machines in each department.

Use of the MICRO-CRAFT [48] package:

Appendix M gives a brief description of this software which is used in material handling cost calculations of both environments compared. In both cases, the layout was first determined solely based on the amount of flow between the machines in each cell and the departments. Once a good layout was found, actual material handling costs for each job type, using different BHC_k values (handling cost of each job type per unit distance) and travel distances, were calculated. Since MICRO-CRAFT uses an integer number of batches, partial last batches were entered as a full ones whenever step 5 indicated that a given job demand should be met in full as is always the case in problem sets No.3 and 4. Last unit loads are always full in problem sets No.1 and 2. As a general example, daily demand for job A should be entered as 110 instead of 104 so that the division by unit load size of 11 results in an integer number of batches.

Functional Facility Procedure:

Each functional facility layout is determined as explained below. Problem set No.1 is used for illustration.

1. Total area to be occupied by each department is found by adding the area requirement of each machine remaining in that department after step 4F. Machines P and J are left in department No.1. Then, department No.1 has an area of 56 + 40 = 96 ft^2. The other six departments have the following areas : 112, 103, 80, 144, 110, and 56 ft^2.
2. The sum of the areas of the above production departments is subtracted from the available total area: 1350 - 701 = 649 ft^2. This space is used in creating two new non-production departments or zones: No.8 as receiving (349 ft^2) and No.9 as shipping (300 ft^2). The amount of space allocated to these departments must add up to 649 ft^2. The receiving department should be allocated a higher portion of the remaining space because incoming raw material is typically bulkier then the finished product.
3. Although MICRO-CRAFT has a special provision for fixing the location of some departments, no attempt was made to fix the locations of departments No.8 and No.9 on the perimeter of the facility. If either or both of these departments are ever located in the interior, it can be assumed that some means such as overhead or underground transportation of raw/finished jobs is possible.
4. A rectangular facility shape is determined by selecting suitable width and length. A width of 33 ft and length of 41 ft were chosen for problem set No.1 as 33 X 41 = 1353 ft^2 is close enough to the total area of 1350 ft^2. Three bays [48] are used in all layouts determined in this Chapter.
5. The actual production levels found in step 5F (in unit load terms) and the job operation precedence requirements given in Appendix D were used as inputs to the MICRO-CRAFT package in determining a FROMTO chart and a good layout for each facility as shown in Figure 18 on page 154. The layout was generated by assigning equal handling costs of one for all jobs (temporarily) and choosing the euclinean distances criteria option. The

FROMTO chart is in terms of the number of unit loads of jobs or just jobs transferred between the departments. This chart and the layout are dependent on precedence requirements, shown in Table 42 on page 153, and the actual production levels of the jobs. Job A, for example, travels through the facility in department order of 8-1-3-4-5-9. Moves of Jobs A and D are shown in Figure 18 on page 154.

6. The amount of distance travelled by each job type k is found and multiplied by its BHC_k value. However, costs due to the job's first move from the receiving area to the first department it visits and the last move from the last department it visits to the shipping area were not included in the total material handling cost calculation. Exclusion of costs due to the first and the last moves was necessary in order to provide a fair comparison with the cellular facility where cells do not have their own receiving and shipping areas.

Table 42. Precedence Order of Departmental Job Visits

Job Name	Problem Set	Starts at	1st Visit	2nd Visit	3rd Visit	4th Visit	5th Visit	Ends at
A	No.1,2,3,4	8	1	3	4	5	-	9
B	No.1,2,3,4	8	1	5	7	2	-	9
C	No.1,2,3,4	8	4	1	2	6	-	9
D	No.1,2,3,4	8	3	6	2	-	-	9
E	No.2,3,4	8	1	3	6	-	-	9
F	No.2,3,4	8	3	6	5	1	7	9
H	No.2,3,4	8	2	1	4	5	6	9
Q	No.3,4	8	1	3	7	5	-	9
R	No.3,4	8	1	2	5	6	3	9
S	No.3,4	8	4	6	2	7	-	9
U	No.4	8	6	4	2	-	-	9
V	No.4	8	3	4	7	2	-	9

Each unit load (of jobs) follows above routes exactly under the functional facility and receives the necessary operations available from each department or class area visited.

Dept	Dept. 1	Dept. 2	Dept. 3	Dept. 4	Dept. 5	Dept. 6	Dept. 7	Dept. 8	Dept. 9
1		8	8		10				
2						6			23
3				8		13			
4	8				8				
5							10		8
6		13							8
7		10							
8	18		13	8					
9									

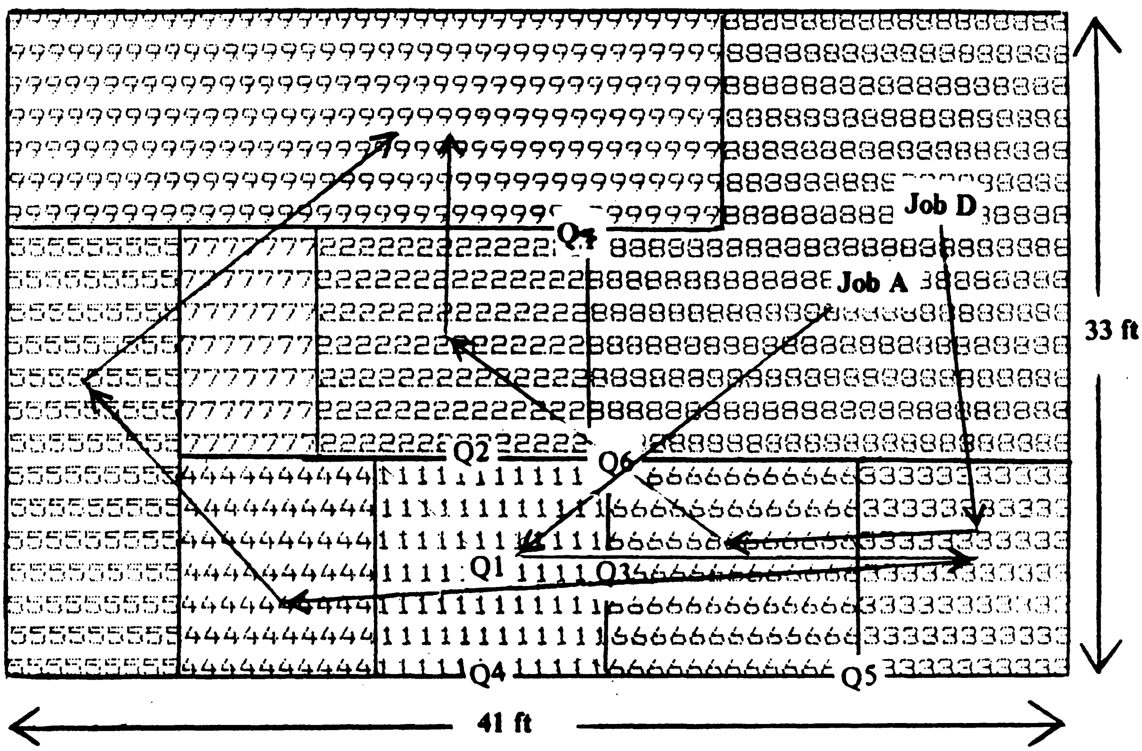


Figure 18. FROMTO Chart and MICRO-CRAFT Generated Layout for Functional Facility in Problem Set No.1

Determination of Travel Distances Between the Departments:

The method described below is applicable to both facilities once the layout of each has been determined via MICRO-CRAFT. Figure 18 of the functional layout is used in illustrating the calculations. The FROMTO charts indicate the department pairs for which material handling distances should be determined as there is no need to calculate these distances for all possible pairs of departments. That is, a distance between a department pair is determined only if there is a non-zero flow between the two departments.

1. Rectilinear routes were used and jobs could not cross through departments on their immediate destination paths. Jobs, loaded on standard pallet as unit loads, could only travel on the perimeter of each department.
2. The distance between two adjacent departments is measured from the center of the source department to the perimeter of the destination department. In Figure 18 on page 154, Q1Q2 is the material handling distance between departments No.1 and No.2 and is calculated by measuring the length from Figure 18 on page 154, in centimeters, and multiplying the measured amount by Width Scale Factor (WSF). The width and length scale (LSF) factors are unique to each layout generated by the MICRO-CRAFT package and are affected by several factors such as facility dimensions, number of bays and departments, and dimension ratios. In this case, one cm of vertical length represents 3.75 ft (WSF) and the LSF is 2.93 ft. The above distance, then, is 1.4665 cm x 3.75 ft/cm = 5.50 ft. Similarly, the distance between departments No.1 and No.6 (Q1Q3) is found by using LSF : 1.50 cm x 2.93 ft/cm = 4.34 ft.
3. The distance between two non-adjacent departments is found by adding rectilinear distances which provide the shortest route from the center of the source department to the perimeter of the destination department. For example, in order to calculate the material handling distance between the departments No.1 and No.3 shown in Figure 18 on page 154, vertical and horizontal distances should be measured and scaled up:

Q1Q4 (WSF) + Q4Q5 (LSF) = [(1.4665 cm X 3.75 ft/cm) + (4.9 cm X 2.93)] = 19.86 ft.

As a final example using departments No.1 and No.9, lengths of the segments of Q1Q2, Q2Q6, and Q6Q7 are measured and scaled up :

1.4665 cm x 3.75 ft/cm + 1.50 cm x 2.93 ft/cm + 3 cm x 3.75 ft/cm = 21.14 ft.

Table 43 shows the travel distances for those department combinations indicated on the FROMTO chart. Units are in feet (ft), but other units can be assumed also.

Table 43. Travel Distances Between Departments of Functional Facility (Problem Set No.1)

Dept	Dept. 1	Dept. 2	Dept. 3	Dept. 4	Dept. 5	Dept. 6	Dept. 7	Dept. 8	Dept. 9
1		5.50	19.86		17.22	4.34			21.14
2						11.49			5.63
3				28.06		3.81			
4	3.81				3.81				
5							3.37		11.06
6		11.36						5.50	22.61
7		3.54							
8	5.63		5.63	13.83					
9									

Cellular Facility Procedure:

The procedure is the same, but mini-departments rather than departments are used and no receiving/shipping areas are considered.

1. Total area occupied by each cell is equal to the sum of the area requirements of all the machines allocated to that cell.
2. The sum of all cell areas can not exceed the total plant space, TA.
3. The layout of each cell is determined separately as if it were the only facility in existence.

4. Each machine type or group of the same/similar machines are used in constructing mini-departments in each cell.

Figure 19 on page 158 and Figure 20 on page 159 show the resulting FROMTO charts and layouts for cells No.1 and No.2 of problem set No.1. The area requirement of each mini-department was found by adding the areas of the machines assigned to each mini-department at the end of step 2C or 4C (binding operating constraints case). Then, the MICRO-CRAFT package was applied as if each cell were a small functional facility with maximum of seven departments. An important difference from the functional facility solution is the lack of departments No.8 and No.9 as explained earlier.

Layout Designs of Problem Sets 2, 3, and 4: Figures from Figure 21 on page 160 through Figure 30 on page 169 show layouts for problem sets 2, 3, and 4. Functional layouts always had nine departments. These layouts were found using the same procedures already discussed. The FROMTO and travel distance charts are not shown, but they were used in calculating material handling costs for each facility. Each figure contains the routings of selected jobs that are part of the job-mix assigned to each facility type. Some of the job routings in the cellular facility are different than the original job precedence orders shown in Table 42 on page 153. These changes are due to post-step 5C analysis in order to increase overall cellular production levels.

Table 44 shows the final number of machines assigned to each facility type whose layout is given in the figures referenced above.

Table 44. Final Number of Machines in Each Facility After Step 5.

	Set No.1		Set No.2			Set No.3			Set No.4		
Problem No. :	1F	1C	2F	2C-2	2C-3	3F	3C-2	3C-3	4F	4C-3	4C-4
Number of Machines	14	15	19	19	19	38	37	39	49	51	52

Dept	Dept. 1	Dept. 2	Dept. 3	Dept. 4	Dept. 5	Dept. 6	Dept. 7
1			7	2	12		
2							
3				7			
4					7		
5		2					12
6							
7		14					

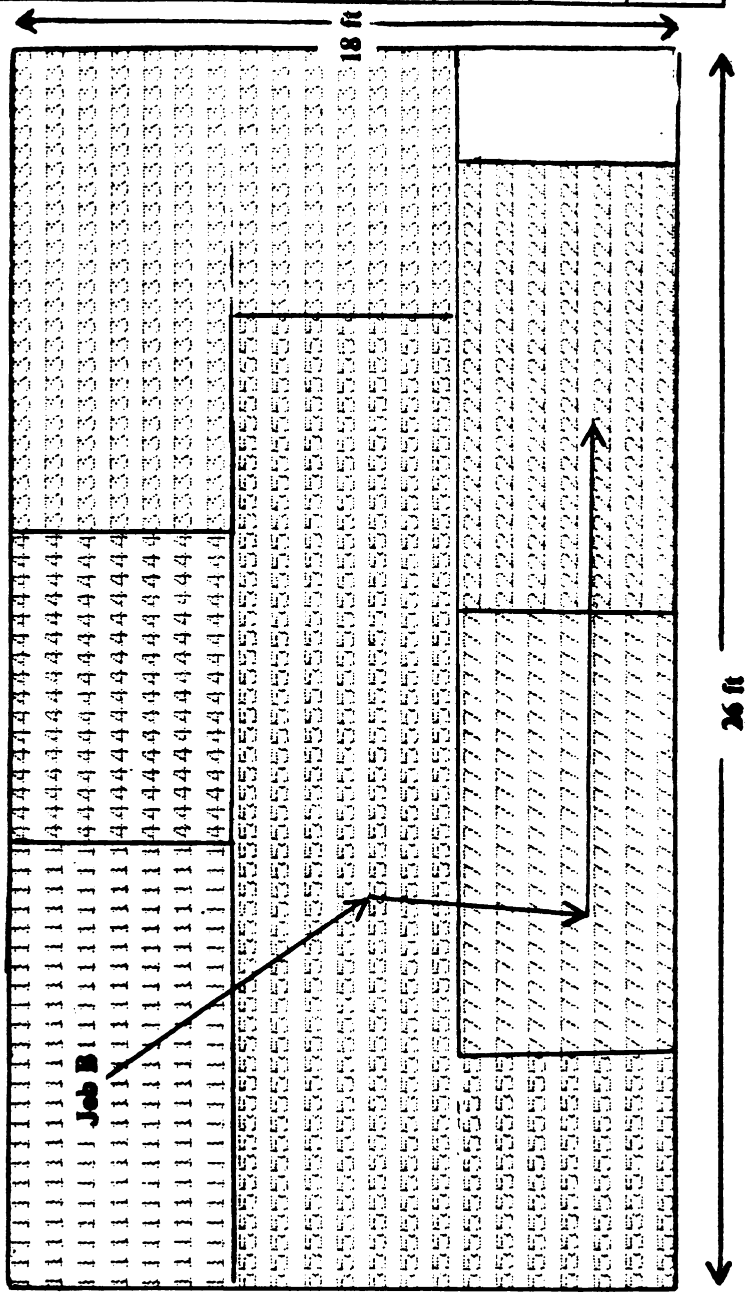
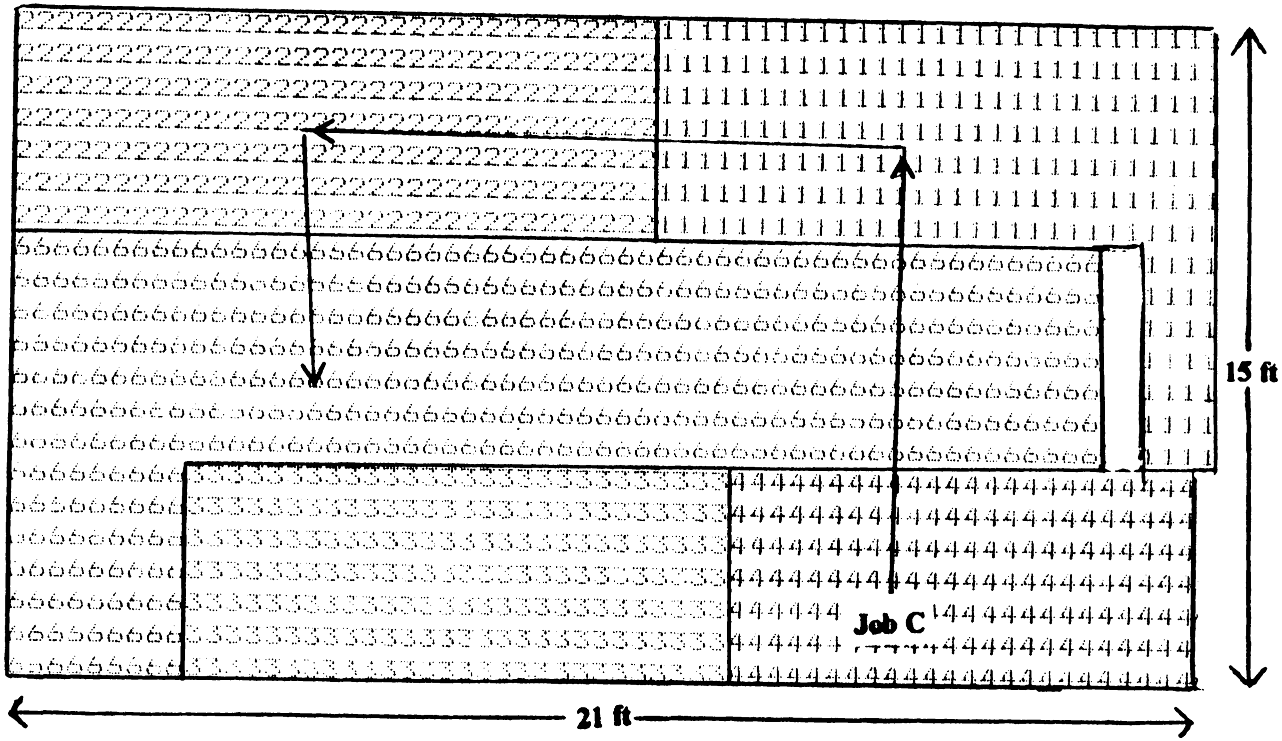
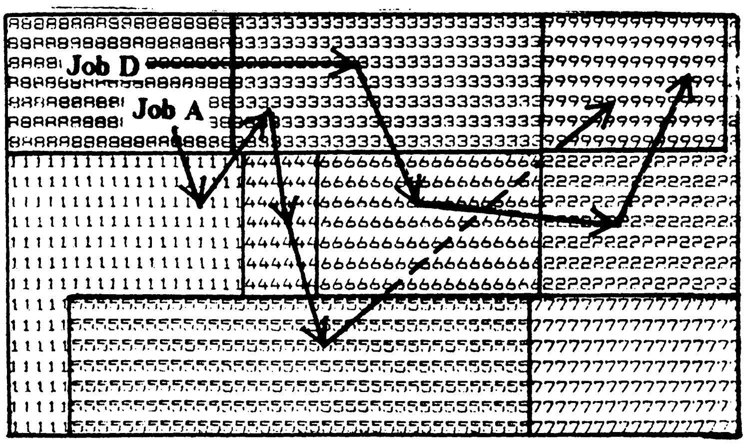


Figure 19. **FROMTO Chart and MICRO-CRAFT Generated Layout for Cell No.1 in Problem Set No.1**



Dept	Dept. 1	Dept. 2	Dept. 3	Dept. 4	Dept. 5	Dept. 6	Dept. 7
1		13					
2						13	
3						11	
4	13						
5							
6		11					
7							

Figure 20. FROMTO Chart and MICRO-CRAFT Generated Layout for Cell No.2 in Problem Set No.1

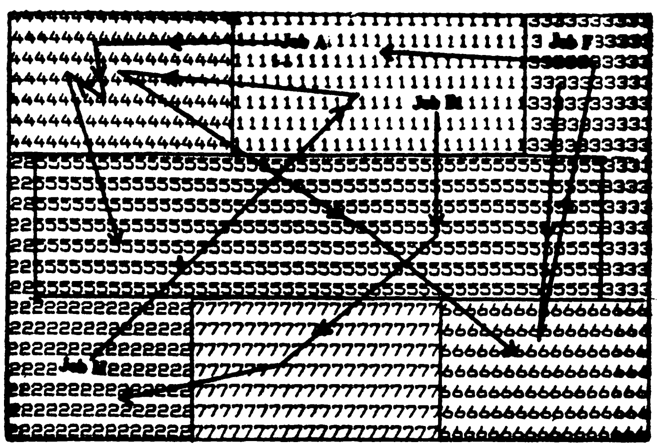


NUMBER OF BAYS: 3
NUMBER OF DEPARTMENTS: 9

PLANT LENGTH: 40
PLANT WIDTH : 30

DEPT SEQUENCE:
8 - 3 - 9 - 2 - 6 - 4 - 1 - 5 - 7

DEPT AREA :
161 - 116 - 168 - 40 - 254 - 120 - 121 - 120 - 100



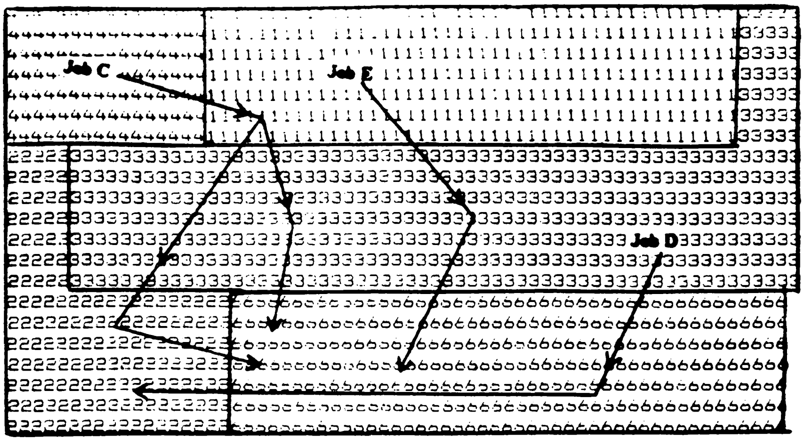
NUMBER OF BAYS: 3
NUMBER OF DEPARTMENTS: 7

PLANT LENGTH: 24.6
PLANT WIDTH : 21

DEPT SEQUENCE:
4 - 1 - 3 - 5 - 2 - 7 - 6

DEPT AREA :
80 - 56 - 48 - 60 - 151 - 55 - 65

Figure 21. Layouts for Problems 2F and 2C-2 Cell No.1

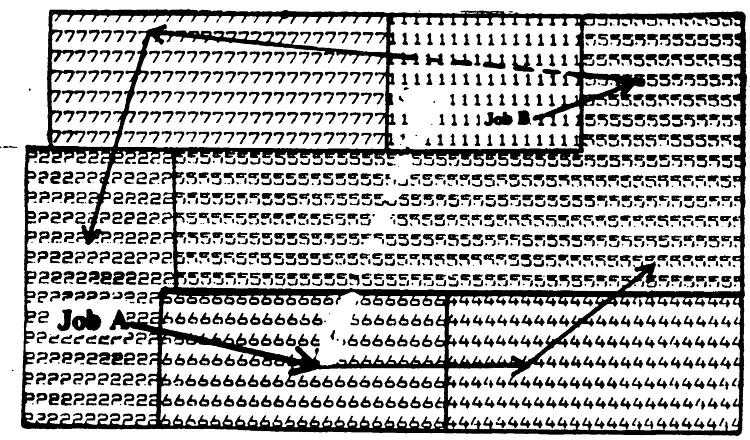


NUMBER OF BAYS: 3
NUMBER OF DEPARTMENTS: 7

PLANT LENGTH: 26.1
PLANT WIDTH : 18

DEPT SEQUENCE:
4 - 1 - 3 - 2 - 6 - 5 - 7

DEPT AREA :
105 - 56 - 156 - 40 - 1 - 110 - 1



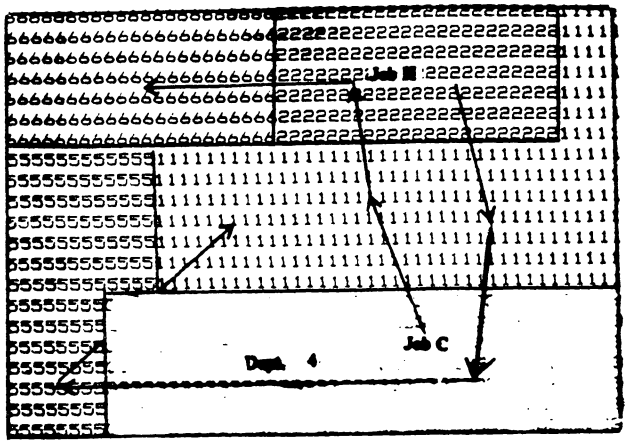
NUMBER OF BAYS: 3
NUMBER OF DEPARTMENTS: 6

PLANT LENGTH: 23.62
PLANT WIDTH : 18

DEPT SEQUENCE:
- 7 - 1 - 5 - 2 - 6 - 4

DEPT AREA :
40 - 56 - - 60 - 144 - 55 - 65

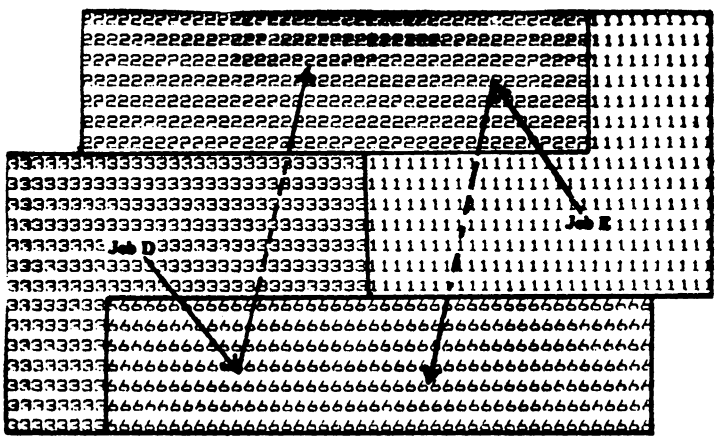
Figure 22. Layouts for Problems 2C-2 Cell No.2 and 2C-3 Cell No.1



NUMBER OF BAYS: 3 PLANT LENGTH: 20.4
NUMBER OF DEPARTMENTS: 5 PLANT WIDTH : 18

DEPT SEQUENCE:
6 - 2 - 1 - 5 - - - 4

DEPT AREA
105 - 56 - 1 - 100 - 48 - 55 - 1

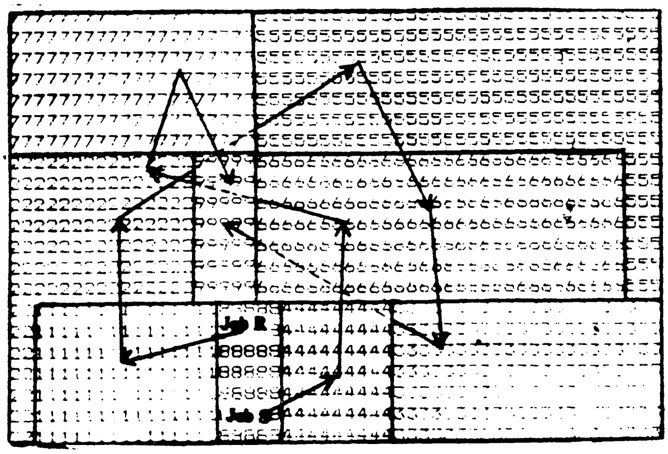


NUMBER OF BAYS: 3 PLANT LENGTH: 18
NUMBER OF DEPARTMENTS: 4 PLANT WIDTH : 14

DEPT SEQUENCE:
- 2 - 1 - 3 - 6 -

DEPT AREA :
56 - 60 - 55 - - - 65 -

Figure 23. Layouts for Problems 2C-3 Cell No.2 and 2C-3 Cell No.3

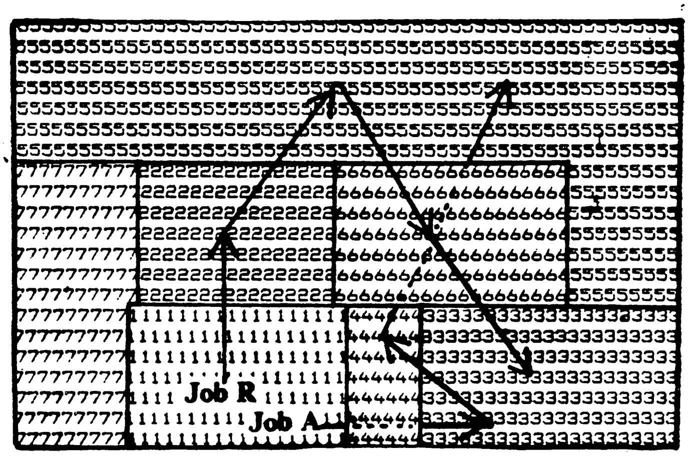


NUMBER OF BAYS: 3
NUMBER OF DEPARTMENTS: 9

PLANT LENGTH: 50
PLANT WIDTH : 42

DEPT SEQUENCE:
7 - 5 - 6 - 9 - 2 - 1 - 8 - 4 - 3

DEPT AREA :
200 - 224 - 238 - 120 - 480 - 390 - 260 - 60 - 60



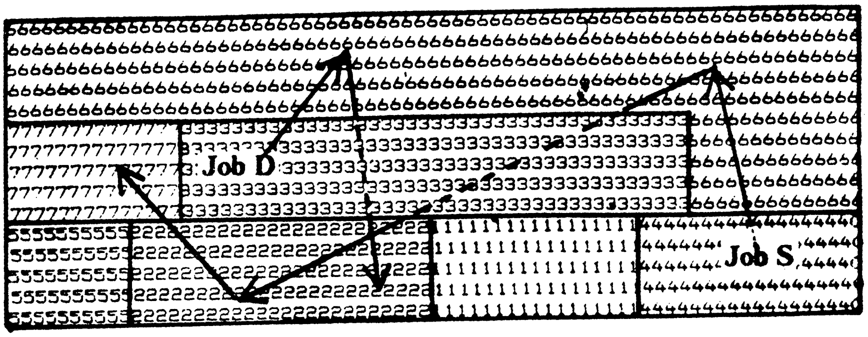
NUMBER OF BAYS: 3
NUMBER OF DEPARTMENTS: 7

PLANT LENGTH: 36.94
PLANT WIDTH : 30

DEPT SEQUENCE:
5 - 6 - 2 - 7 - 1 - 4 - 3

DEPT AREA :
120 - 112 - 144 - 40 - 432 - 130 - 130

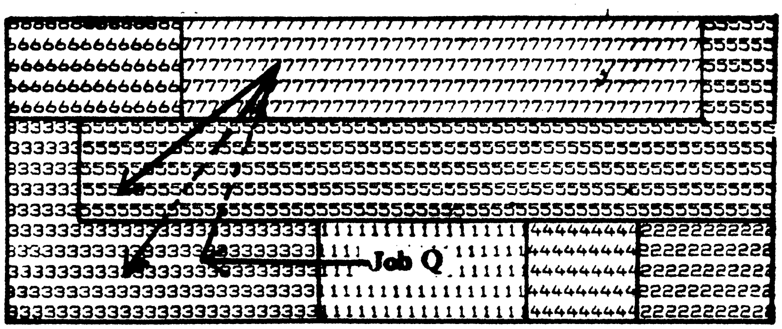
Figure 24. Layouts for Problems 3F and 3C-2 Cell No.1



NUMBER OF BAYS: 3 PLANT LENGTH: 46.05
NUMBER OF DEPARTMENTS: 7 PLANT WIDTH : 21

DEPT SEQUENCE:
6 - 3 - 7 - 5 - 2 - 1 - 4

DEPT AREA :
80 - 112 - 192 - 80 - 48 - 390 - 65

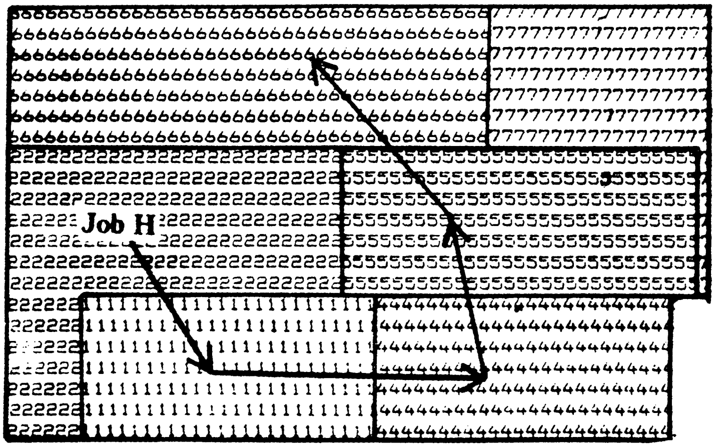


NUMBER OF BAYS: 3 PLANT LENGTH: 41.4
NUMBER OF DEPARTMENTS: 7 PLANT WIDTH : 21

DEPT SEQUENCE:
6 - 7 - 5 - 3 - 1 - 4 - 2

DEPT AREA :
80 - 56 - 144 - 40 - 288 - 65 - 195

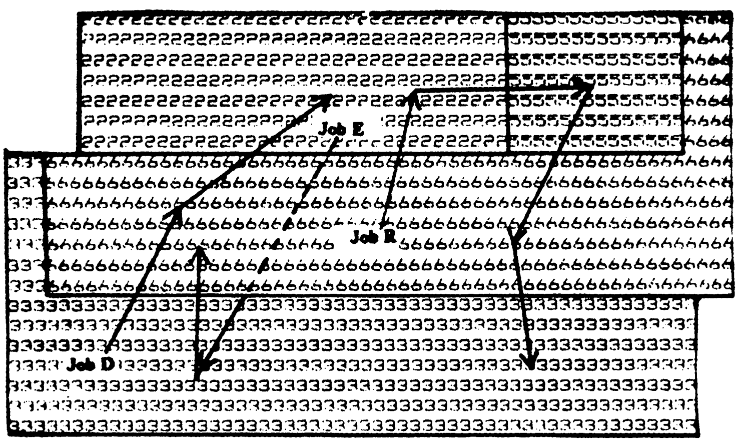
Figure 25. Layouts for Problems 3C-2 Cell No.2 and 3C-3 Cell No.1




```
NUMBER OF BAYS:  3            PLANT LENGTH:  27.3
NUMBER OF DEPARTMENTS:  7     PLANT WIDTH :  21

DEPT SEQUENCE:
 6 - 7 - 5 - 2 - 1 - 4 -

DEPT AREA      :
 80 - 112 -      - 80 - 96 - 130 - 65
```

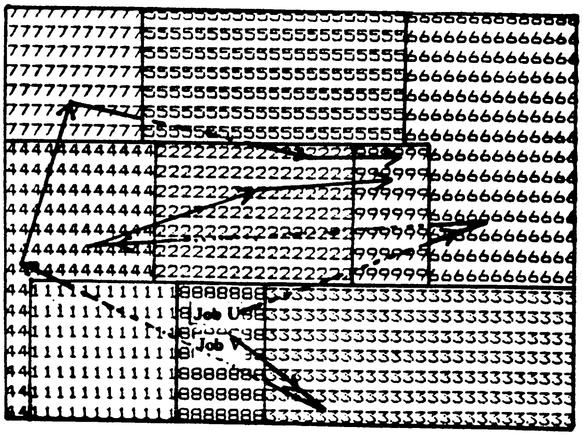



```
NUMBER OF BAYS:  3            PLANT LENGTH:  27.5
NUMBER OF DEPARTMENTS:  7     PLANT WIDTH :  21

DEPT SEQUENCE:
                2 - 5 - 6 - 3

DEPT AREA      :
   - 112 - 192 -      - 48 - 195 -
```

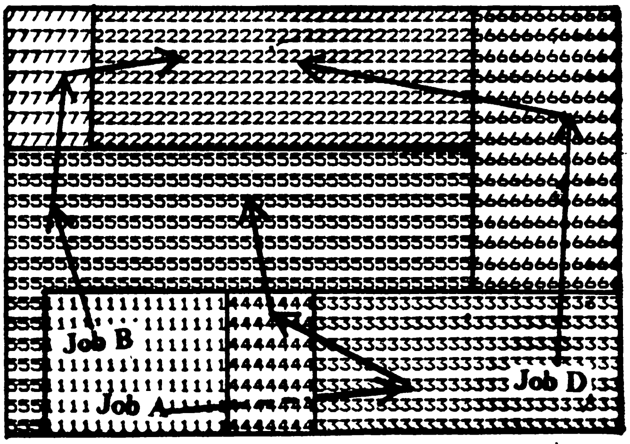
Figure 26. Layouts for Problems 3C-3 Cell No.2 and 3C-3 Cell No.3



NUMBER OF BAYS: 3 PLANT LENGTH: 50
NUMBER OF DEPARTMENTS: 9 PLANT WIDTH : 47.8

DEPT SEQUENCE:
7 - 5 - 6 - 9 - 2 - 4 - 1 - 8 - 3

DEPT AREA :
200 - 280 - 432 - 240 - 370 - 455 - 185 - 126 - 100

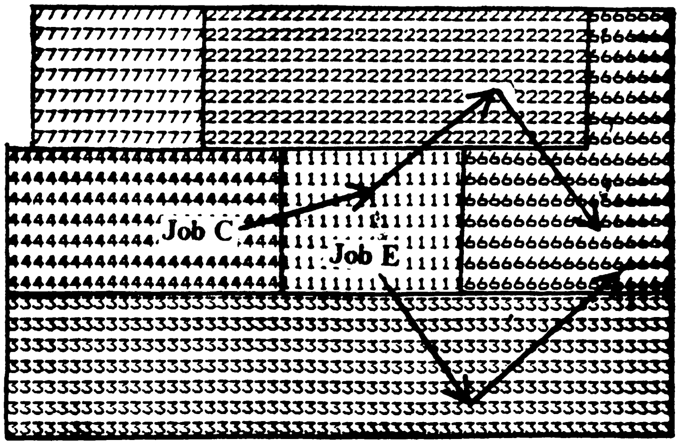


NUMBER OF BAYS: 3 PLANT LENGTH: 30.41
NUMBER OF DEPARTMENTS: 7 PLANT WIDTH : 27

DEPT SEQUENCE:
7 - 2 - 6 - 5 - 1 - 4 - 3

DEPT AREA :
80 - 168 - 144 - 40 - 222 - 130 - 37

Figure 27. Layouts for Problems 4F and 4C-3 Cell No.1

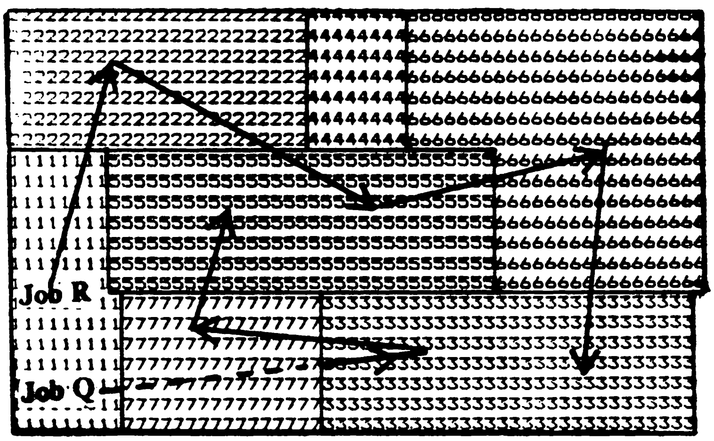


NUMBER OF BAYS: 3
NUMBER OF DEPARTMENTS: 7

PLANT LENGTH: 32.7
PLANT WIDTH : 27

DEPT SEQUENCE:
- 7 - 2 - 6 - 1 - 4 - 3

DEPT AREA :
80 - 168 - 300 - 120 - - 130 - 74



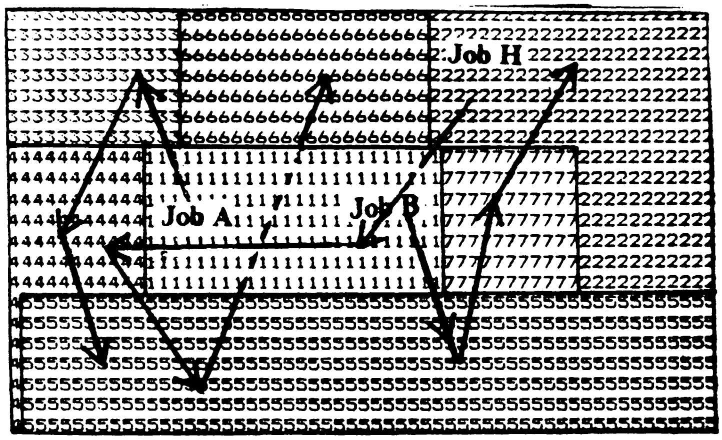
NUMBER OF BAYS: 3
NUMBER OF DEPARTMENTS: 7

PLANT LENGTH: 31.8
PLANT WIDTH : 25

DEPT SEQUENCE:
2 - 4 - 6 - 5 - 1 - 7 - 3

DEPT AREA :
80 - 112 - 144 - 40 - 148 - 195 - 74

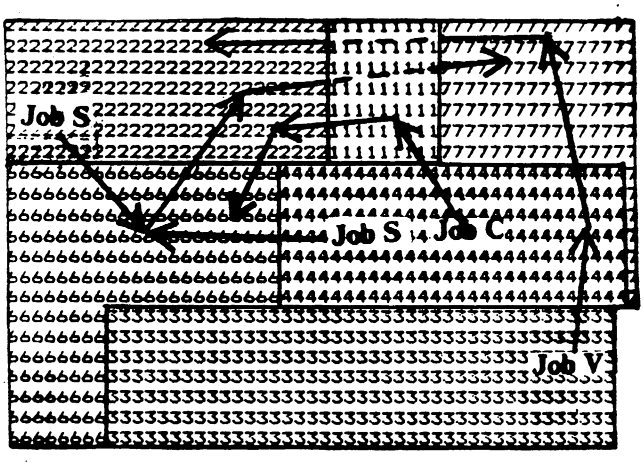
Figure 28. Layouts for Problems 4C-3 Cell No.2 and 4C-3 Cell No.3



NUMBER OF BAYS: 3
NUMBER OF DEPARTMENTS: 7
PLANT LENGTH: 27
PLANT WIDTH : 21

DEPT SEQUENCE:
3 - 6 - 2 - 7 - 1 - 4 - 5

DEPT AREA :
80 - 112 - 48 - 40 - 185 - 65 - 37

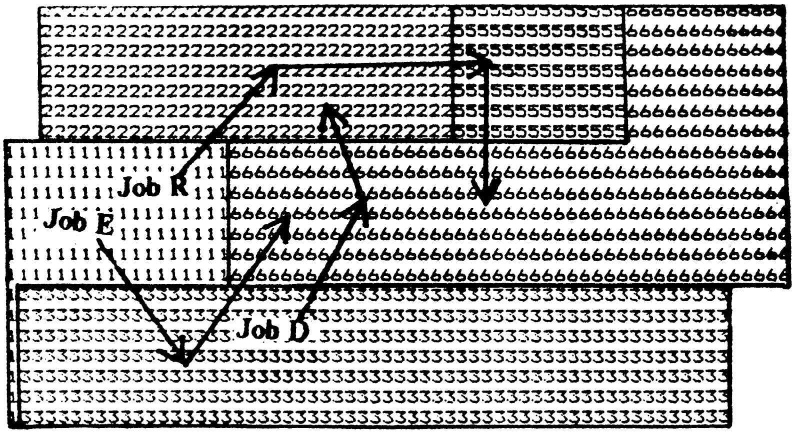


NUMBER OF BAYS: 3
NUMBER OF DEPARTMENTS: 6
PLANT LENGTH: 27.8
PLANT WIDTH : 24

DEPT SEQUENCE:
2 - 1 - 7 - 4 - 6 - 3

DEPT AREA :
40 - 112 - 180 - 120 - 10 - 130 - 74

Figure 29. Layouts for Problems 4C-4 Cell No.1 and 4C-4 Cell No.2

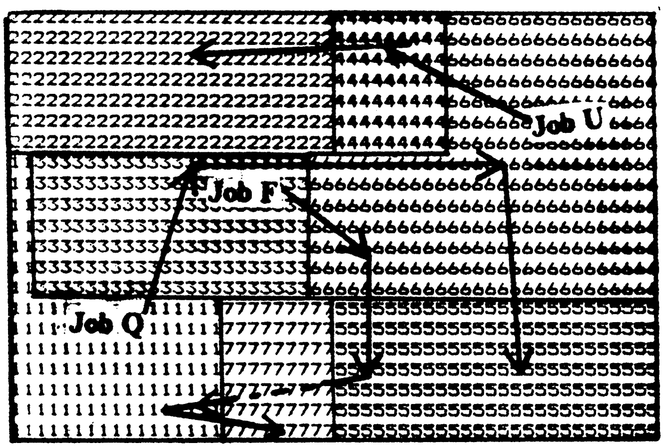


NUMBER OF BAYS: 3
NUMBER OF DEPARTMENTS: 5

PLANT LENGTH: 30.1
PLANT WIDTH : 21

DEPT SEQUENCE:
- 2 - 5 - 6 - 1 - 3 -

DEPT AREA :
65 - 112 - 192 - - 48 - 195 -



NUMBER OF BAYS: 3
NUMBER OF DEPARTMENTS: 7

PLANT LENGTH: 28
PLANT WIDTH : 24

DEPT SEQUENCE:
2 - 4 - 6 - 3 - 1 - 7 - 5

DEPT AREA :
80 - 112 - 96 - 40 - 111 - 195 - 37

Figure 30. Layouts for Problems 4C-4 Cell No.3 and 4C-4 Cell No.4

5.1.2 Final Item Cost Calculations for Each Facility

Outputs from steps 1, 2, 4, 5, and 6 can now be combined to find cost-based performance measures, cost of each job type and average item cost in each problem set, for both facility types. Such measures would help decision maker in weighing relative merits of each environment and deciding between the two facility types. Components of the total daily production cost of meeting the demand for each job type can be divided into two broad classes, direct and indirect production costs.

A) Direct Production Costs: These costs are directly attached to each item produced in either facility type.

1. **Actual Variable Cost:** Total variable costs found in step 2 should be revised as they do not include reductions in production levels of most jobs in step 5. In case steps 1 and 2 indicate that the investment and the area constraints are not binding, step 2 variable costs can be used as the actual variable costs after some adjustments. Following step 5 solutions, actual variable costs can be calculated by carefully analyzing the final machine/unit load assignments of each job type and multiplying the number of items for each operation needed with corresponding variable costs shown in Table 64 on page 249 in Appendix D.
2. **Set-up Cost**: Set-up times can be found by first calculating actual cutting time for each machine/unit load assignment and then subtracting the actual cutting time from the corresponding unit load time which already includes set-up time. Set-up costs are then found by multiplying the set-up time with the unit set-up cost rate of the machine used in the final step 5 assignment. If steps 1 and 2 are feasible (no binding operating constraints), the resulting assignments must be modified to include set-up effects using the proper average set-up factors discussed in the latter part of Chapter three because set-up considerations were ignored earlier if steps 1 and 2 were feasible.

3. **Material Handling Cost:** The total amount of travel for each job type in either facility can be found by adding the distances travelled according to the precedence requirement of each job. Total distances are then multiplied by the actual production level and proper BHC_k values. Table 48 on page 177 shows material handling distances for each job type in all facilities the job belongs.

B) Indirect Production Costs: These costs relate to the general production activity at either facility and must be allocated to each job type based upon a ratio derived by using actual production levels.

1. **Lost Sales Cost:** This cost, one of the outputs of step 5, is incurred as a result of a production plan accepted by management. This cost is considered an overhead item and is equally allocated to each item produced. For example, 16 items of job A not (problem set No.1F) produced represents \$560 of contribution to total daily lost sales. Instead of allocating \$560 to 88 job A items actually produced, total lost sales cost due to all job types is first found. Then, the total amount is divided by total number of jobs produced as explained in the numerical examples which follow.
2. **Daily Equivalent Investment Cost:** The total investment cost of machine mix of each facility (as determined after step 2 or step 4, and occasionally after step 5) is found and converted into uniform equivalent daily investment cost by using an annual interest rate of fifteen percent and a five year (250 workdays a year) machine depreciation period. A Capital Recovery Factor (CRF) of 0.00113738 is found (via engineering economy formulae) given the number of periods is 1250 days with a per period interest rate of 0.0006 percent (0.15/250). This cost is also an overhead item and it should be allocated to jobs according to production levels. Since each cell is an independent facility, investment cost of a cell's machine mix should be directly allocated to each cell's own job mix.

Cost Per Item Produced: Both total direct and indirect costs assigned to each job type are added and then divided by actual production level of each job type in a given facility. These final item costs should serve as a reference in judging the merits of the two competing production environments in a very concise and fair manner. Total and per item fixed and lost sales costs are shown Table 47 on page 176.

Examples of Final Item Cost Calculations:

The final item cost of job A in problem set No.1 was calculated under both daily production facilities. Actual level of production was 88 for the functional and 77 for the cellular facility.

Functional Facility: Table 45 shows calculations of the variable and the set-up cost components of the final item cost for the functional facility case :

Table 45. Calculation of Variable and Set-up Cost Components of Final Item Cost (Problem Set No.1F, Job A)

Operation Needed	In Dept. No.	Machine Assigned To	Total Variable Cost	Unit Load Time (mins.)	Actual Cutting Time (mins.)	Set-up Time (mins.)	Set-up Cost
2	1	J(1)	$220.00	197.80	184.80	13.0	$20.15
8	3	K(1)	$255.20	317.00	299.20	17.8	$19.76
11	4	J(1)	$123.20	199.90	184.80	15.1	$23.41
14	5	K(1)	$99.00	367.20	357.50	9.7	$10.67
14	5	K(2)	$33.00	149.50	143.00	6.5	$ 7.22
Total			**$730.40**				**$81.21**

Explaination of Entries in Table 45:

The variable cost of any operation No.2 is $2.5/item using machine J (Appendix D). 88 items of job A cost 88*$2.5 = $220.00 as shown in the first row above. It is already known that eight unit loads of job A requires 197.80 minutes on machine J (calculated with UNIT FORTRAN code) including set-up times. Processing time of operation No.2 is 2.1 minutes/item (any item) and 88 items of job A takes a total cutting time of 88*2.1 minutes = 184.8 minutes. Then, the set-up time portion of the unit load time is found as 197.8 - 184.8 = 13.0 minutes on machine J including major set-up and reset times (this set-up time could have been separately listed as another output of the code, but it is more convenient to retrieve it as needed). The set-up time needs to be known because it is costed at a higher rate than the regular operation rate. According to Table 65 on page 251 in Appendix D, it costs $1.55/minute to set-up machine J for any operation and 13.0 min. * $1.55/min = $20.15 for this operation on all 88 items of job A.

Simplification of Variable and Set-up Cost Calculations:

It is tedious and error prone to retrieve inputs from the proper appendix tables as shown above. Code UNIT FORTRAN was modified to perform the above calculations for all feasible combinations and print the results for each unit load segment in the following format :

```
SET 1  CLS 5 MHN N JB B UN   5 VC = $  84.00   SC = $24.80
SET 1  CLS 5 MHN N JB B UN   6 VC = $ 100.80   SC = $24.80
SET 1  CLS 5 MHN N JB B UN   7 VC = $ 117.60   SC = $27.28
SET 1  CLS 5 MHN N JB B UN   8 VC = $ 134.40   SC = $27.28
SET 1  CLS 5 MHN N JB B UN   9 VC = $ 151.20   SC = $29.76
SET 1  CLS 5 MHN N JB B UN  10 VC = $ 168.00   SC = $32.24
SET 1  CLS 5 MHN N JB B UN  11 VC = $ 184.80   SC = $32.24
```

Legend : Five unit loads (5 x 12 = 60 items) of job B's (the first row above) class No.5 operation (operation No.13) costs $84 in variable and $24.80 in set-up costs.

Necessary Variable Cost Adjustments When the Last Unit Load is a Partial One:

Since full production is to be achieved in problem sets No.3 and No.4, a partial last unit load possibility should be considered whenever a complete job order is assigned to more than one machine for the same operation. For example, Table 34 on page 143 showing the step 5F solution for problem set No.3 indicates that eight unit loads of job A (88 items) are assigned to the first machine J for a class No.1 operation (No.2) while two unit loads of job A (22 items) are assigned to the second machine J for the same operation. Total number of job A items assigned is now 110, but the mean daily demand of job A is only 104. Direct use of the tabulated variable costs would reflect the total variable cost for 110 items and manual calculation of the last unit loads's cost contribution could prevent this error. The difference in set-up cost will be small, but, it too can be adjusted similarly. No additional set-up is needed if the tabulated set-up cost of the previous unit load amount is equal to the set-up cost of the last unit load considered.

Material Handling Cost Calculation for Job A: Job A visits departments 1, 3, 4, and 5 as shown in Figure 18 on page 154, and it takes total of 51.73 feet of movement for each item of job type A before the last operation is completed. Distances between the departments are taken from Table 43 on page 156 and summed: 19.86 + 28.06 + 3.81 = 51.73 ft as each Job A item moves from department No. 1 to No.3, No.3 to No.4, and No.4 to No.5. The BHC_A equals $0.15 per foot and the total material handling cost of job A's order is $0.15/ft * 88 items * 51.73 ft/item = $682.84 per day. The sum of the above three direct production costs (variable, set-up, and material handling) is $1494.55/day or $16.98/item after dividing by 88.

Lost Sales Cost Calculation for Job A: The functional facility incurs $5776/day in lost sales. A portion of this amount is allocated to the job A order using the ratio of 88/466 where 466 is the total number items of all jobs (A,B,C, and D) produced in the facility : 88/466 * $5776 = $1090.75/day for all 88 job A items or $12.40/item (or directly $5776/466 = $12.40).

Daily Equivalent Investment Cost Calculation for Job A: The machine mix of the functional facility cost $1,111,000 to purchase (four machine P's at $97000 each, three machine J's at $61000 each, four machine K's at $75000 each, and three machine N's at $80000 each). In this example, Table 13 on page 125 which lists final machine mix for functional facility is used in calculating the total investment cost. This cost is multiplied by the CRF of 0.00113738, and $1263.63 is found as the daily equivalent investment or henceforth referred to as the daily fixed cost for all four job types. As above, item cost for each job A is found by dividing $1263.63 by 466 ($2.71/item).

Cellular Facility: Table 46 on page 175 shows the calculation of the variable and set-up costs of the final item cost for the cellular facility case:

Table 46. Calculation of Variable and Set-up Cost Components of Final Item Cost (Problem Set No.1C, Job A)

Operation Needed	Mini Dept. No.	Machine Assigned To	Total Variable Cost	Unit Load Time (mins.)	Actual Cutting Time (mins.)	Set-up Time (mins.)	Set-up Cost
2	1	P	$132.00	140.10	126.50	13.6	$18.36
2	4	J	$55.60	52.20	46.20	6.0	$ 9.30
8	3	K	$223.30	275.00	261.80	13.2	$14.65
11	4	J	$84.70	172.90	161.70	11.2	$17.36
14	5	K	$82.50	364.70	357.50	7.2	$8.00
14	2	K	$33.00	147.80	143.00	4.8	$5.33
Total			**$610.50**				**$73.00**

Two of the four operations needed by job A (No.2 and No.14) are met in two different mini-departments as allowed under cellular facility. Next direct cost item is material handling cost of job A in cell No.1. Table 20 on page 129 and Table 46 indicate that five of the seven unit loads of job A travel from mini-department No.1 to No.3 (14.1 ft on Figure 19 on page 158), from mini-department No.3 to No.4 (4.98 ft), and from mini-department No.4 to No.5 (2.86 ft) resulting in a total of 21.94 feet of material handling for 55 job A items at the cost of 0.15 * 55 * 21.94 = $181.01. The other two unit loads travel in the order of mini-departments No.4, No.3, No.4, and again No.3 and receive the required operations in the proper precedence order. This trip takes 10.11 feet for each item and costs $33.36 for two unit loads or twenty-two job A items. The total material handling cost of job A in Cell No.1 is equal to $214.37 with an average travel distance of 18.56 feet.

The sum of the three direct costs equal $897.87/day or $11.66/item. Each job A item is also allocated lost sales cost of $9.97 ($4574/459). To calculate daily fixed cost, the final machine mix of cell No.1, listed in Table 18 on page 127, is used in calculating the investment cost as $732,000. The resulting daily fixed cost is $3.40/item. A cost-based performance comparison of the two facilities is given below for Job A in problem set No.1.

Facility Type	(1)	(2)	(3)	(4)	(5)	(6)
Functional	88	$16.98	$2.71	$12.40	$32.09	51.73 ft
Cellular	77	$11.66	$3.40	$ 9.97	$25.03	18.56 ft

Legend : All entries above are on per item basis.

- (1) Daily Production Level (2) Daily Direct Cost (3) Daily Fixed Cost
- (4) Daily Lost Sales Cost (5) Total Daily Cost (6) Material Handling Distance

Table 47. Indirect Daily Production Costs and Production Levels

Problem Set No.	Total Fixed Cost Per Day	Per Item Fixed Cost	Total Lost Sales Cost Per Day	Per Item Lost Sales	Items Produced Per Day
1F	$1263.63	$ 2.71	$ 5776	$12.40	466
1C	$1389.88		$ 4574	$ 9.97	459
Cell No.1	$ 832.56	$ 3.40			
Cell No.2	$ 557.32	$ 5.06			
2F	$1711.76	$ 3.06	$ 8881	$15.64	568
2C-2	$1707.21		$ 7789	$11.21	695
Cell No.1	$ 896.26	$ 3.22			
Cell No.2	$ 810.95	$ 1.91			
2C-3	$1781.04		$10637	$18.47	576
Cell No.1	$ 735.89	$ 3.50			
Cell No.2	$ 634.66	$ 3.08			
Cell No.3	$ 410.59	$ 2.57			
3F	$3509.96	$ 2.88	$ 0.0	$ 0.0	1220
3C-2	$3395.96		$ 0.0	$ 0.0	1220
Cell No.1	$1896.01	$ 3.25			
Cell No.2	$1499.07	$ 2.35			
3C-3	$3636.71		$ 0.0	$ 0.0	1220
Cell No.1	$1631.00	$ 3.31			
Cell No.2	$1013.41	$ 3.27			
Cell No.3	$ 991.80	$ 2.38			
4F	$4625.73	$ 2.75	$ 0.0	$ 0.0	1683
4C-3	$4720.13		$ 0.0	$ 0.0	1683
Cell No.1	$1632.14	$ 2.76			
Cell No.2	$1451.30	$ 2.42			
Cell No.3	$1636.69	$ 3.33			
4C-4	$5006.74		$ 0.0	$ 0.0	1683
Cell No.1	$1337.56	$ 3.31			
Cell No.2	$1213.58	$ 2.79			
Cell No.3	$1106.67	$ 2.65			
Cell No.4	$1348.93	$ 3.16			

Table 48. Material Handling Distances

Problem Set	Job A	Job B	Job C	Job D	Job E	Job F	Job H
1F	51.73	24.13	20.80	15.17	-	-	-
1C	18.56	9.91	13.12	4.94	-	-	-
2F	25.38	23.18	33.12	10.76	16.51	43.39	n/a
2C-2	9.11	11.93	15.72	12.26	5.42	9.43	27.35
2C-3	27.33	12.89	10.78	9.42	10.51	n/a	16.10
3F	66.52	54.01	107.53	33.40	35.06	80.18	60.74
3C-2	41.14	36.08	27.40	26.81	6.78	31.78	34.26
3C-3	25.56	49.99	12.70	7.06	16.30	52.35	17.53
4F	68.49	55.68	42.46	35.68	30.49	80.75	47.81
4C-3	26.27	18.24	21.38	14.51	15.50	20.21	56.42
4C-4	15.16	12.88	11.38	7.06	7.06	30.29	30.97

The following jobs are only in problem sets No.3 and No.4.

Problem Set	Job Q	Job R	Job S	Job U	Job V
3F	69.82	40.21	40.40	-	-
3C-2	20.89	28.59	36.03	-	-
3C-3	21.94	16.66	36.41	-	-
4F	78.93	48.12	59.58	46.52	56.01
4C-3	32.82	29.84	19.01	10.55	16.13
4C-4	13.86	17.98	27.89	6.74	17.14

Direct and indirect per item costs are added to determine final item costs under each facility type. Table 49 on page 178 shows the results. Then, the total daily costs are found for each facility and divided by actual number items to be produced to find average item costs. Average item costs, shown in Table 50 on page 179 along with total daily costs, serve as guides in judging the merits of each facility for the given data.

Table 49. Final Item Costs Under Each Facility Type

Problem Set	Job A	Job B	Job C	Job D	Job E	Job F	Job H
1F	$32.09	$28.99	$29.41	$27.86	-	-	-
1C	$25.03	$23.73	$25.90	$23.54	-	-	-
2F	$32.49	$31.94	$35.25	$29.48	$33.20	$44.04	n/a
2C-2	$24.76	$25.36	$26.18	$24.81	$23.41	$32.86	$45.56(*)
2C-3	$34.91	$32.27	$33.84	$31.46	$32.65	n/a	$38.84
3F	$22.08	$22.35	$31.87	$18.46	$23.33	$36.45	$33.35
3C-2	$18.44	$18.62	$17.52	$16.88	$13.32	$25.05	$33.35
3C-3	$16.09	$21.47	$16.07	$13.19	$16.25	$29.83	$20.38
4F	$22.17	$22.75	$20.70	$19.35	$21.87	$36.80	$29.10
4C-3	$15.83	$15.26	$16.30	$14.94	$14.03	$22.44	$32.11
4C-4	$14.41	$14.46	$14.97	$13.19	$13.18	$24.93	$24.39

(*) This high cost is largely due to the production of only one unit load of job H. Small production results in a high set-up cost burden on each item produced. Only one unit load or five job H items are produced in problem No.2C-2 of set No.2 while incurring the initial major set-up before each machine is visited.

Problem Set	Job Q	Job R	Job S	Job U	Job V
3F	$16.42	$23.92	$24.00	-	-
3C-2	$13.20	$21.73	$21.86	-	-
3C-3	$14.18	$18.32	$23.16	-	-
4F	$17.10	$23.85	$30.18	$16.02	$17.83
4C-3	$15.02	$22.92	$16.38	$12.81	$13.87
4C-4	$14.10	$18.91	$20.26	$12.03	$13.90

Table 50. Total Daily Costs Comparison of the Facilities

Problem Set No.	Variable Cost	Set-up Cost	Material Handling Cost	Fixed Cost	Lost Sales Cost	Total Daily Cost	Average Item Cost
1F	$ 4092	$ 415	$ 2129	$ 1264	$ 5776	$13676	$ 29.35
1C	$ 3891	$ 274	$ 893	$ 1390	$ 4574	$11022	$ 24.01
2F	$ 4994	$ 643	$ 2861	$ 1712	$ 8891	$19091	$ 33.61
2C-2	$ 6204	$ 474	$ 1622	$ 1707	$ 7789	$17796	$ 25.61
2C-3	$ 4827	$ 495	$ 1635	$ 1781	$10637	$19375	$ 33.64
3F	$11516	$ 1228	$14298	$ 3510	$0	$30552	$ 25.04
3C-2	$11452	$ 1001	$ 6927	$ 3396	$0	$22776	$ 18.67
3C-3	$11506	$ 851	$ 6439	$ 3637	$0	$22433	$ 18.39
4F	$15650	$ 1634	$16519	$ 4626	$0	$38429	$ 22.83
4C-3	$15519	$ 1304	$ 6577	$ 4720	$0	$28120	$ 16.71
4C-4	$15392	$ 1169	$ 4652	$ 5007	$0	$26130	$ 15.53

Example : In problem set 1F, average item cost is found by dividing the total daily cost with the number of items produced: $13676/466 = $29.35.

5.1.3 Sensitivity Analysis of Average Item Costs

Average item costs shown in Table 50 are based on the data in Appendix D. While variable, set-up, and fixed costs may be known with high certainty, lost sales and material handling cost coefficients of each job type are somewhat arbitrary. To provide more comprehensive comparison of the two production facilities, these cost coefficients were allowed to vary within $\pm$ one hundred percent of the original values. Figures from Figure 31 on page 180 through Figure 36 on page 185 show plots of changes in average item cost (AVGCOST) in each facility type with respect to changes in material handling costs (MHCCHNG) in all four problem sets and lost sales cost (LSCCHNG) in problem sets No.1 and 2.

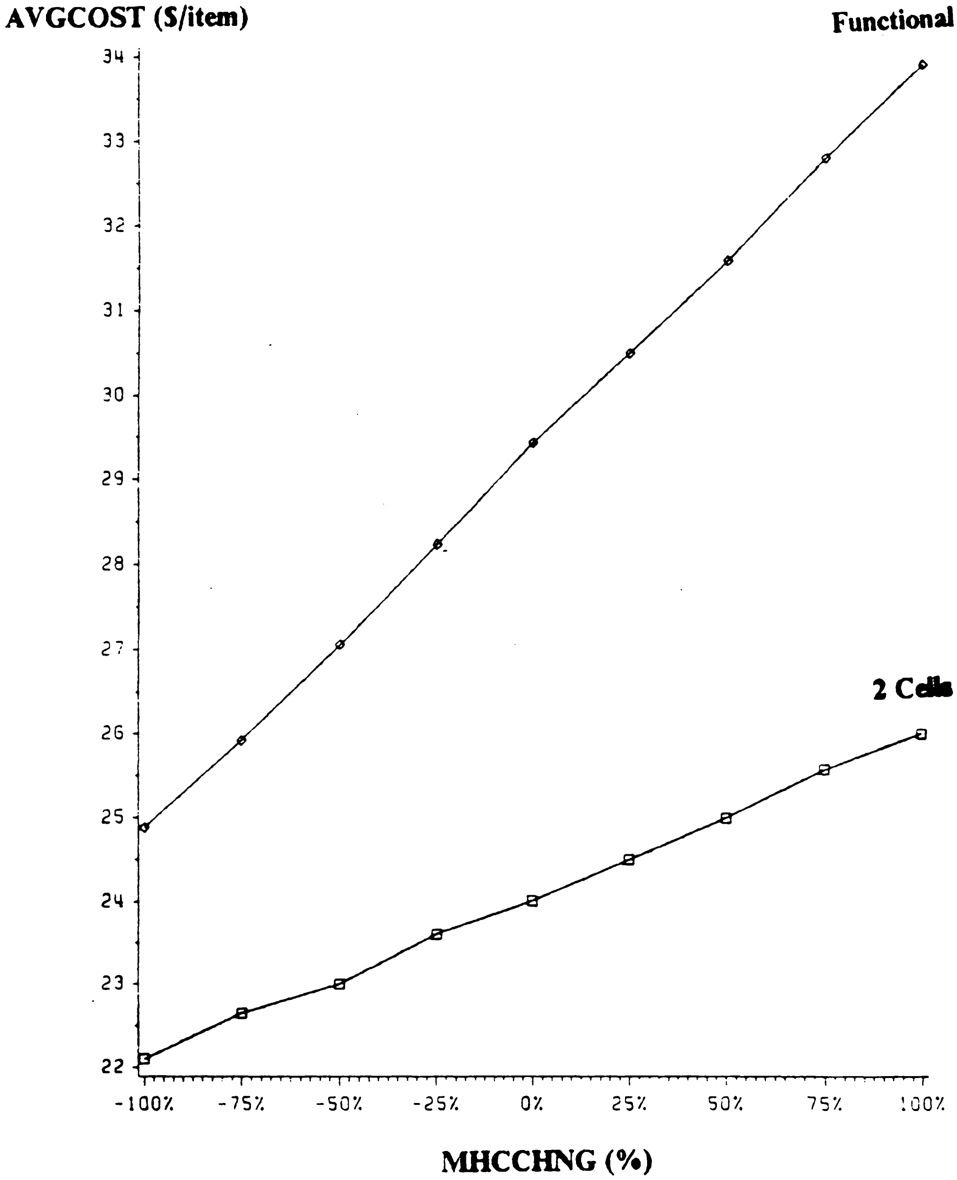


Figure 31. Average Item Cost Under Varying Material Handling Costs in Problem Set No.1

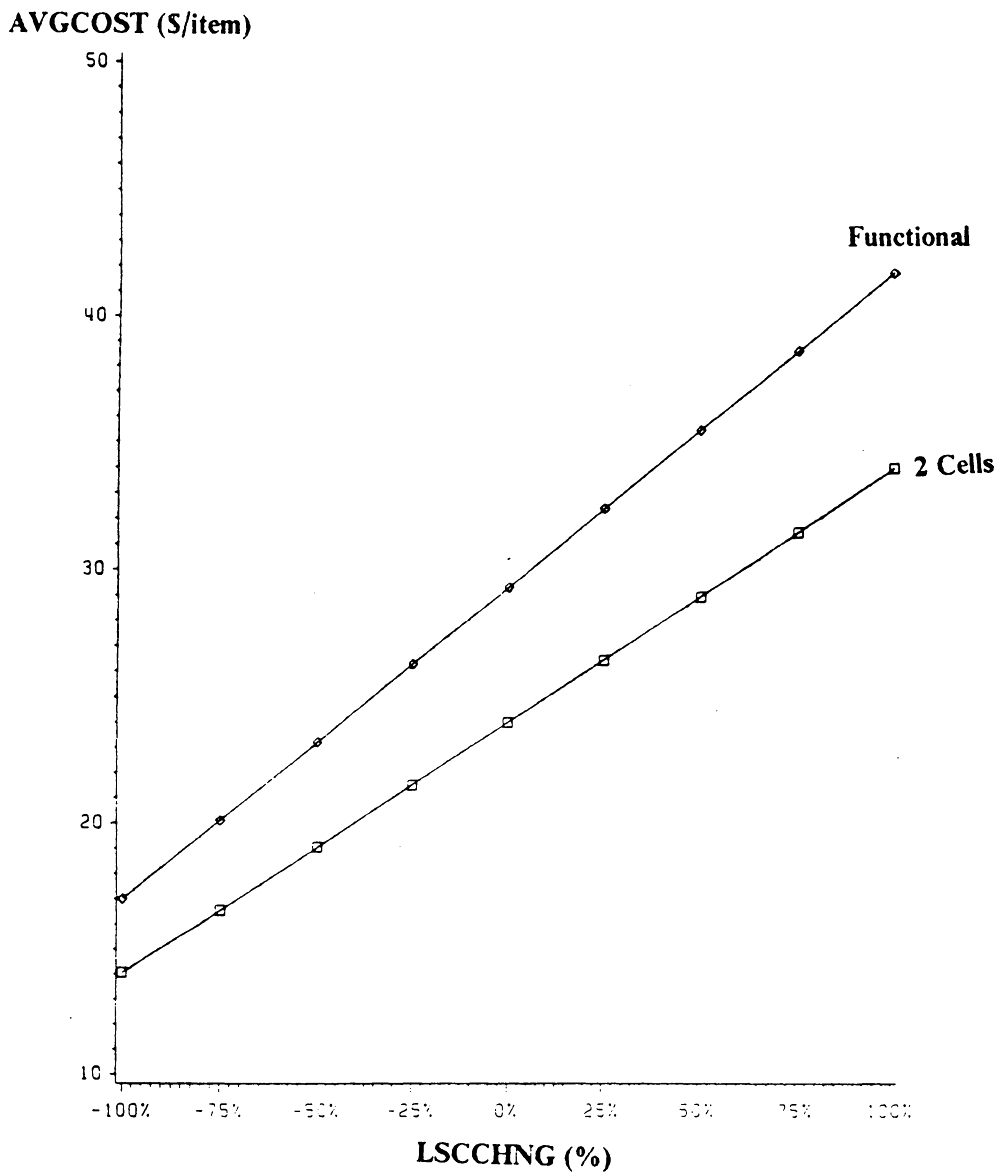


Figure 32. Average Item Cost Under Varying Lost Sales Costs in Problem Set No.1

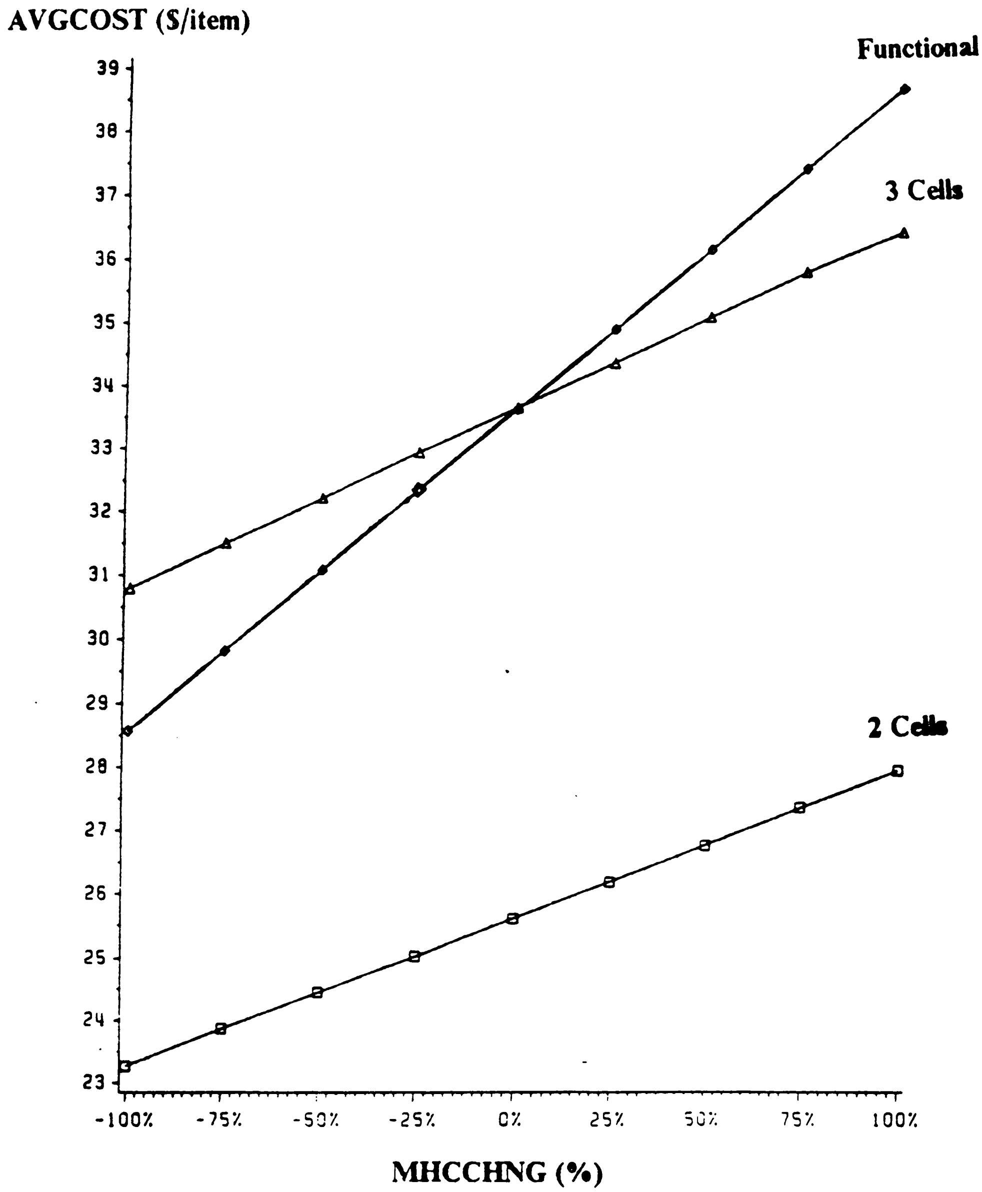


Figure 33. Average Item Cost Under Varying Material Handling Costs in Problem Set No.2

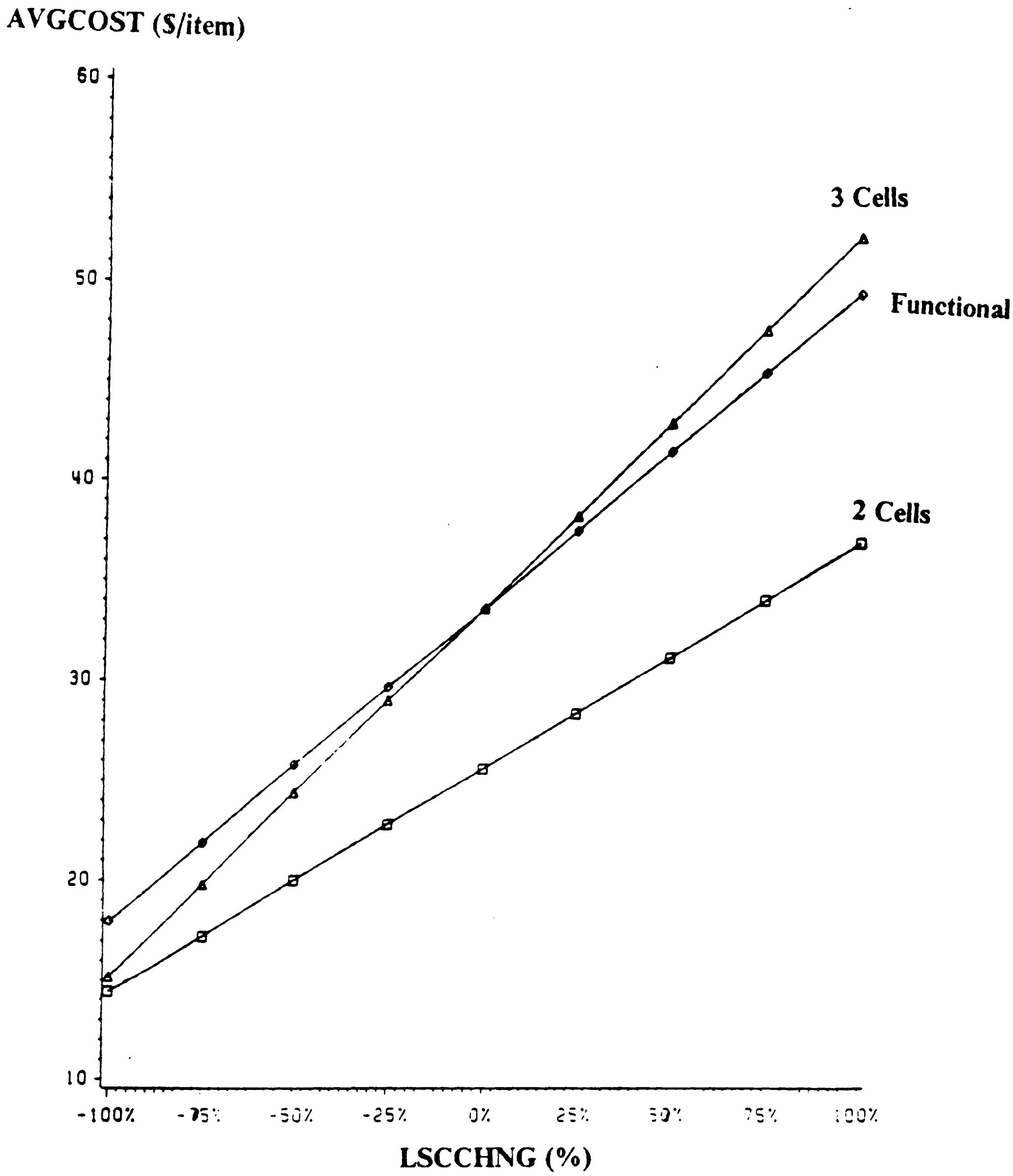


Figure 34. Average Item Cost Under Varying Lost Sales Costs in Problem Set No.2

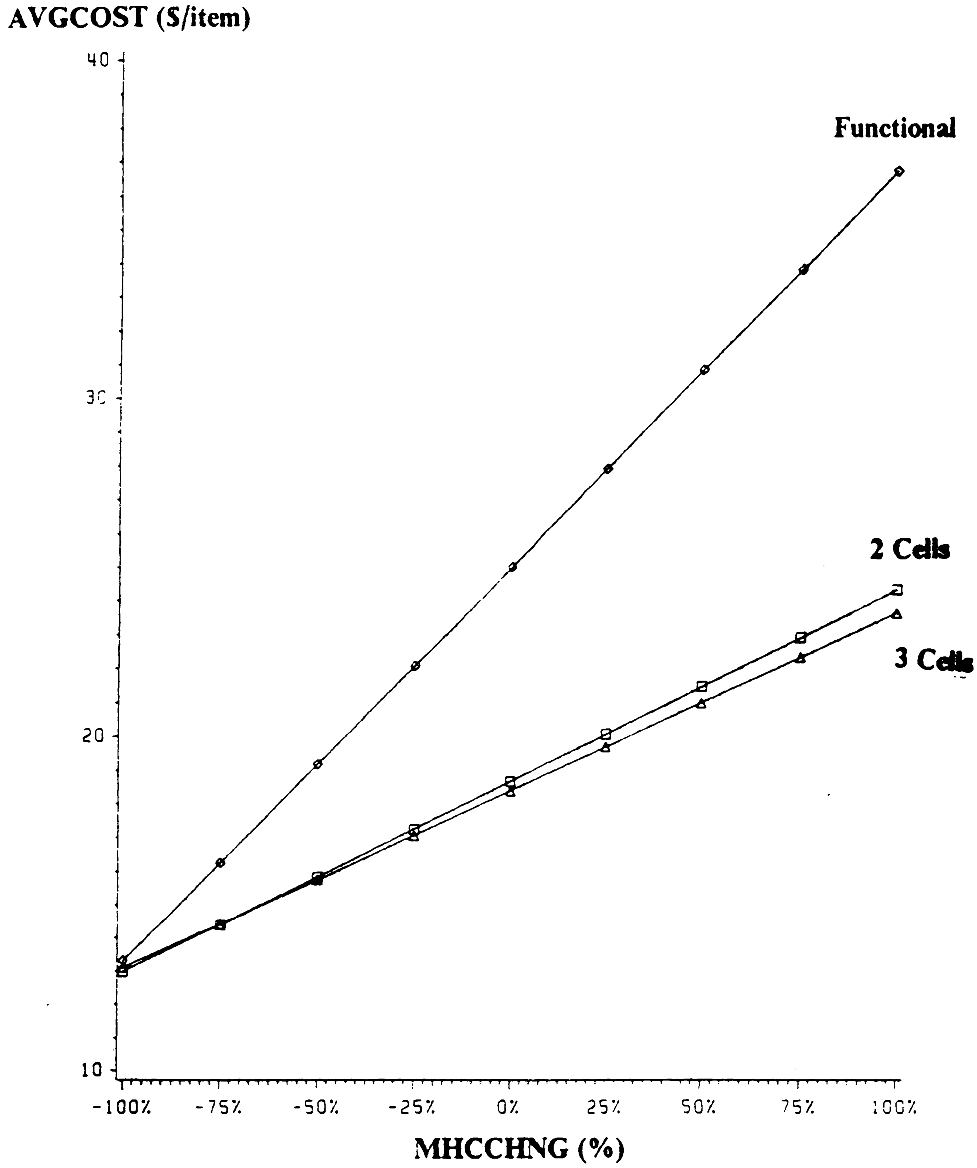


Figure 35. Average Item Cost Under Varying Material Handling Costs in Problem Set No.3

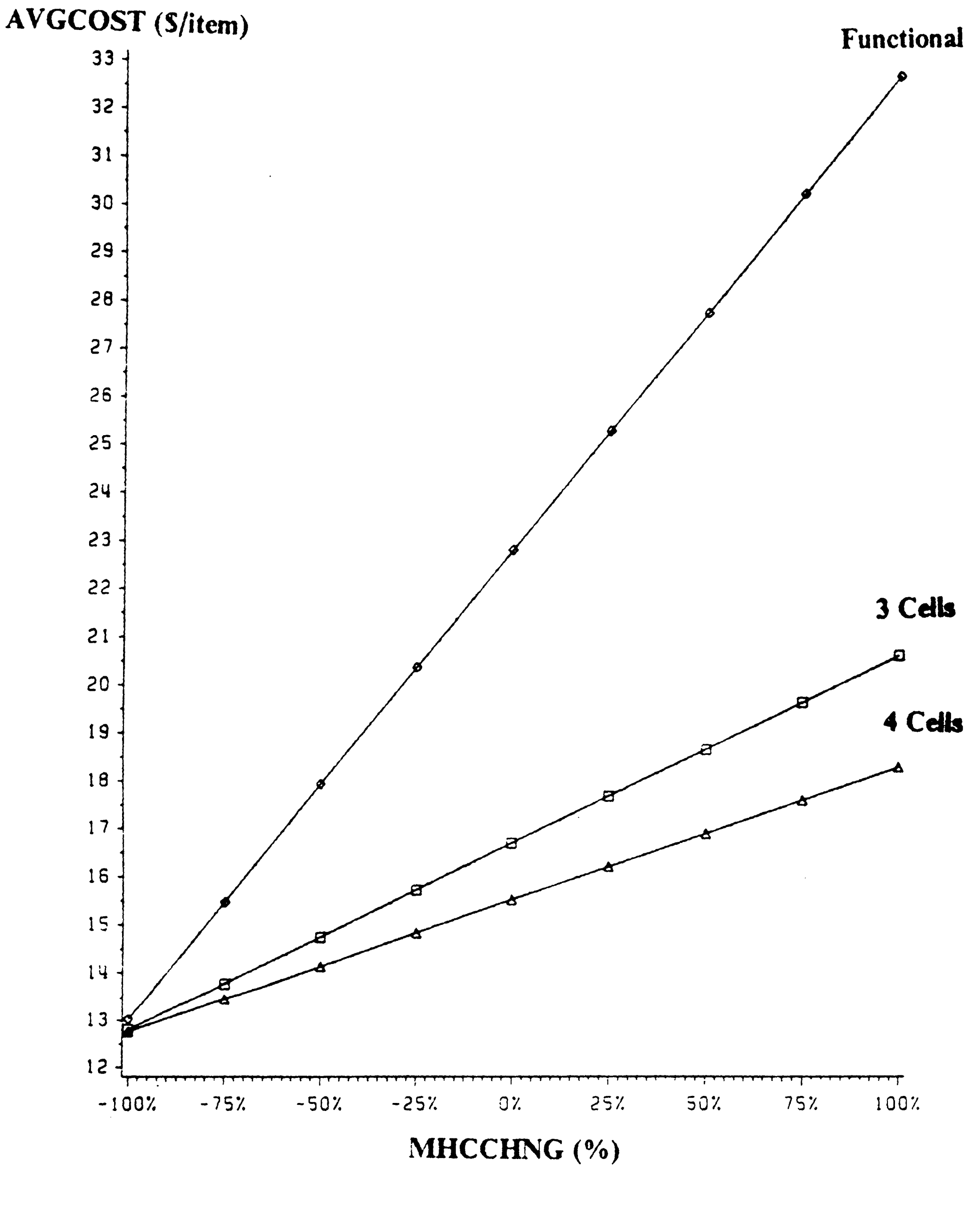


Figure 36. Average Item Cost Under Varying Material Handling Costs in Problem Set No.4

Summary:

As expected, most jobs required less material handling under the cellular facility. Jobs, on the average, required 59 percent less material handling in problem set No.1, 40 percent less in problem set No.2, 46 percent less in problem set No.3, and 63 percent less in problem set No.4. Increasing the number of cells within the cellular layout also reduced the amount of material handling requirements, but these reductions were not drastic and they ranged from 10 to 25 percent as the number of cells was increased from two to three (problem set No.2 and 3) and three to four (problem set No.4).

Cellular facilities appeared to have lower final item costs in general, but this advantage was partly due to the arbitrary cost coefficients assumed, in Appendix D, for material handling and lost sales cost component calculations. While Table 50 on page 179 indicates, on the average, 12 to 29 percent lower average final item cost for cellular facilities, Figures 30 through 35 show that the differences in average final item costs for each facility are usually reduced if lower cost coefficients are used in the total facility and the average item cost calculations. In fact, the difference approaches zero in some cases and the functional facility becomes cheaper than the cellular facility with three cells in problem set No.2. Set-up costs were always less for the cellular facilities, but the set-up cost component only ranged between three to five percent of the total daily costs in all problem sets for both facility types.

This Chapter has shown that, in stage one, cellular facilities may offer lower average production costs per item. The gap in average item production costs is likely to be narrower as better material handling means are introduced to the facilities. Then, however, the cost of automating/improving the current material handling equipment needs to be considered as an additional fixed cost item for the functional facility option. Traditional material handling means such as those based largely on human power, are likely to keep the cellular option more economical.

6.0 Simulation of the Facilities (Stage Two)

Stage one has presented a methodology to perform both capacity planning and general scheduling tasks for both types of production environments. The resulting performance measures, total item cost and total production cost per period, do not adequately reflect each environment's relative quality since stage one can not account for the dynamic nature of the facilities. The use of simulation is one method to examine the dynamics of each environment. The simulation model was utilized as a laboratory in which design alternatives were tested and compared. While simulation analysis is experimentation rather than optimizing, a hybrid approach as in this research, combines the strengths of simulation and optimization.

The purpose of simulation in this Chapter, outlined in Figure 37 on page 188, is not that of evaluation of scheduling rules, effects of various overtime policies, or determination of bottleneck machines. Instead the purpose is to achieve:

- A balanced treatment of the components of both environments,
- Good adherence to the details of both environments,
- An in-depth look at the dynamic behavior of both environments and,
- A way to understand the impact of the random behavior of the components of both environments.

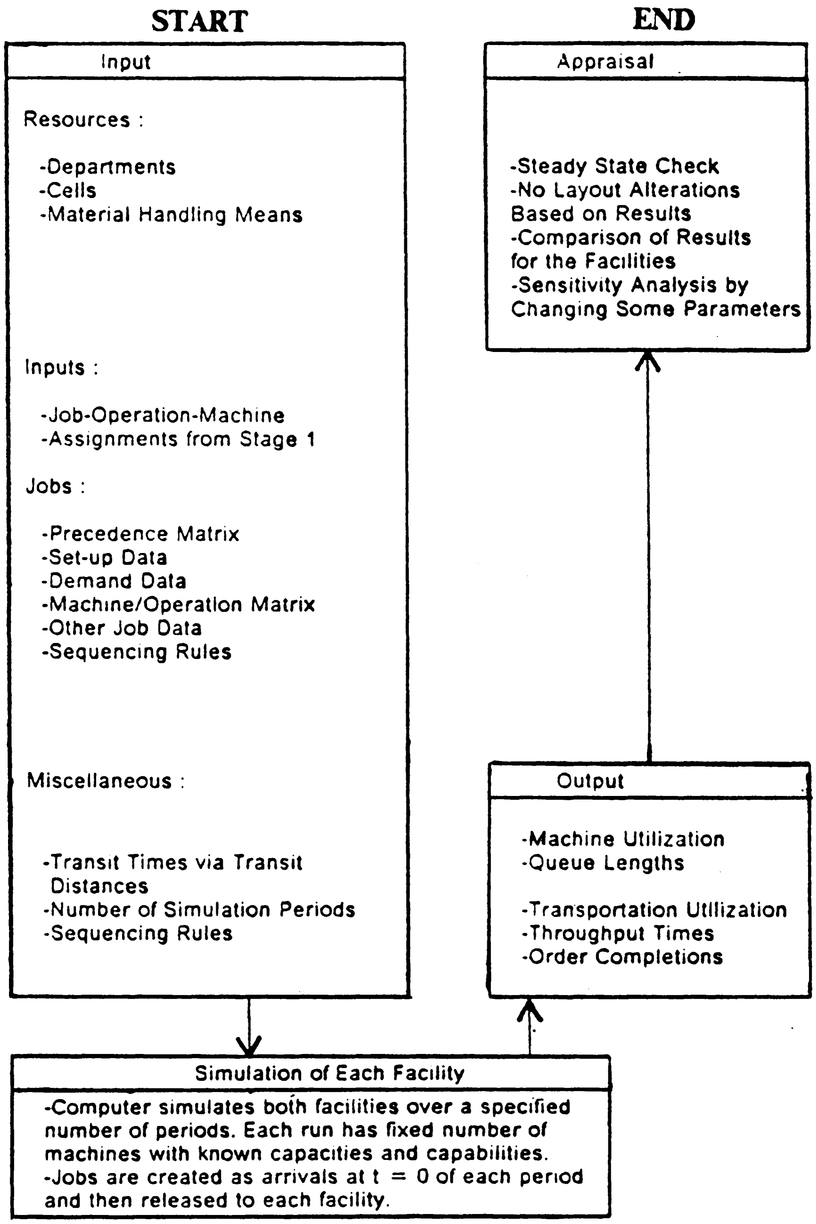


Figure 37. Major Components of Simulation of Facilities

6.1.1 General Description of the Simulation Analysis

Each facility receives a new load of jobs at the beginning of each production period, and it is likely that some of the jobs from the previous period are still in the system (facility) requiring processing. Both production environments are subject to the following assumptions once all stage one decisions are made, and the physical location of all machines in cells and departments are determined:

1. All jobs arrived at the beginning of the production period (day), and all became available at that time. The daily demand of each job was found by drawing a random number from the demand distribution. For example, daily demand for job A was drawn from N(104,18) (no negative demand is allowed).
2. If there were investment constraints (Problem Sets No.1 and No.2), deterministic production levels found in Chapter four were used because these levels do not require more capacity the available capacity.
3. Remaining jobs of each type were divided by MNK_k and then rounded down to determine the integer number of unit loads of each job type by ignoring the possibility that last unit load may be a partial one. Such a simplification does not cause significant deviation from the stage one solution because any overloading should be compensated by rounding down of fractional number of unit loads.
4. All due-dates were common and equal to the end of the production period (day) and there was no cost penalty for early completion. Jobs in unit loads (entities) had priority only based upon their arrival dates to the facility (FIFO).
5. No preempting, alternate routing (unless predefined in some cases), rework, or scrap allowance was considered and all jobs had the same priority.
6. Machine breakdowns were considered in stage one by allocating higher machine capacities to account for down times. Machine breakdowns may only be considered as embellishments in this stage.

7. The sequence of operations for each unit load of job type, routing, was an input to the simulation stage from stage one, so no route generation was necessary.
8. Queues (files) were maintained for all unit loads that needed to move to and from a machine in a department or a mini-department (production zone) using one of the limited number of movers. Each queue operated on the priority basis of FIFO for regular jobs.
9. Within facility travel distances and times are not negligible; each production environment used limited number of material/WIP movers for transport among the machines in cells and departments within the shop. Three major move types are possible :
   - Between two machines in a cell,
   - Between two adjacent departments (functional case), and
   - Between two non-adjacent departments (functional case).

   These transportation distances were determined in Chapter five for all problem sets. To accommodate SIMAN's requirement that the distances be entered as an upper triangular matrix. Average distances were used whenever the distance between two production zones were different in opposite directions. Also, all distances were rounded off to the nearest integer as required by the SIMAN simulation language.
10. Transporters, carts, were allocated for each problem set such that each cell was assigned one transporter unit. Problem set No.1, 2, 3, and 4 were allocated 2, 3, 3, and 4 transporters respectively. Nearest available transporter selection rule was used and no job type including special set-up jobs, discussed later, was assigned higher priority in requesting a cart.
11. Move from the storage to the first processing zone was assumed instant. Distances between all production zones and the exit zone were taken as one unit length since no such moves were considered in Chapter five.
12. Machine area includes sufficient space to store machined parts so that the machine can start working on a new batch even if completed batches have not been moved away (no buffer limitations).

13. The mathematical modelling stage indicates exactly which machine each unit load of job is to visit for its operations, but the condensed form of this detail was implemented in stage two. Instead of specifying exact assignment for each unit load, all unit loads of different jobs were routed to each necessary zone through a single queue. This assumption prevents the inclusion of additional attributes into SIMAN code and simplifies overall programming effort.
14. Processing time of each operation of a unit load of job was treated as the sum of normally distributed random variables whose means are given in Appendix D. For example, whenever a single job item arrives to machine J for operation No.12 (class 4), its processing time is found by drawing (redraw a new operation time if $t \leq 0$) a random number from N(3.2,0.64) (standard deviation of each operation time is equal to twenty percent of its mean). Then :
    - Mean operation time of each unit load of job type k is equal to [$MNK_k \, t^c_{in}$],
    - with standard deviation of [$0.20 \; t^c_{in} \sqrt{MNK_k}$].

    To illustrate using job A with unit load size of eleven items, parameters of one unit load of job A for operation No.12 are $11*3.2 = 35.2$ minutes for mean and $0.2*3.2*\sqrt{11} = 2.12$ minutes for standard deviation [N(35.2,2.12)].
15. At the end of the total production period (day), there should be no incomplete jobs left in either facility if stage one, modelling stage, could really account for all the uncertainty in the data. All incomplete jobs were reported as such, costed accordingly, and carried forward. Some delays, however, were expected to occur due to transportation times which were ignored in stage one.
16. There were always seven stations in the SIMAN model frame of all facilities in all problem sets even though some cells had fewer than seven mini-departments in stage one. Each station with one or more machines of one or more different types represented a production zone. In cellular cases with less than seven mini-departments, extra stations were left out of the model by assigning a zero number of resources in the experiment frame of SIMAN.

17. One simulation model was written for each of four functional facilities in the four problem sets. To model all the cellular facilities in the four problem sets, nineteen separate simulation models were written. Appendix L shows some sample SIMAN codes as it is not necessary to include all models, which are similar in many ways, here.
18. General simulation outputs are shown in Figure 37 on page 188. Summary results along with a detailed comparison of the two facility types are tabulated later in this Chapter.

Adjustment of Set-up Requirements for Simulation:

The following guidelines were used in making job-operation-machine assignments in Chapter four as a part of the overall hierarchical procedure :

- If the capacity requirements of a single job type's demand, in unit load terms, was equal to or exceeded the available capacity of a given machine type, there was to be one major set-up before processing the first unit load and periodic minor set-ups.
- If the capacity of a machine was shared by two or more job types, then, ideally, unit loads of each job type should be grouped and ordered such that the major set-up requirements due to switches was minimized.

In this Chapter, the above guidelines were modified to handling set-up requirements. While the set-up requirements were not ignored, no attempt was made to actually sequence the jobs before each machine. Although ideal, such sequencing was not essential, and it required the inclusion of FORTRAN subroutines to the current simulation model because SIMAN does not handle such modelling details in its network format. But, a portion of the total capacity of each machine in every production zone was allocated for set-up at the beginning of each production period of 480 minutes. The procedure is :

1. Determine total set-up time of each machine in a given production zone. For example, in problem set No.2F, six unit loads of job A assigned to machine J(1) in department No.1

requires 10.7 minutes of total set-up time which includes the major and the periodic minor set-up requirements. This data was obtained by altering segments of code UNIT FORTRAN to output total set-up times. The same machine J(1) was also assigned ten unit loads of job C which requires 12.2 minutes of set-up work increasing the total set-up requirement on machine J(1) to 22.9 minutes. The other two machines in department No.1, P(1) and Z(1), have job assignments which require total of 36.8 and 23.5 minutes of set-up respectively.

2. Determine the average set-up time per machine in each production zone considered, functional or cellular: $(22.9 + 36.8 + 23.5)/3 = 27.7$ minutes.
3. Create special set-up jobs as entities along with the real jobs within both SIMAN frames. Set-up jobs represent set-up requirements and visit only the production zone targeted and the exit station. Using the same example, there were three set-up jobs that arrived every 480 minutes to department/station No.1 to occupy one of the three available machines before any of the regular jobs were picked from the common queue. Set-up jobs had priority over the others in order to insure that each machine received only one set-up job at the beginning of each production period. Each set-up job duration in the above case was assumed to follow a normal distribution and have a standard deviation which is equal to ten percent of its mean: [N(27.7,2.8)].

The procedure was the same for the cellular facility. Set-up times calculated as above and used in simulation are included in Appendix L as a part of the experiment (data) frame of selected SIMAN models and not repeated here.

Provisions for Multiple Routings in Cellular Facilities:

As pointed out in Chapters three and four, members of a cell's job mix are allowed to deviate from the primary job flow sequences shown in Table 42 on page 153 and make use of the excess capacity in other mini-departments. For example, Table 20 on page 129 shows that five unit loads of job A (cell No.1 in problem set No.1) follow the main routing of visiting mini-departments in 1-3-4-5 order while two unit loads visit mini-departments 4-3-4-3 to receive the same four distinct operations in correct precedence order as in the main routing. The following guidelines were used in reflecting such routing changes in simulation :

1. In problem sets No.1 and No.2, each job mix was divided into new job types with specific routings and daily demands in fixed amounts as determined in Chapter four. Job A, for example, was divided into two jobs, A1 and A2, with demand levels and routings as indicated in Chapter four.
2. In problem sets No.3 and No.4, each random daily demand was determined by using its parameters, converted to unit loads, and rounded down. Next, secondary sequences were assigned the same number of deterministic unit loads as listed in tables of Chapter four. Remaining unit loads, random amount less the fixed amount assigned to secondary sequences, followed the main sequence shown in Table 42 on page 153. For example, Table 38 on page 147 showing step 5C solution for cell No.1 of problem set No.4C-3 indicates that twenty-one unit loads of job H follow the main routing of visiting mini-departments 2-1-4-5-6 and three unit loads of job H follow a secondary routing of visiting mini-departments 2-1-1-5-6. During the simulation, three unit loads were always assigned to the secondary routing while the remaining random number of unit loads were assigned to the primary routing.
3. If the secondary sequence has been assigned the majority of the mean daily demand for a given job type, then the primary sequence was assigned the deterministic number of jobs (in unit loads). The remaining random number of jobs followed the secondary sequence.

4. If no portion of a given job type followed the primary sequence as shown in Table 42 on page 153, then the sequence with the most number of jobs was treated as the primary sequence in the procedure explained above. Table 51 on page 197 shows the sequences for all cellular facilities of problem sets No.1 and 2. For example, job A has two routes. Table 52 on page 198 and Table 53 on page 199 show the sequences for problem sets No.3 and No.4. Mean daily demand, in unit load terms, for each route of a given job type was retrieved from the proper tables in Chapter four.
5. Stochastic unit load times of the same job types were added when such secondary routings required that the unit loads remain in the same mini-department for the next operation. For example, three unit loads of job H, now a new job type of H1, visit mini-departments 2-1-1-5-6 to receive operations No.5, 2, 11, 14, and 18. Since operations No.2 and No.11 were both performed in mini-department No.1 by using one of the two available machine J's, the revised secondary routing could be written as 2-1-5-6 with operation time of N(10.5,0.9) + N(10.5,0.9) = N(21,1.3) in mini-department No.1.

Figure 38 on page 196 shows the general flowchart of all simulation models. Variables A(2), A(3), A(4), and A(6) are various attributes and are defined in Appendix L where sample simulation codes are presented. Attributes of each exiting job were analyzed and stored for final statistical analysis. Precedence requirements of each job type was entered via SEQUENCES element and the moves between the production zones were controlled by SYNONYMS element. Combined use of these two elements [189,206] has eliminated the need for extensive coding for specifying job flows in accordance with precedence requirements. Explanation of other attributes, A(1) and A(5), and details of simulation logic are available in Appendix L as comments within both MODEL and EXPERIMENT frames.

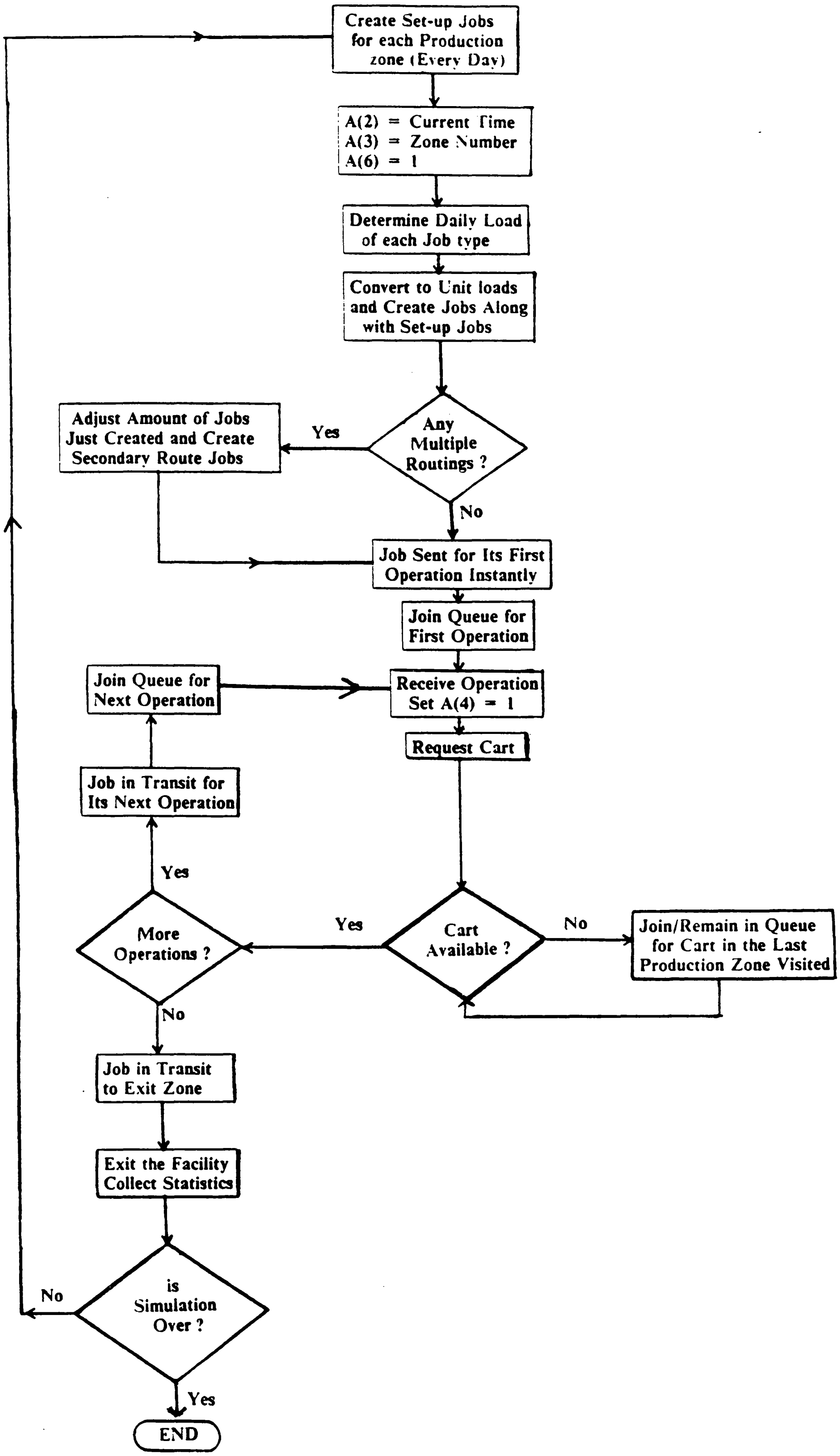


Figure 38. General Flowchart of the SIMAN Simulation Model

Table 51. Sequence of Station Visits in Cellular Facilities of Problem Sets No.1 and 2

Job Name	Problem Code	Demand	1st Visit	2nd Visit	3rd Visit	4th Visit	5th Visit	Ends at
A (!)	1C21	5	1	3	4	5	-	8
A1	1C21	2	4	3	4	3	-	8
B (!)	1C21	12	1	5	7	2	-	8
B1	1C21	2	1	3	2 (*)	2 (*)	-	8
C(!)	1C22	13	No	multiple	routings			
D(!)	1C22	11	No	multiple	routings			
A1	2C21	6	1	4 (*)	4 (*)	5	-	8
A2	2C21	1	1	3	1	3	-	8
B (!)	2C21	11	1	5	7	2	-	8
B1	2C21	1	1	3	7	2	-	8
F1	2C21	4	3	6 (*)	6 (*)	1	2	8
F2	2C21	1	3	6	3	1	2	8
H (!)	2C21	1	No	multiple	routings			
C (!)	2C22	8	4	1	2	6	-	8
C1	2C22	10	4	1	3	6	-	8
D (!)	2C22	14	No	multiple	routings			
E (!)	2C22	8	1	3	6	-	-	8
E1	2C22	16	1	3	1	-	-	8
A1	2C31	6	2	6	4	5	-	8
B	2C31	17	No	multiple	routings			
F	2C31	0	No	multiple	routings			
C (!)	2C32	17	No	multiple	routings			
H1	2C32	14	2	1	4	5	1	8
D (!)	2C33	10	No	multiple	routings			
E1	2C33	10	1	2	6	-	-	8

(!) : Primary sequence is as shown in Table 42 on page 153.

(*) : Two operations will be combined into one.

All demand levels are deterministic in Problem sets No.1 and No.2.

Table 52. Sequence of Station Visits in Cellular Facilities of Problem Set No.3

Job Name	Problem Code	Mean Demand	1st Visit	2nd Visit	3rd Visit	4th Visit	5th Visit	Ends at
A (!)	3C21	10	No	multiple	routings			
B (!)	3C21	12	1	5	7	2	-	8
B1	3C21	3(d)	1	5	2 (*)	2 (*)	-	8
F (!)	3C21	13	No	multiple	routings			
H (!)	3C21	18	2	1	4	5	6	8
H1	3C21	4(d)	2	1	4	3	6	8
H2	3C21	2(d)	2	1 (*)	1 (*)	3	6	8
R (!)	3C21	15	1	2	5	6	3	8
R1	3C21	2(d)	1	2	5	7	3	8
C (!)	3C22	18	No	multiple	routings			
D (!)	3C22	19	No	multiple	routings			
E (!)	3C22	28	No	multiple	routings			
Q (!)	3C22	14	1	3	7	5	-	8
Q1	3C22	5(d)	1	3	7	3	-	8
S (!)	3C22	9	No	multiple	routings			
A (!)	3C31	2(d)	1	3	4	5	-	8
A1	3C31	8	1	3	1	5	-	8
B (!)	3C31	15	No	multiple	routings			
F1	3C31	13	3	6	5	4	7	8
Q (!)	3C31	19	No	multiple	routings			
C (!)	3C32	18	No	multiple	routings			
H (!)	3C32	24	No	multiple	routings			
S	3C32	9	4	7	2	7	-	8
D (!)	3C33	19	No	multiple	routings			
E	3C33	28	2	3	6	-	-	8
R1	3C33	15	6	2	5	6	3	8
R2	3C33	2(d)	6	2	3	6	3	8

(!) : Primary sequence is as shown in Table 42 on page 153.

(*) : Two operations will be combined into one.

d : Deterministic demand levels for secondary and tertiary routings.

Table 53. Sequence of Station Visits in Cellular Facilities of Problem Set No. 4

Job Name	Problem Code	Mean Demand	1st Visit	2nd Visit	3rd Visit	4th Visit	5th Visit	Ends at
A (!)	4C31	10	No	multiple	routings			
B (!)	4C31	14	1	5	7	2	-	8
B1	4C31	1(d)	1	5 (*)	5 (*)	2	-	8
D (!)	4C31	19	No	multiple	routings			
H (!)	4C31	21	2	1	4	5	6	8
H1	4C31	3(d)	2	1 (*)	1 (*)	5	6	8
C (!)	4C32	18	No	multiple	routings			
E (!)	4C32	28	No	multiple	routings			
S	4C32	9	1	6	2	7	-	8
V (!)	4C32	15	No	multiple	routings			
F (!)	4C33	13	No	multiple	routings			
Q (!)	4C33	19	No	multiple	routings			
R (!)	4C33	17	No	multiple	routings			
U (!)	4C33	16	6	4	2	-	-	8
U1	4C33	1(d)	6	1	2	-	-	8
A (!)	4C41	10	No	multiple	routings			
B (!)	4C41	14	1	5	7	2	-	8
B1	4C41	1(d)	1	5 (*)	5 (*)	2	-	8
H (!)	4C41	22	2	1	4	5	6	8
H1	4C41	2(d)	2	1 (*)	1 (*)	5	6	8
C (!)	4C42	18	No	multiple	routings			
S (!)	4C42	6	4	6	2	-	-	8
S1	4C42	3(d)	3	6	2	-	-	8
V (!)	4C42	14	3	4	7	2	-	8
V1	4C42	1(d)	3	4	7	3	-	8
D (!)	4C43	19	No	multiple	routings			
E (!)	4C43	28	No	multiple	routings			
R (!)	4C43	14	1	2	5	6	3	8
R1	4C43	3(d)	6	2	5	6	3	8
F (!)	4C44	13	No	multiple	routings			
Q	4C44	19	1	3	6	5	-	8
U (!)	4C44	17	No	multiple	routings			

(!) : Primary sequence is as shown in Table 42 on page 153.

(*) : Two operations will be combined into one.

d : Deterministic demand levels for secondary and tertiary routings.

Provisions for Different Machine Types in One Production Zone:

Stage one sometimes allocated two or three different machine types for the same production zone. For example, Table 26 on page 136 shows that two type K and one type N machines were assigned to department No.5 of the functional facility in problem set No.2. Both machine K and N can provide all three operations (13,14,15) of operation class No.5, but machine K takes less time. Unit load of jobs that need to visit department No.5 waited in a single queue before any of the above machines (resources) became available. It was assumed that any unit load has equal probability of being processed on any of the three machines.

In this stage, weighted average of all possible operation times and the maximum of standard deviations were used as single parameter for normally distributed unit load operation times. For example, if a unit load of Job A needs to visit department No.5 where it may be processed on machine N with parameter of N(78.1,4.7) or on one of the two machine K's with parameter N(71.5,4.3). The above rule results in a parameter of N(73.7,4.7) for operation time of a unit load of Job A in this case. The procedure is the same for cellular facilities. Operation times, whether weighted average values or the value for a specific machine types, are included in the parameters section of SIMAN experiment frame in Appendix L since tabulation of extensive amount of operation time data here would not constitute any new and significant information.

Number of Simulation Periods:

A terminating system was assumed for simulation of the facilities. While production facilities could better fit to a non-terminating system class, period of five year was assumed in Chapter five for machine depreciation and used in average item cost calculations. The aim of simulation was to determine the best estimate of output variables, shown in Figure 37 on page 188, in order to further compare the two production facilities. At 250 workdays a year and 480 minutes of production per day, each facility was planned to be simulated for a period of 250 * 5 * 480 = 600,000 minutes (five years) in each replication. Pilot runs showed that the steady state flowtime values, the main output from simulation, were reached at around only one hundred days or 48,000 minutes of production in problem sets No.1 and 2 which have deterministic demands at every production period. Steady state took longer (288000 minutes) to reach in problem set No.4 because this problem set has a larger job mix with stochastic daily demands. Simulation of a functional facility of problem set No.4 with twelve job types took over nine minutes of CPU time for each replication which lasted 600000 minutes. But, Figure 39 on page 202 and Figure 40 on page 203 showing the individual and cumulative average flowtimes of job A in the functional facility of problem set No.4 indicate that 288000 is sufficient to reach to steady state. While individual flow times of each job A varied around the mean of 514 minutes, the cumulative average remained steady around the mean. The other eleven jobs in this problem set had similar flow time plots. The cellular facilities usually required lesser times in all problem sets in reaching steady state levels, but the final results were found by using steady state time of the functional facility in problem set No. 4F.

Current array sizes of SIMAN (version 3.0) available at one of VPI's mainframe computers, IBM 3090 Model 200/VF, were too small for all, but the first problem set of this research. To handle larger job mixes and higher amount of each job type, with some jobs requiring long operations, it was necessary to reinstall SIMAN software from a VM/CMS tape and set 250000 for the dimension of the array RSET and the value of the variable LEND in two of the source codes as indicated in reference [206]. Then, all ten source FORTRAN codes were recompiled, optimized, and linked before any SIMAN runs were performed.

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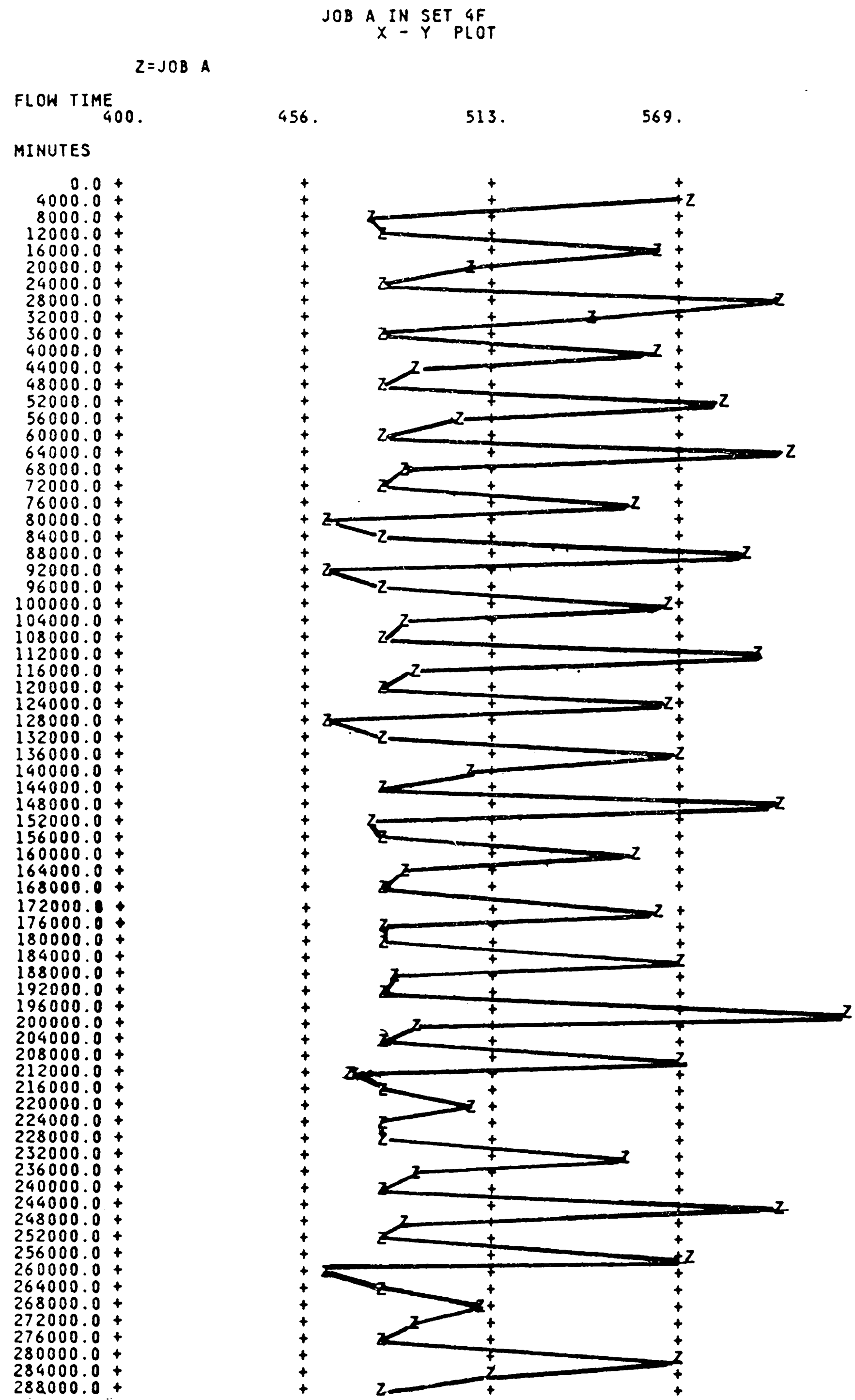

Figure 39. Plot of Flow Times of Job A in Problem Set No.4F

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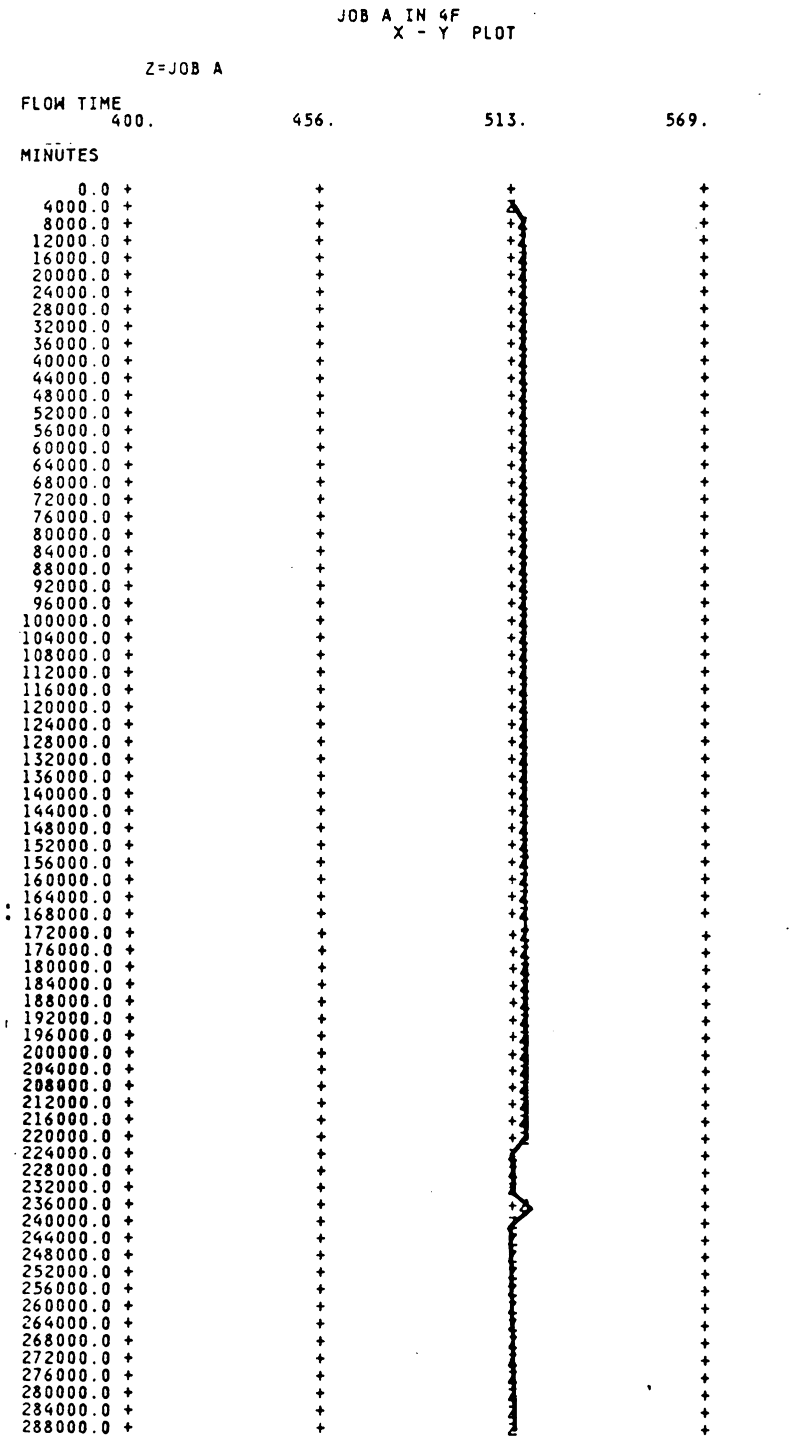

Figure 40. Plot of Cumulative Average Flow Times of Job A in Problem Set No.4F

6.1.2 Comparison of Both Facility Types

Table 54 on page 205 shows the mean flow times and a ninety-five percent confidence interval for each mean flow time. Mean flow times were found by simulating each facility for 288000 minutes and clearing statistics at 10000 minutes to filter out the initial bias. Each run was replicated five times and the average of each run's mean was found using OUTPT/TAVG elements of the SIMAN experiment frame. The INTERVALS option of SIMAN output processor [189] was utilized in calculating of the ninety-five percent confidence intervals for mean job flow times. For example, job A in problem set No.1F had a mean flow time of 527 minutes and its confidence interval ranged from 525 to 528 minutes. No confidence interval (n.c.i.) was specified in Table 54 on page 205 if a given job had more than one route with a different mean flow time for each route. In problem set No.1C, job A's mean flow time was 278 minutes, but no confidence interval could be specified. If the mean flow times of the multiple routes of the same job type were very close to each other, the extreme values of the confidence intervals were chosen as the upper and lower levels.

Due to having only one or two of some key machines, certain job types had very long flow times in some cellular facilities. For example, severe bottlenecks, evidenced by utilization of hundred percent in mini-department No.6 and 97.2 percent in mini-department No.2 displayed in the simulation output, caused job H in cell No. 3C2-1 to have mean flow time of 49.9 days. No confidence interval was specificed when flow times were excessively long. Such long flow times were also excluded in output analysis in the next section. All mean flow times in excess of 2000 minutes were tabulated in units of days by defining a day as 480 minutes.

Table 54. Mean Job Flow Times (Minutes) and Ninety-five Percent Confidence Intervals (C.I.) of Each Mean

Problem Set	Job A	Job B	Job C	Job D	Job E	Job F	Job H
1F C.I.	527 525-528	488 485-491	417 415-418	249 246-251	-	-	-
1C C.I.	278 n.c.i.	619 614-637	296 294-297	345 343-346	-	-	-
2F C.I.	503 502-504	417 415-419	427 425-428	203 202-205	490 489-491	566 564-567	n/a
2C-2 C.I.	441 415-449	539 n.c.i.	490 n.c.i.	349 346-352	359 339-370	529 n.c.i.	611 607-615
2C-3 C.I.	48.0 Days	84.1 Days	448 446-451	444 440-445	248 245-249	n/a	579 576-583
3F C.I.	445 444-446	328 327-330	434 434-435	175 174-175	349 349-350	487 485-488	468 467-469
3C-2 C.I.	467 465-470	399 395-410	435 434-436	203 202-204	301 301-302	49.6 Days	49.9 Days
3C-3 C.I.	1728 n.c.i.	452 450-455	289 288-291	343 343-345	321 321-322	27.2 Days.	310.7 Days
4F C.I.	514 513-515	341 341-342	456 455-456	279 279-280	353 352-353	501 500-502	511 510-512
4C-3 C.I.	660 657-664	522 505-526	448 446-451	301 299-302	430 429-432	697 693-700	665. n.c.i.
4C-4 C.I.	411 408-416	499 466-505	311 310-314	213 212-215	389 388-390	505 503-508	584 551-589

Table 55. Mean Job Flow Times (Minutes) and Ninety-five Percent Confidence Intervals (C.I.) of Each Mean (II)

Problem Set	Job Q	Job R	Job S	Job U	Job V
3F C.I.	539 539-540	441 441-441	325 325-326	-	-
3C-2 C.I.	720 n.c.i.	42.5 Days	483 479-487	-	-
3C-3 C.I.	548 547-550	497 n.c.i	456 454-459	-	-
4F C.I.	533 533-534	444 444-445	366 366-367	229 228-229	494 494-495
4C-3 C.I.	337 335-339	415 415-416	267 266-269	342 339-363	470 468-472
4C-4 C.I.	598 597-599	675 n.c.i.	190 n.c.i.	348 345-350	506 n.c.i.

Output Analysis:

SIMAN output listing (RUNLIST) of each facility was analyzed and condensed from its detailed format. Appendix L shows the output for the functional facility in problem set No.3 as an example. Table 56 on page 208 shows the output summary for the original data in Appendix D. Long term order completion ratio was found by dividing the total number of completed jobs with the total number of jobs that entered the facility before the end of the simulation period. A high ratio verifies the accuracy stage one capacity planning decisions. Weighted average flow time was found by adding the term (mean flow time * number of jobs completed) for each job type and then dividing the sum with the total number of completed jobs of all types. If the weighted average flow time is less than 480 minutes, the facility is able to process most of the jobs in one production period as required in stage one. But, as seen in Table 54 on page 205 and Table 55 above, some job types with a high number of operation requirements, have mean flow times in excess of 480 minutes. For most of the facilities, simulation verified stage one capacity planning and assignment decisions in the long term, but, due to few long queues and the transportation requirements ignored in stage one, demand for some job types could not be met in full without some delays. The length of each of the seven department or mini-department queues and the utilization of resources in each department or mini-department are listed in RUNLIST output file (Appendix L). These values were averaged and listed in Table 56 on page 208. Utilization of transporters was taken directly from RUNLIST and converted into percentages. Cart speed was specified as 9.0 feet per minute in all facilities.

According to Table 56 on page 208, all four functional facilities were able to complete the job orders in the long term, but cellular facilities of 2C-3, 3C-2, and 3C-3 failed to fully meet the demand in the long term. Further averaging of the entries in RUNLIST, e.g. taking average of the performance measures for 2C-2 and 2C-3 in problem set No.2, shows that the average machine utilizations were higher under functional facility (1.4, 3.6, and 7.0 percent higher in problem sets No.1, 2, and 4) or almost equal in problem set No.3. Weighted average flow times were equal in problem set No.1 and lower (4.3, 3.6, and 8.6 percent) under functional facility in the other three problem sets (this comparison excludes some cells as discussed next). If all the cells were used in comparison, there would be even higher margins by which the functional facility would look preferable. The functional facilities had higher average queue lengths in problem sets No.1 and 4 and lower average queue lengths in sets No.2 and 3. Cart utilizations were generally lower under cellular facilities due to the shorter distances travelled by parts.

Table 56. Comparison of Simulation Output of the Facilities

Problem Set No.	Long Term Order Completion Rate	Weighted Average Flow Time (minutes)	Average Queue Length	Average Machine Utilization	Average Cart Utilization
1F	99.9%	403.84	4.03	85.2%	16.4%
1C	99.9%	405.69	2.44	79.1%	7.9%
2F	99.9%	419.66	5.38	87.4%	15.0%
2C-2	99.9%	433.80	4.72	90.2%	17.1%
2C-3	92.5%	444.01 ex1	4.28 bn1	82.3%	7.2%
3F	99.9%	398.43	14.14	85.3%	79.2%
3C-2	95.1%	417.14 ex2	8.83 bn2	86.7%	67.3%
3C-3	98.9%	408.91 ex3	7.55 bn3	86.8%	44.9%
4F	99.9%	414.63	17.03	84.3%	72.5%
4C-3	99.9%	461.01	7.07	81.4%	52.8%
4C-4	99.9%	445.89	5.55	81.4%	26.6%

Legend :

- ex1 : Jobs A1 and B with long mean flow times are excluded.
- bn1 : Cell No.1 with two long queues is excluded.
- ex2 : Jobs F, H, H1, H2, and R are excluded.
- bn2 : Cell No.1 is excluded.
- ex3 : Jobs A, F1, and H are excluded.

Above exclusions were made in order to prevent the very poor performance of some cells from overshadowing other cellular performance measures in contrast to the functional facility performance measures.

6.1.3 Sensitivity Analysis of the Facilities

Although each facility was designed to meet the production load defined in stage one, it would be instructive to examine the response of the facilities under sudden changes in demand and the other production conditions. Such changes may be in one or more of the following forms :

1. Increase in demand of all or some of the job types.
2. Changes in ratio of each job type in the total expected demand.
3. Net decrease in total demand.
4. Changes in the demand distribution of some jobs.
5. Machine breakdowns.
6. Cart breakdowns and/or speed changes.

Mechanical changes however were not considered, partly because the machine uptime ratio considered in stage one allows machine breakdowns through reductions in available capacity at each day. Increased demand for some or all job types would entail additional set-up times on most machines, but such extra set-up times were not added to simulation data. Demand alterations were made to the original demand data shown in Table 66 on page 252 of Appendix D. Revised daily demand for each job type, in unit loads, was then found by dividing the new daily demand by the constant unit load size. The purpose of the sensitivity analysis was to examine the consequences of changes in daily demand parameters on each facility. If such increased or modified demand structure seems acceptable to the management, then more detailed simulation study can be conducted. As in the original simulation runs, a simulation length of 288000 minutes and five replications was used.

Four scenarios were designed :

1) - Ten Percent Increase in Daily Demand of all Job Types in Problem Sets No.1 and 2 : This scenario was used to test the sensitivity of each facility using deterministic daily demand increases. If the increased amount of a given job type was fractional, it was rounded off to the nearest integer. In the case of a cellular facility with multiple routings, a portion of the demand increase was assigned to secondary and tertiary routes (sequences) in ratios consistent with initial demand allocations among the routes. Table 57 shows the results for this scenario. The additional load caused congestion in all facilities, but the functional facility, in both problem sets, was able to better cope with such sudden demand surge because the resources of the functional facility were not divided into small modules.

Table 57. Sensitivity Analysis: Scenario One

Problem Set No.	Long Term Order Completion Rate	Weighted Average Flow Time (Days)	Average Queue Length	Average Machine Utilization	Average Cart Utilization
1F	98.7%	4.53	32.3	92.8%	18.2%
1C	94.0%	18.84	83.8	89.8%	8.9%
2F	94.2%	18.02	175.4	95.2%	16.2%
2C-2	92.9%	12.88	166.4	89.5%	17.9%
2C-3	84.6%	43.32	258.1	84.8%	7.4%

In both problem sets, the functional and cellular facilities were not able to complete all orders in the long term, but the functional facility completed five percent more jobs than the cellular facility. Both facility types had higher average machine utilizations. The increase in average machine utilization was much more significant under the functional facility indicating that functional facility was better able to make use of its resources under a demand surge. Increased demand caused weighted average flow time and average queue length performance measures to deteriorate more under the cellular facility as opposed to the functional facility when compared to their original performance measures shown in Table 56 on page 208.

2) - Doubling of Standard Deviations of Daily Demands for all Jobs in Problem Set No.3 :

3) - Quadrupling of Standard Deviations of Daily Demands for all Jobs in Problem Set No.4 :

Scenarios No. 2 and No. 3 were designed to test the response of each facility when the variance of stochastic daily demands was increased. Such increases should lead to more uncertain processing requirements for each facility.

Table 58. Sensitivity Analysis: Scenarios Two and Three

Problem Set No.	Long Term Order Completion Rate	Weighted Average Flow Time (Days)	Average Queue Length	Average Machine Utilization	Average Cart Utilization
3F	99.9%	0.83	14.20	85.3%	79.4%
3C-2	95.0%	14.10	181.10	88.8%	67.1%
3C-3	98.9%	46.76	35.70	86.7%	44.8%
4F	99.9%	0.87	17.10	84.2%	71.7%
4C-3	99.9%	1.02	7.58	81.3%	52.7%
4C-4	99.8%	1.15	7.23	81.6%	26.6%

In scenario No.2, all five performance measures were virtually unchanged under the functional facility. The same was true for the cellular facility except for a small increase in average machine utilization. In scenario No.3, performance measures were, once again, unchanged for the functional facility eventhough the amount of demand uncertainty was doubled. Cellular facility had a 14.8 percent higher weighted average flow time and a 17.4 percent higher average queue length compared to the original values shown in Table 56 on page 208.

4) - Simultaneous Changes to Mean Demand of Some Job Types in Problem Set No.4 : In order to test the response of both facility types to changes in demand structure for which each facility was originally designed for, following demand changes were made :

1. Mean daily demands of jobs A, C, D, and F were increased by thirty percent to 135, 182, 243, and 148.

2. Mean daily demands of jobs B, E, Q, and V were decreased by thirty percent to 126, 116, 67, and 172.
3. Mean daily demands of jobs H, R, S, and U were unchanged.

Standard deviations were unchanged. The above job groups were chosen by making sure that each cell's job mix was represented in each of the above three groups. Table 59 shows the results of the simulation runs for this scenario.

Table 59. Sensitivity Analysis: Scenario Four

Problem Set No.	Long Term Order Completion Rate	Weighted Average Flow Time (Days)	Average Queue Length	Average Machine Utilization	Average Cart Utilization
4F	99.9%	0.86	18.2	83.8%	78.0%
4C-3	98.0%	6.54	62.5	81.1%	51.5%
4C-4	97.9%	6.80	52.0	78.3%	25.7%

With the exception of a slight increase in the average queue length and a slight decrease in the average machine utilization, the functional facility showed that it could withstand to the changes in demand mix. The cellular facility failed to cope with the demand mix change depicted above and produced a seven times worse weighted average flow time and a nine times worse average queue length compared to the original cellular performance measures shown in the last line of Table 56 on page 208.

Summary

The SIMAN simulation language was used in testing the feasibility of stage one capacity planning decisions tabulated in Chapter four. This simulation study has produced results in direct contrast with those reported in references [20,75,96]. There was no evidence that the cellular facility is superior to functional facility. In fact, functional facility performed better in general.

7.0 Conclusions and Recommendations

This research has presented a methodology for designing a functional and cellular production environments with the main purpose of comparing the two and recommending the one which offers better manufacturing performance. A fair comparison was made and, unlike some of the previous research, realistic factors were considered. The main contribution of this research is the hybrid design methodology. Four problem sets were intended as means of explaining the implementation of the design process. The methodology, however, could be used as a design tool of either production environment if a comparison is not needed and one of the production environments has already been chosen. The research resulted in a two stage methodology and to reach the methodology following tasks were performed.

1. Review of the relevant concepts and the subject areas.
2. Review of the literature on all relevant areas.
3. Development of a hierarchical methodology which determines per item costs under each production environment by first solving machine requirements planning problem and then finding good layout for each environment.
4. Development of simulation models to further compare both alternatives for non-cost performance measures.

Conclusions which follow must be viewed according to the restrictive assumptions under which this research was carried out. These limitations include :

- Limited number of cellular facilities were considered in each problem set.
- No intercell workload transfers were allowed.
- No remainder cell was considered.
- The data of each problem set was generated. Then, it is possible to construct counter-examples which can conflict with the conclusions reached for the current problem sets.

7.1.1 Conclusions

Based upon the four problem sets considered, this research has shown that cellular manufacturing(CM) and GT in general are not superior to traditional functional facility or production environment when the two are compared under equal terms. This research has consistently rejected the idea of intercell work transfers which lead to hybrid facilities and have often been considered in the previous research [35,36,91] as a way to artificially promote GT/CM. The cellular facility usually appeared more economical in stage one, but it failed to continue being preferred when the system dynamics were also considered in stage two. GT/CM was not found to be better solution for the majority of batch manufacturing examples considered. In others, there was no apparent difference between the functional and the cellular options. Promotion of GT/CM as the best answer for most manufacturing and general production problems may well be ill-founded.

Although part families and the possible capacity savings due to set-up time reductions were explicitly considered in stage one, cellular facilities usually required the same or higher number of machines than the functional facilities as seen in Table 44 on page 157. Bottlenecks formed quickly in some cells and this led to poor performances especially in weighted average flow time and average queue length measures in contrast to functional facilities. Bottlenecks were partly caused by similar precedence requirements within the cell's job-mix. It became clear that job grouping and job/cell assignment process should also attempt to group jobs according to the diversity of the precedence requirements while still seeking to group jobs with operation and/or design similarity. For example, a job grouping methodology should, if possible, avoid grouping two jobs that need operations in 4-1-2 and 4-3-2 order since both jobs have to first wait for operation No.4 in their cell. Later, these two jobs have to wait in the same queue again for operation No.2. These two jobs may have a high design similarity and do have high operation commonalty, but the use of these two similarity measures (as in Chapter three) may lead to bottlenecks under heavy capacity use. If the second job had the precedence requirement of 3-2-4, jobs would probably not be waiting in the same queue. Then, job precedence dissimilarity should be used along the other similarity measures in making job/cell assignments.

GT/CM seemed at its best (problem set No.4) when each cell's job-mix was small, three job types per cell in all cells with prefix 4C-4. In these four cells, Jobs had dissimilar precedence requirements in addition to having good similarities in the other two similarity measures. For example, in cell No.4C4-3, job precedence requirements for job D is 3-6-2, 1-3-6 for job E, and 1-2-5-6-3 for job R. No major bottleneck problems were encountered in any of the functional facilities whose departments had more machines for a given operation type than the machines dedicated for the same operation in the cells of the equivalent cellular facility. Then, sound application of GT/CM requires careful analysis and prevention of any bottlenecks.

Obvious savings in material handling and set-up requirements did not make the GT/CM option or the cellular facility superior to the functional facility, but, at times, helped the two environments have roughly equal performance measures in cost and non-cost terms. Other GT/CM drawbacks such as the initial cost of the necessary investment for a classification and coding system was not considered. If considered, this would increase the total cost of each cellular facility further and make it even less desirable. It is also uncertain if smaller batch sizes could have made a large difference in performance measures in favor of GT/CM. It was determined that a cellular environment with high number of cells and small job-mixes for each cell is a better alternative than having few cells and large job-mixes for each cell.

The simulation study did not directly consider machine breakdowns at random intervals for random time durations. If such machine breakdowns were considered, small cells would be highly vulnerable since the machine mix of such cells consist of very limited, one or two, number of each necessary machine type. Machine breakdowns could cause excessive under-utilization of other machines to be visited in sequence and result in serious difficulties in meeting the demand on time.

Following prediction quoted by Shunk [91] in 1976 has not been realized :

> "GT concepts will be used on 25 percent of all manufacturing applications by 1979 and the use will increase to 50 percent of all manufacturing applications by 1988".

While some GT concepts such as the classification and coding of parts have indeed found widespread use, GT as a whole philosophy has not been adopted in a large extent even in England where it received the most attention.

The methodology used in this research provides the means of capturing intricate details of the components in production design of two major production methods. Once the details were stated and modelled, certain heuristics were used in order to find a solution with reasonable amount effort. Exact solutions would be too difficult to implement for all practical purposes.

7.1.2 Recommendations

Stage one consisted of six computation steps (step 3 is implied) which pass and receive information mostly with manual connections. Application of the hierarchical methodology requires careful arrangement and use of the numerous data files, FORTRAN codes, and the available packages such as MPSIII and MICRO-CRAFT. In stage two, use of SIMAN simulation language also requires computation and manual arrangement of data. All problem sets were solved under a single insurance factor (minimum probability of meeting the daily demand for job type as discussed in Chapters two and three) of ninety-nine percent. Use of the additional insurance factors is desirable, but this would have almost doubled the amount of computation and the manual interface requirements. In order to easily resolve the problem after altering the raw data, following steps should be implemented :

1. Call MPSIII package as a subprogram in steps 1, 2, and 5. Currently, all MPSIII inputs files are created by manually running FORTRAN codes. Attempts to incorporate, MPSIII as a subprogram failed due to the JCL problems.
2. Install an EXEC file which executes all stage one steps (except step 6), prepares data for stage two, and calls SIMAN EXEC for automatic simulation runs.

Iterations Between the Stages of the Hybrid Methodology :

Since stage one and stage two have usually resulted in conflicting preferences between the functional and cellular facilities, it would be instructive to carry out a complete sensitivity analysis which spans both stages. Chapters five and six have sensitivity analysis sections for testing the sensitivity of individual results of each stage. But, no attempt was made to test the overall sensitivity of the combined cost/non-cost performance measures of either facility type.

Severe bottlenecks experienced by some of the cellular facilities could be eased by successively adding machines to such cells and re-calculating a new vector of performance measures for each facility. A typical iterative procedure, similar to the one Chen [14] used in FMS design, should be as follows if there are no investment constraints :

1. Identify a candidate cell.
2. Determine a bottleneck machine in that cell based on stage two results.
3. Add one such machine to cell's machine-mix and re-run the simulation model.
4. If non-cost performance measures of the cell do improve, determine the daily fixed cost contribution of the added machine to the total daily item production cost and the average item cost.
5. Tabulate the revised performance vector for the cell for further evaluation against the functional facility option.

In stage one, most cells showed lower costs with respect to per item and the average item costs. Then, each cell's costs could be raised until such costs are comparable to the costs of the functional facility while improving the non-cost performance measures. If there are operating constraints which prohibit the inclusion of any new machines to a facility, it may still be helpful to exchange some of the existing machines between the cells and re-run the simulation model to improve non-cost performance measures of those cellular facilities whose stage two (simulation) results appear very poor.

Other possible improvements are as follows :

1. Steps 1 and 2 of stage one should be modified to allow cases where a job receives more than one operation in each production zone. Current models do not allow multiple operations (e.g. a part having four holes drilled in one visit to some department) to be performed successively.

2. Larger job and machine mixes should be used in setting up and solving additional example problems with higher number of cells.
3. Other insurance factors should be tested to examine the response of each facility to changing insurance factors.
4. Machine capability should be varied between a single operation and maximum number of operations to determine the impact of the availability of sophisticated machines on the performance of both facility types.
5. The impact of allowing the use of overtime and some subcontracting should be tested on both facility types.
6. Eventhough, intercell work transfers were not considered, feasible cells for a given job type should be identified after stage one so that a part of the demand can be sent (still no transfers for partial work or no transfer once a job enters to a cell is allowed) to a secondary cell if the original cell is congested.
7. Similarly, a remainder cell (RC) can be set-up as a large back-up cell for other cells to divert some of their load (before admitting a job from the queue) if that cell is congested. But, additional machines made available to the RC should be made available for functional facility too in order to keep the comparison fair.
8. The simulation model can be improved by including external, user-written, FORTRAN subroutines and specifying double ranking rule for each queue. Then, FIFO/SPT rules could be jointly applied. Current simulation model uses FIFO rule based on arrival to each queue. The model does not necessarily give priority based on job's initial arrival to the facility. Unlike some other simulation languages, e.g. SLAM II, SIMAN does not have provisions for multiple job selection rules from a queue.
9. The simulation model can be further improved by coding a design similarity based job selection rule from each queue. This enhancement would make it unnecessary to use average set-up times.
10. The simulation model can be easily modified to test the use of other probability distributions for demand and operation times parameters.

List of Applicable Literature

After a carefull study of about 450 publications in seven major areas as listed in Chapter one, 228 of them were deemed relevant and useful with respect to the problem considered in this research. Applicable literature was broken into two sets :

1. References : This set includes 105 highly relevant publications.
2. Bibliography : This set contains the remaining publications of varying degrees of relevance and importance.

References

1. Ang, C.L. and Willey, P.C.T., "A Comparative Study of the Performance of Pure and Hybrid Group Technology Manufacturing Systems Using Computer Simulation Techniques:", *International Journal of Production and Research*, Volume 22, No.2, pp.193-233, 1984.

2. Askin, R.G. and Subramanian, S.P., " A Cost-Based Heuristic for Group Technology Configuration ", *International Journal of Production and Research*, Volume 25, No.1, pp. 101-113, 1987.

3. Athersmith, D. and Crookall, J.R., " Some Organizational Aspects of Cellular Manufacturing Based on Computer Simulation", *Proceedings of the 15th International Machine Tool Design and Research Conference*, pp. 45-54, 1974.

4. Avonts, L.H. et.all, "Allocating Work Between an FMS and a Conventional Jobshop: A Case Study ", *European Journal of Operational Research*, Volume 33, pp. 245-256, 1988.

5. Ballakur, A. and Steudel, H.J.,"A Within-Cell Utilization Based Heuristic for Designing Cellular Manufacturing Systems ", *International Journal of Production and Research*, Volume 25, No.5, pp. 639-665, 1987.

6. Bitran, G.R. et.all," Production Planning of Style Goods with High Set-up Costs and Forecast Revisions " , *Operations Research*, Volume 34, No. 2, pp. 226-236, 1986.

7. Bitran, G.R. and Ellenrieder, A.R.V., " A Hierarchical Approach for the Planning of a Complex Production System ", *Disaggregation*, (Ritzman, L.P. et.all, editors), pp. 107-125, Martinus Nijhoff Publishing Co. 1979.

8. Bitran, G.R. and Hax, A.C.," On the Design of Hierarchical Production Planning Systems ", *Decision Sciences*, Volume 8, pp. 28-55, 1977.

9. Bookbinder, J.H. and H'ng, B., " Rolling Horizon Production Planning for Probabilistic Time-Varying Demands " , *International Journal of Production and Research*, Volume 24, No.6, pp. 1439-1458, 1986.

10. Boucher, T.O. and Mucstadt, J.A., " Cost Estimating Methods for Evaluating the Conversion from Functional Manufacturing Layout to Group Technology ", *IIE Transactions*, Volume 17, No.3, pp. 268-276, 1985.

11. Bruvold, N.T. and Evans, J.R., " Flexible Mixed-Integer Programming Formulations for Production Scheduling Problems ", *IIE Transactions*, Volume 17, No.1, pp. 2-7, 1985.

12. Cai, J., et.all, " Solution of a Single-Stage Machine Load Planning Problem ", *Report No. 396, School of Operations Research and Industrial Engineering*, Cornell University, 1978.

13. Carrie, A.S., " Estimation of Handling Cost Reduction Due to Layout Changes ", *Proceedings of the 19th International Machine Tool Design and Research Conference*, pp. 307-313, 1978.

14. Chen, C., *Methodologies for Manufacturing System Selection and for Planning and Operation of A FMS System*, Ph.D Dissertation, Virginia Polytechnic Institute and State University, 1985.

15. Chen, F.F. et.all, " An Integrated Approach to FMS Production Planning ", *Proceedings of the Annual Industrial Engineering Conference*, pp.512-518, Spring 1988.

16. Choobineh, F.C., " A Framework for the Design of Cellular Manufacturing Systems ", *International Journal of Production and Research*, Volume 26, No.7, pp. 1161-1172, 1988.

17. Choobineh, F.C., " Optimum Loading for GT/MRP Manufacturing Systems ", *Computers and Industrial Engineering*, Volume 8, No.3/4, pp. 197-206, 1984.

18. Chu, C. and Pan, P., " The Use of Clustering Techniques in Manufacturing Cellular Formation ", *Proceedings of the Annual Industrial Engineering Conference*, pp. 495-500, Spring 1988.

19. Crawen, F.W., " Some Constraints, Fallacies and Solutions in GT Applications ", *Proceedings of the 14th International Machine Tool Design and Research Conference* , pp.169-174, 1973.

20. Cumming, G.F., " Simulation to Compare Group Technology and Functional Layout ", *Summer Simulation Conference*, pp. 626-630, 1980.

21. Dale, B.G. and Dewhurst, F., " Simulation of a Group Technology Product Cell ", *Engineering Costs and Production Economics*, Volume 8, pp. 45-54, 1984.

22. Davis, R.P., "Determining Optimum Operating Characteristics for a Continuous Processing Machining Center ", *International Journal of Production and Research*, Volume 16, No. 5, 1978.

23. Davis, R.P. and Miller, D.M., " A Model for Determining Machine Requirements Planning in a Multistage Manufacturing System with Discretely Distributed Demand ", *Applied Math. Modelling* , Volume 2, pp. 119-122, 1978.

24. Demmy, W.S., " Multi-item Scheduling with Reflection Programming ", *Disaggregation*, (Ritzman, L.P. et.all, editors) , pp. 195-206, Martinus Nijhoff Publishing Co. 1979.

25. Dempster, M.A.H. et.all, " Analytical Evaluation of Hierarchal Planning Systems ", *Operations Research* , Volume 29, No.4, pp. 707-716, 1981.

26. Duran, F.," A Large Mixed Integer Production and Distribution Program ", *European Journal of Operational Research*, Volume 28, No. 2, pp. 207-217, 1987.

27. Egbelu, P.J., " Planning for Machining in a Multi-Job, Multi-Machine Manufacturing Environment" , *Journal of Manufacturing Systems*, Volume 5, No.1, pp.1-13, 1986.

28. Erschler, J. et.all, " Consistency of the Disaggregation Process in Hierarchical Planning ", *Operations Research* , Volume 34, No. 3, pp. 464- 469, 1986.

29. Falk, P.G., " Experiments in Mathematical Linear Programming in a Manufacturing System ", *OMEGA*, Volume 8, No.4, pp. 473-490, 1980.

30. Fazakerley, G.M., "A Research report on the Human Aspects of Group Technology and Cellular Manufacture" , *International Journal of Production and Research*, Volume 14., No.1, pp. 123-134, 1976.

31. Flynn, B.B., " The Effects of Set-up Time on Output Capacity in Cellular Manufacturing ", *International Journal of Production and Research*, Volume 25, No.12, pp. 1761-1772, 1987.

32. Flynn, B.B. and Jacobs, F.R., " An Experimental Comparison of Cellular (Group Technology) Layout with Process Layout ", *Decision Sciences*, Volume 18, pp. 562-581, 1987.

33. Flynn, B.B., " Group Technology vs Process Layout: The Small and Large Shop Models" , *Working Paper No. 850066*, Louisiana State University, 1985.

34. Flynn, B.B., " Repetitive Lots: The Use of Sequence-Dependent Set-up Time Scheduling Procedure in Group Technology and Traditional Shops ", *Journal of Operations Management* (forthcoming).

35. Flynn, B.B. and Jacobs, F.R., "A Simulation Comparison of Group Technology with Traditional Job Shop Manufacturing ", *International Journal of Production and Research*, Volume 24, No.5, pp.1171-1192, 1986.

36. Flynn, B.B., *Group Technology versus Process Layout: A Comparison Using Computerized Job Shop Simulation* , Ph.D Dissertation, Indiana University, 1984.

37. Foo, F.C. and Wager, J.G., " Set-up Times in Cyclic and Acyclic Group Technology Scheduling Systems ", *International Journal of Production and Research*, Volume 21, No.1, pp. 63-73, 1983.

38. Gonzales, J.J. and Reeves, G.R., " Master Production Scheduling: A Multiple Objective Linear Programming Approach ", *International Journal of Production and Research*,Volume 21, No.4, pp. 553-562, 1983.

39. Greene, T.J., *Loading Concepts in Cellular Manufacturing*, Ph.D Dissertation, Purdue University, 1980.

40. Gunther, H.O., " The Design of an Hierarchical Model for Production Planning and Scheduling ", *Multi-Stage Production Planning and Inventory Control*, (Axsater, S. et al, editors), pp. 227-260 Springer-Verlag Co., 1986.

41. Hayes, G.M. et al, " A Dynamic Programming Approach to Machine Requirements Planning ", *IIE Transactions*, Volume 13, No.2, pp.175-181, 1981.

42. Hayes, G.M., *A Generalized Machine Requirements Planning Algorithm for Serial Flow Machining Systems*, M.S. Thesis, Virginia Polytechnic Institute and State University, 1978.

43. Hax, A.C. and Meal, H.C., " Hierarchical Integration of Production Planning and Scheduling" , *Logistics*, (M.A. Geisler, editor), pp. 53-69, North Holland /American Elsevier, 1975.

44. Hitomi, K. and Ham, I., " Product-Mix and Machine-Loading Analysis of Multistage Production System for Group Technology ", *Transactions of ASME*, Paper No. 82-Prod-24, 1983.

45. Hitomi, K. et al, " An Experimental Investigation of Group Technology Scheduling ", *Proceedings of the International Conference on Production Research*, 1977, Japan.

46. Huber, V.L. and Hyer, N.L., " The Human Factor in Cellular Manufacturing ", *Journal of Operations Management*, Volume 5, No.2, pp. 213-228, 1985.

47. Hyer, N.L. and Wemmerlov, U., "A Framework for Production Planning and Control of Cellular Manufacturing" *Decision Sciences*, Volume 13, pp. 681-701, 1982.

48. Institute of Industrial Engineers, *MICRO-CRACT*, Atlanta, GA 1986.

49. Iwata, K. et al, "A Probabilistic Approach to the Determination of the Optimum Cutting Conditions ", *Journal of Engineering for Industry*, Nov. 1972, pp. 1099-1107.

50. James, C.S., "Cell Layout Utilizing the CIM Data Base", *Proceedings of the 1985 Annual Industrial Engineering Conference*, pp. 239-246.

51. Kalro, A.H. and Arora, A.R., " Optimal Capacity Decisions for Production Facilities" , *IIE Transactions*, Volume 2, No.4, pp. 321-325, 1970.

52. Karni, R., " Capacity Requirements Planning A Systematization ", *International Journal of Production and Research*, Volume 20, No. 6, pp. 715-739, 1982.

53. Karni, R. " Capacity Requirements Planning - Optimal Workstation Capacities ", *International Journal of Production and Research*, Volume 19, No. 5, pp. 595-611, 1981.

54. Kekre, S., " Performance of a Manufacturing Cell with Increased Product Mix ", *IIE Transactions*, Volume 19, No.3, pp. 329-339, 1987.

55. Kendall, K.E. and Schniederjans, M.J., " Multi-Product Production Planning: A Goal Programming Approach ", *European Journal of Operational Research*, Volume 20, pp. 83-91, 1985.

56. Keown, A.J. and Taylor, B.W., " A Chance-Constrained Integer Goal Programming Model for Capital Budgeting in the Production Area ", *Journal of Operational Research Society*, Volume 31., No.7, pp. 579-589, 1980

57. Koeing, D.T. et al, " Applications of Group Technology Concept for Plant Layout and Management of a Miscellaneous Parts Shop ", *SME Transactions , 9th North American Manufacturing Research Conference*, pp. 497-502, 1981.

58. Kusiak, A., "The Generalized Group Technology Concept ", *International Journal of Production and Research*, Volume 25., No.4, pp. 561-569, 1987.

59. Lasserre, J.B. et al, "Aggregate Model and Decomposition Method for Mid-Term Production Planning ", *International Journal of Production and Research*, Volume 21, No. 6, pp. 835-843, 1983.

60. Lawrence, K.D. and Burbridge, J.J., " A Multiple Goal Linear Programming Model for Coordinated Production and Logistics Planning ", *International Journal of Production and Research*, Volume 14, No.2, 1976.

61. Lee, L.C., " A Study of System Characteristics in a Manufacturing Cell ", *International Journal of Production and Research*, Volume 23, No.6, pp. 1101-1114, 1985.

62. Leonard, R. and Rathmill, K., " The Group Technology Myths ", *Management Today*, pp. 66-69, 1977.

63. Leung, L.C. and Tanchoco, J.M.A., "A Profit Maximization Model for Machine/Part Assignment in a Manufacturing System ", *Engineering Costs and Production Economics*, Volume 10, pp. 57-67, 1986.

64. Lilly, M.T. and Driscoll, J., " Simulating Changes in Manufacturing Plants ", *Proceedings of the 1st International Conference on Simulation in Manufacturing*, pp. 37-55, 1985.

65. Lingaraj, B.P. and Wolfe, H., "A Model for Optimizing Facilities Design ", *Decision Sciences*, Volume 7, No.3, pp. 479-495, 1976.

66. Lingaraj, B.P. and Wolfe, H., " Optimal Design of a Tyre Plant ", *OPSEARCH*, Volume 13, No.3-4, pp. 182-197, 1976.

67. Mangiameli, P.M., " Large Scale .Optimization for Master Production Scheduling ", *Disaggreation*, (Ritzman, L.P. et.all, editors), pp.183-194, Martinus Nijhoff Publishing Co. 1979.

68. Masud, A.S.M. and Hwang, C.L., " An Aggregate Production Planning Model and Application of Three Multiple Objective Function Decision Methods ", *International Journal of Production and Research*, Volume 18, No.6, 1980.

69. Meal, H.C., " A Study of Multi-Stage Production Planning" , *Studies in Operations Management*(A.C. Hax, editor), pp. 253-285, North Holland Publishing Company, 1978.

70. Miller, D.M. and Davis, R.P., " A Dynamic Allocation Model for a Machine Requirement Problem ", *IIE Transactions*, Volume 10, No.3, pp. 237-243, 1978.

71. Miller, D.M. and Davis, R.P., " The Machine Requirements Problem ", *International Journal of Production and Research*, Volume 15, No.2., pp. 219-231, 1977.

72. Morito, S. and Salkin, H.M., " A Disaggreation Problem and a Search Enumeration Algorithm for a Multiplant, Multiproduct Scheduling Application ", *Disaggreation*, (Ritzman, L.P. et.all, editors), pp. 139-153, Martinus Nijhoff Publishing Co. 1979.

73. Mosier, C.T. and Taube, L. "The Facets of Group Technology and Their Impacts on Implementation-A State-of-the-Art Survey", *OMEGA*, Volume 13, No.5, pp. 381-391, 1985.

74. Naslund, B., " A Model of Capital Budgeting Under Risk ", *The Journal of Business*, Volume 39, No. 2, pp. 257-271, 1966.

75. Nisanci, H.I. and Sury, R.J., "An Application of Group Technology Concepts in Shoe Manufacturing ", *International Journal of Production and Research*, Volume 19, No.3, pp. 267-275, 1981.

76. Oliff, D.M. and Burch, E.E., "Multi-Product Production Scheduling at Owens-Corning Fiberglass ", *Interfaces*, Volume 15, No.5, pp. 25-34, 1985.

77. Osterfeld, D.H., "Operations Research and Capacity Planning at General Motors " , *Proceedings of the 1982 Fall IIE Transactions*, pp. 368-373.

78. Pegels, C. and Narayan, P., "Simulation as a Planning Technique for a Complex Machine Shop ", *International Journal of Production and Research*, Volume 14, No.3, pp. 387-400, 1976.

79. Rakes, T.R. et al, "Aggregate Production Planning Using Chance-Constrained Goal Programming ", *International Journal of Production and Research*, Volume 22, No.4, pp. 673-684, 1984.

80. Rao, S.S., *Optimization Theory and Applications*, 2nd Ed., John Wiley and Sons, N.Y. 1984.

81. Rathmill, K. and Leonard, R., "The Fundamental Limitations of Cellular Manufacturing When Contrasted with Efficient Functional Layout ", *Proceedings of the 4th Int. Conf. on Production Research*, pp. 523-546, 1978, Japan.

82. Ravignani, G.L.,"Machining for a Fixed Demand ", *International Journal of Production and Research*, Volume 12, No.3, 1974.

83. Reasor, R., *Determination of Machine Requirements via Simulation*, M.S. Thesis, Virginia Polytechnic Institute and State University, 1981.

84. Ring, E.A., *A Computerized Shop Floor Control System Utilizing Simulation for Scheduling and Planning*, M.S. Thesis, Virginia Polytechnic Institute and State University, 1983.

85. Rosenblatt, M.J. and Lee, H.U., "A Robustness Approach to Facilities Design ", *International Journal of Production and Research*, Volume 25., No.4, pp. 479-486, 1987.

86. Sarper, H., *Machine Requirements Planning in Cellular Manufacturing Systems*, M.S. Thesis, Virginia Polytechnic Institute and State University, 1982.

87. Saul, G.W. and Sadowski, R.P., "An Intermediate Resource Planning Methodology" , *Journal of Manufacturing Systems*, Volume 5, No.2, pp. 113-121, 1986.

88. Seppala, Y. and Orpana, T., "Experimental Study on the Efficiency and Accuracy of a Chance Constrained Programming Algorithm ", *European Journal of Operational Research*, Volume 16, pp. 345-357, 1984.

89. Seppala, Y., "A Chance Constrained Programming Algorithm", *BIT*, Volume 12, pp. 376-399, 1972.

90. Shtub, A."Capacity Allocation and Material Flow in Planning Group Technology Cells", *Engineering Costs and Production Economics*, Volume 13, No.3 pp. 217-228, 1988.

91. Shunk, D.L., *The Measurements of the Effect of Group Technology by Simulation* , Ph.D Dissertation, Purdue University, 1976.

92. Sposito, V.A., *Linear Programming and Non-Linear Programming*, The Iowa State Univ. Press, Ames, Iowa, 1975.

93. Stadtler, H., "Hierarchical Production Planning : Tuning Aggregate Planning with Sequencing and Scheduling", *Multi-Stage Production Planning and Inventory Control*, (Axsater, S. et al, editors), pp. 195-226, Springer-Verlag Co., 1986.

94. Stecke, K.E.,"Formulation and Solution of Nonlinear Integer Production Planning Problems for Flexible Manufacturing Systems", *Management Science*, Volume 29, No.3, pp. 273-289, 1983.

95. Steinhoff, H., "Daily System for Sequencing Orders in a Large Scale Job Shop", *Productions and Operations Management*, (Readings by E.S. Buffa), John Wiley and Sons, N.Y., pp. 155-165, 1966.

96. Steudel, H., "SIMSHOP: A Job Shop/Cellular Manufacturing Simulator", *Journal of Manufacturing Systems*, Volume 5, No.3, pp.181-189, 1986.

97. Tabucanon, M.T. et al, "A Probabilistic Programming Model for Blending Aggregates", *Applied Math. Modelling*, Volume 4, pp. 257-260, 1980.

98. Tarsusligil, M. and Bloor, J., "The Use of Similarity Coefficients and Cluster Analysis in Production Flow Analysis", *Proceedings of the ?? th International Machine Tool Design and Research Conference*, pp. 525-531.

99. Taylor, B.W. and Anderson, P.F., "Goal Programming Approach to Marketing / Production Planning", *Industrial Marketing Management*, Volume 8, pp.136-144, 1979.

100. Tilsey, R. et al, "Flexible Cell Production Systems - A Realistic Approach", *Annals of the CIRP*, Volume 25, No.1, pp. 269-271, 1977.

101. Tsubone, H. and Sugawara, M., "A Hierarchical Production Planning System in the Motor Industry", *OMEGA*, Volume 15., No.3, pp. 113-120, 1987.

102. Vakharia, A.S., "Methods of Cell Formation in Group Technology: A Framework for Evaluation", *Journal of Operations Management*, Volume 6, No.3, pp. 257-271, 1986.

103. Webster, D.B. and Tyberghein, M.B., "Measuring Flexibility of Job-shop Layouts", *International Journal of Production and Research*, Volume 18, No.1, pp. 21-29, 1980.

104. Wemmerlov, U. and Hyer, N.L., "Research Issues in Cellular Manufacturing", *International Journal of Production and Research*, Volume 25, No.3, pp. 413-431, 1987.

105. Willey, P.C.T. and Ang, C.L.,"Computer Simulation of the Effects of Inter-Cell Workload Transfer on the Performance of Group Technology Systems", *Proceedings of the 21th International Machine Tool Design and Research Conference*, pp. 559-567, 1980.

Bibliography

106. Amirahmadi, F., *Designing Cellular Manufacturing Systems by Graph-Theoretic Approach*, Ph.d Dissertation, University of Nebraska, 1986.

107. Aneke, N.A.G. and Carrie, A.S., "A Design Technique for the Layout of Multi-Product Flowlines", *International Journal of Production and Research*, Volume 24, No.3, pp. 471-481, 1986.

108. Aneke, N.A.G. and Carrie, A.S.,"Flow Complexity-A Data Suitability Index for Flowline Systems", *International Journal of Production and Research*, Volume 21, No. 3, pp. 425-436, 1983.

109. Armstrong, R.D. and Balintfy, J.L., "A Chance Constrained Multiple Choice Programming Algorithm with Applications", *Stochastic Programming*, (edited by M.A.H. Dempster), pp. 301-325, 1980.

110. Arn, E.A., *Group Technology*, Springer-Verlag, N.Y., 1975.

111. Axsater, S.,"On the Feasibility of Aggregate Production Plans", *Operations Research*, Volume 34., No.5, pp. 796-800, 1987.

112. Baker, K.R. et al, "An Algorithm for the Dynamic Lot-Size Problem with Time-Varying Production Capacity Constraints", *Management Science*, Volume 24, No. 16, pp.1710-1720, 1978.

113. Banerjee, A. and Flynn, B., "A Simulation Study of Some Maintenance Policies in a Group Technology Shop", *International Journal of Production and Research*, Volume 25, No.11, pp. 1595-1609, 1987.

114. Barlett, T.E., "Determining Optimal Machine Configurations for Multi-Stage Machining Processes", *Production and Inventory Management*, Volume 8, No.1, 1967.

115. Baybars, I. et al ,"Batching and Capacity Models for Manufacturing Cells with Metered Flow", *Journal of Manufacturing Systems*, Volume 5, No.2, pp. 123-130, 1986.

116. Beer, C.D. et al, "Production Flow Synthesis", *Annals of the CIRP*, Volume 27, No. 1, pp. 389-392, 1978.

117. Bertrand, J.W.M., "Multiproduct Optimal Batch Sizes with In-Process Inventories and Multi Work Centers", *IIE Transactions*, Volume 17, No.2, pp. 157-163, 1985.

118. Boucher, T.O., "Lot Sizing in Group Technology Production Systems", *International Journal of Production and Research*, Volume 22, No. 1, pp. 85-93, 1984.

119. Brown, G.G. et al, "Production and Sales Planning with Limited Shared Tooling at the Key Operation", *Management Science*, Volume 27, No.3, 1981.

120. Browne, J. et al., "Job Shop Control", *International Journal of Production and Research*, Volume 19, No.6, pp. 633-643, 1981.

121. Bulkin, M.J. et al, "Load Forecasting Priority Sequencing and Simulation in a Job Shop Control System", *Productions and Operations Management*, (Readings by E.S. Buffa), J.W. and Sons, N.Y., N.Y., pp. 166-194, 1966.

122. Burbidge, J.L., *Group Technology in the Engineering Industry*, Stephen Austin and Sons Ltd., England, 1979.

123. Burbidge, J.L., *The Introduction of Group Technology*, John Wiley and Sons, 1975.

124. Carrie, A.S. and Mannion, J., "Layout design and Simulation of Group Cells", *Proceedings of the ..th International Machine Tool Design and Research Conference*, pp. 99-105, 197?.

125. Carrie, A.S.,"Numerical Taxonomy Applied to Group Technology and Plant Layout", *International Journal of Production and Research*, Volume 11, No.4, pp. 399-416, 1973.

126. Chakravarty, A.K. and Shtub, A., "An Integrated Layout for Group Technology with In-process Inventory Costs", *International Journal of Production and Research*, Volume 22, No. 3, pp. 431-442, 1984.

127. Chan, H.M. and Milner, D.A.,"Direct Clustering Algorithm for Group Formation in Cellular Manufacture", *Journal of Manufacturing Systems*, Volume 1, No.1, pp. 65-74.

128. Chandrasekharan, M.P. and Rajagopalan, R.,"MODROC: an Extension of Rank Order Clustering for Group Technology", *International Journal of Production and Research*, Volume 24., No.3, pp. 1221-1233, 1986.

129. Charles-Owaba, O.E. and Lambert, B.K., "Sequence Dependent Machine Set-Up Times and Similarity of Parts: A Mathematical Model", *IIE Transactions*, Volume 20, No.1, pp. 12-21, 1988.

130. Charnes, A. and Cooper, W.W., "Deterministic Equivalents for Optimizing and Satisfying Under Chance Constraint", *Operations Research*, Jan-Feb. 1963.

131. Cho, K.K., "Group Scheduling Heuristic for Minimum Makespan in Multi-Stage Manufacturing Systems", *Proceedings of the 1985 Annual Industrial Engineering Conference*, pp. 130-136.

132. Cooper, M.W., "A Survey of Methods for Pure Nonlinear Integer programming" , *Management Science*, Volume 27, No.3, pp. 353-361, 1981.

133. Darrow, W.P., *Group Scheduling in a Manufacturing Resource Planning Environment*, Ph.D Dissertation, The Pennsylvania State University, 1980.

134. Davis, R.P. et al, "Manufacturing Systems Planning - The Key to Production Control", *Proceedings of the 1979 Annual Industrial Engineering Conference*, pp. 295-303.

135. De., P.K. et al, "A Chance-Constrained Goal Programming Model for Capital Budgeting", *Journal of Operational Research Society*, Volume 33, pp. 635-638, 1982.

136. Deckro, R.F. and Hebert, J.E., "Goal programming Approaches to Solving Linear Decision Rule Based Aggregate Production Planning Models" , *IIE Transactions*, Volume 16, No.4, pp. 308-315, 1984.

137. Deming, D.D., "When to Shift to Straight-Line Production", *Harvard Business Review*, pp. 62-68, Nov./Dec. 1959.

138. Dutta, S.P. et al, "A Heuristic Procedure for Determining Manufacturing Families from Design-Based Grouping for Flexible Manufacturing Systems", *Computers and Industrial Engineering*, Volume 10, No.3, pp. 193-201, 1986.

139. Edwards, G.A.B. , "Readings in Group Technology" , Whitefriars Press Ltd., London, 1971.

140. Eilon, S., "Five Approaches to Aggregate Production Planning", *IIE Transactions*, Volume 7, No.2, pp.118-131, 1975.

141. Eisenhut, P.S., "A Dynamic Lot Sizing Algorithm with Capacity Constraints", *IIE Transactions*, Volume 7, No. 2, pp. 170-176, 1975.

142. Elgomayel, J. and Nader, V., "Optimization of Machine Set-up and Tooling Using the Principles of Group Technology", *Computers and Industrial Engineering*, Volume 7., No.3, pp. 187-198, 1983.

143. Fetter, R.B., "A Linear Programming Model for Long Range Capacity Planning", *Management Science*, Volume 7., No.4, pp. 372-378, 1961.

144. Fisk, J.C. and Seagle, J.P., "The Integration of Aggregate Planning with Resource Requirements Planning", *Production and Inventory Management*, 3rd. Qtr., pp. 81- 91, 1978.

145. Florian, M. and Klein, M., "Deterministic Production Planning with Concave Costs and Capacity Constraints", *Management Science*, Volume 18, No.1, pp. 203-213, 1970.

146. Fontan, G. et al, "Consistency Analysis in a Hierarchical Production Planning System", *Engineering Costs and Production Economics*, Volume 9, pp. 193-199, 1985.

147. Foulds, L.R., "Techniques for Facilities Layout: Deciding Which Pairs of Activities Should be Adjacent", *Management Science*, Volume 29, No. 12, pp. 1414-1426, 1983.

148. Gallagher, C.C. and Knight, W.A., *Group Technology Production Methods in Manufacture* , Ellis Horwood Limited, U.K., 1986.

149. Gallagher, C.C. and Knight, W.A., *Group Technology*, Redwood Press Ltd., U.K., 1973.

150. Geoffrion, A.M.,"The Purpose of Mathematical Programming is Insight, Not Numbers", *INTERFACES*, Volume 7, No. 1, pp.81-92, 1976.

151. Glover, F., "Improved Linear Integer Programming Formulations of Nonlinear Problems", *Management Science*, Volume 22, pp. 455-460, 1975.

152. Glover, F. and Woolsey, E., "Converting the 0-1 Polynomial Programming Problem to a 0-1 Linear Program", *Operations Research*, Volume 22, No. 1, pp.180-182, 1974.

153. Goodman, D.A., "A New Approach to Scheduling Aggregate Programming and Work Force", *IIE Transactions*, Volume 5, No.2, pp. 135-141, 1973.

154. Goyali, S.K. , "Lot Size Scheduling on a Single Machine for Stochastic Demand" , *Management Science*, Volume 19, No.11, pp. 1322-1325, 1973.

155. Greene, T.J. and Clearly, C.M., "Is Cellular Manufacturing Right for You ?", *Proceedings of the 1985 Annual Industrial Engineering Conference*, pp.181-190.

156. Greene, T.J. and Sadowski, R.P., "A Review of Cellular Manufacturing Assumptions, Advantages and Design Techniques", *Journal of Operations Management*, Volume 4, No.2, pp. 85-97, 1984.

157. Greene, T.J. and Sadowski, R.P.,"Cellular Manufacturing Control", *Journal of Manufacturing Systems*, Volume 2, No.2, pp. 137-144, 1984.

158. Gunther, H.O., "Planning Lot Sizes and Capacity Requirements in a Single Stage Production System", *European Journal of Operational Research*, Volume 31, pp. 223-231, 1987.

159. Gupta, R.M. and Tompkins, J.A., "An Examination of the Dynamic Behavior of Part-families in Group Technology", *International Journal of Production and Research*, Volume 20, No.1, pp.73-86, 1982.

160. Gupta, R.M., *An Examination of the Dynamic Behavior of Part Families in Group Technology*, M.S. Thesis, North Carolina State University, 1978.

161. Haddock, J. and Rodriguez, M., "Modelling a Product-Mix Determination Problem", *Applied Math. Modelling*, Volume 9, pp.370-374, 1985.

162. Ham, I. et al, *Group Technology*, Kluwer-Nijhoff Publishing, 1985.

163. Han, C. and Ham, I., "Multiobjective Cluster Analysis for Part Family Formations", *Journal of Manufacturing Systems*, Volume 5, No.4, pp.223-229, 1986.

164. Hansotia, B.J., "Stochastic Linear Programming with Recourse: A Tutorial", *Decision Sciences*, Volume 11, pp. 151-168, 1980.

165. Hillier, F.S., "Chance Constrained Programming with 0-1 or Bounded Continuous Decision Variables", *Management Science*, Volume 14, No. 1, pp. 34-57, 1967.

166. Hitomi, K. and Ohashi, K., "Optimum Process Design for a Single- Stage Multifunctional Production System", *Journal of Engineering for Industry*, Volume 103, No. 2, pp. 218-223, 1981.

167. Hitomi, K., *Manufacturing Systems Engineering*, Taylor and Francis Ltd., London, 1979.

168. Hitomi, K. and Ham, I.,"Machine Loading for Group Technology Applications", *Annals of the CIRP*, Volume 25, No.1, 1977.

169. Hogan, A.J. et al, "Decision Problems Under Risk and Chance Constrained Programming: Dilemmas in the Transition", *Management Science*, Volume 27, No.6, pp. 698-716, 1981.

170. Holstein, W.K. and Berry, W.L.,"Work Flow Structure: An Analysis for Planning and Control", *Management Science*, Volume 16, No.6, pp. B-324/B-336, 1970.

171. Igel, M., "Experiences with Job-Shop Planning", *International Journal of Production and Research*, Volume 19, No.2, pp. 153-164, 1981.

172. Iwata, K. et al, "Optimization of Selection of Machine-Tools, Loading Sequence of Parts and Machining Conditions in Job-Shop Type Machining Systems", *Annals of the CIRP*, Volume 27, No.1, pp. 447-451, 1978.

173. Jackson, D. *Cell System of Production*, Business Books, London, 1978.

174. King, J.R. and Nakornchai, V., "Machine-Component Group Formation in Group Technology: Review and Extension", *International Journal of Production and Research*, Volume 18, No.2, pp. 117-133, 1982.

175. King, J.R., "Machine-Component Grouping in Production Flow Analysis : An Approach Using A Rank Order Clustering Algorithm", *International Journal of Production and Research*, Volume 18, No. 2, pp. 213-232, 1980.

176. Kolbin, V.V., *Stochastic Programming*, D. Reidel Publishing Company, The Netherlands, 1977.

177. Kusiak, A. and Heragu, S.S., "The Facility Layout Problem", *European Journal of Operational Research*, Volume 29, pp. 229-251, 1987.

178. LeGrande, E., "The Development of a Factory Simulation System Using Actual Operating Data", *Productions and Operations Management*, (Readings by E.S. Buffa), J.W. and Sons, N.Y., N.Y., pp. 132-154, 1966.

179. Leong, G.K.,"A Search Algorithm for the Bicriterion Group Technology Machine Loading and Product Mix Problem", *Journal of Engineering for Industry*, Volume 108, No. 3, pp. 237-239, 1986.

180. Lunz, A.G.,"The Missing Factors - The Real Keys to Effective Capacity Requirements Planning and Control", *Production and Inventory Management*, 2nd Qtr., pp. 1-13, 1981.

181. Mabert, V.A., "A Case Study of Encoder Shift Scheduling Under Uncertainty", in Production Planning and Scheduling: Mathematical Programming Applications, (edited by K.D. Lawrence and S.H. Zanakis), Industrial Engineering and Management Press, 1984.

182. Montgomery, D.C., *Some Techniques for Determining Machine Center Capacity in a Job Shop*, Ph.D Dissertation, Virginia Polytechnic Institute and State University , 1969.

183. Mohanty, R.P. and Kulkarni, R.V., "Hierarchical Production Planning: Comparison of Some Heuristics", *Engineering Costs and Production Economics*, Volume 11, pp. 203-214, 1987.

184. Morris, W.T., *Engineering Economic Analysis*, Reston Pub. Company, 1976.

185. Mosier, C.T. et all, "Analysis of Group Technology Scheduling Heuristics", *International Journal of Production and Research*, Volume 22, No.5, pp.857 - 875, 1984.

186. New, C., *Requirements Planning*, Gower Press Ltd. , Epping, Essex, U.K., 1973.

187. Noonan, F. and Giglio, R.J., "Planning Electric Power Generation: A Nonlinear Mixed Integer Model Employing Bender's Decomposition", *Management Science*, Volume 23, No.9, pp. 946-956, 1977.

188. Olson, D.L. and Swenseth, S.R., "A Linear Approximation for Chance-Constrained Programming", *Journal of Operational Research Society*, Volume 38, No.3, pp. 261-267, 1987.

189. Pegden, C.D., *Introduction to SIMAN*, Systems Modelling Corp., State College, PA, 1985.

190. Perng. K, *Group Technology and Machine Scheduling Problems with Sequence-Dependent Set-up Times*, Ph.D Dissertation, The Ohio State University, 1981.

191. Perry, C. and Preston, W.J., "Production Planning with Linear programming: From Textbook to Factory", *OMEGA*, Volume 14, No.3, pp. 233-238, 1986.

192. Purcheck, G.,"Machine-Component Group Formation: An Heuristic Method for Flexible Production Cells and Flexible Manufacturing Systems", *International Journal of Production and Research*, Volume 23, No.5, pp. 911-943.

193. Purcheck, G.F. and Lopez, E.O., "Suitability Testing for Group Technology", *Proceedings of the ..th International Machine Tool Design and Research Conference*, pp. 353-364, 19??.

194. Plossl, G.W. and Wight, O.W., "Capacity Planning and Control", *Production and Inventory Management* , 3rd Qtr., pp. 31-67, 1973.

195. Rajagopalan, R. and Batra, J.L.,"Design of Cellular Production Systems A Graph-theoretic Approach", *International Journal of Production and Research*, Volume 13., No.6, pp. 567-579, 1975.

196. Ranson, G.M., *Group Technology*, Mc.Graw-Hill Book Co., England, 1972.

197. Rao, S.S. and Hati, S.K., "Computerized Selection of Optimum Machining Conditions for a Job Requiring Multiple Operations", *Journal of Engineering for Industry*, Volume 100, No. 3, pp. 356-361, 1978.

198. Rathmill, K. et al, "Batch Size Selection for Group Technology", *Proceedings of the .. th International Machine Tool Design and Research Conference*, pp. 29-36.

199. Reed, R., "A Probabilistic Model for Machine Determination", *Proceedings of the 17th Annual Industrial Engineering Conference*, 1966.

200. Rodriguez, R. and Adaniya, O., "Group Technology Cell Allocation", *Proceedings of the 1985 Annual Industrial Engineering Conference*, pp. 125-127.

201. Sato, N. et al.,"Group Technology and Material Requirements Planning: An Integrated Methodology for Production Control", *Annals of the CIRP*, Volume 27, No.1, pp. 471-473, 1978.

202. Sato, N., *Integrated Group Scheduling and Material Requirements Planning* , M.S. Thesis, The Pennsylvania State University, 1977.

203. Sawik., T.J., "Multilevel Scheduling of Multistage Production with Limited In-Process Inventory", *Journal of Operational Research Society*, Volume 38, No.7, pp. 651-664, 1987.

204. Seifoddini, H., *Cost Based Machine-Component Grouping Model: in Group Technology*, Ph.D Dissertation, Oklahoma State University, 1984.

205. Shearon, W.T., *A Study of the Aggregate Production Planning Problem*, Dba. Dissertation, University of Virginia, 1974.

206. The SIMAN Simulation Language Reference Manual, *Systems Modelling Corporation*, Pittsburg, PA, 1987.

207. Sinclair, M., "A Linear Mixed-Integer Model for a Purchasing Problem Involving Discount Structures", *Applied Math. Modelling*, Volume 7, pp. 372-373, 1983.

208. Singh, H. and Foster, J.B., "Production Scheduling with Sequence Dependent Set-up Costs", *IIE Transactions*, pp. 43-49, March, 1987.

209. Sinha, R.K. and Hollier, R.H., "A Review of Production Control Problems in Cellular Manufacture", *International Journal of Production and Research*, Volume 22, No.5, pp. 773-789, 1984.

210. Solberg, J.J., "Capacity Planning with a Stochastic Flow Model", *IIE Transactions*, Volume 13, No. 2, pp. 116-122, 1981.

211. Spencer, M.S., "Scheduling Components for Group Technology Lines (A New Application for MRP)", *Production and Inventory Management*, 4th Qtr., pp. 42-49, 1980.

212. Stanfel, L.E., "Machine Clustering for Economic Production", *Engineering Costs and Production Economics*, Volume 9, pp. 73-81, 1985.

213. Steudel, H.J. and Berg, L.E., "Evaluation the Impact of Flexible Manufacturing Cells via Computer Simulation", *Large Scale Systems*, Volume 11, pp. 121-130, 1986.

214. Steudel, H.J.,"Job-Shop Layout Analysis via Computer Simulation", *International Journal of Production and Research*, Volume 19, No.1, pp. 59-67, 1981.

215. Sung, C.S. and Chang, S.H., "A Capacity-Constrained Single-Facility Multi-Product Production Planning Model", *Journal of Operations Research Society of Japan*, Volume 29, No.3, pp. 232-245, 1986.

216. Swanson, R.E., *A Generalized Approach to the Department Composition Problem in Group Technology*, Ph.D Dissertation, Arizona State University, 1974.

217. Taylor, J.F. and Ham, I., "The Use of a Micro Computer for Group Technology", *SME Transactions, 9 th North American Manufacturing Research Conference*, pp. 483-491, 1981.

218. Vollmann, T.E., "Capacity Planning: The Missing Link", *Production and Inventory Management*, 1st Qtr., pp. 61-74, 1973.

219. Waghodekar, P.H. and Sahu, S., "Machine Component Cell Formation", *International Journal of Production and Research*, Volume 22, No.6, pp. 937-948, 1984.

220. Waghodekar, P.H. and Sahu, S., "Group Technology : a Research Bibliography", *OPSEARCH*, Volume 20, 1983.

221. Weeks, J.K., "WIP Inventory Management, Productivity and Cost", *Production and Inventory Management*, 1st Qtr., pp. 40-49, 1978.

222. Weston, F.C., "Mathematical Programming and Aggregate Production Planning in a Multi-Organizational System", *Production and Inventory Management*, 1st Qtr., pp. 37-48, 1974.

223. Wilhelm, W.E., "A Model to Evaluate Job Shop Productive Capability" , *IIE Transactions*, Volume 8, No.2, pp. 176-183, 1976.

224. Witte, J.D., "The Use of Similarity Coefficients in Cellular Manufacturing", *International Journal of Production and Research*, Volume 2, No.1, pp. 16-21.

225. Wu, H.L., "Design of Cellular Manufacturing System : A Syntactic Pattern Recognition Approach", *Journal of Manufacturing Systems*, Volume 5, No.2, pp. 81-87, 198?.

226. Zanakis, S.H. and Smith, J.S., "Chemical Production Planning via Goal Programming", *International Journal of Production and Research*, Volume 18, No.6, 1980.

227. Zanakis, S.H.. and Lawrence,K.D," Effective Shift Allocation in Multiproduct Lines : A Mixed Integer Programming Approach", *Operational Research Quarterly*, Volume 28, No.4, 1977.

228. Zelenovic, D.M. et al, "An Approach to the Design of More Effective Production Systems", *International Journal of Production and Research*, Volume 25, No.1, pp. 3-15, 1987.

Appendices

Appendix A. Deterministic Equivalents of Chance Constrained Linear Programs

Consider the following LP :

$$\text{Minimize } F(X) = \sum_{j=1}^{n} c_j x_j \tag{A.1}$$

Subject to :

$$\Pr \left[\sum_{j=1}^{n} a_{ij} \leq b_i \right] \geq p_i \quad \text{for } i = 1,2,\ldots\ldots m \tag{A.2}$$

$$x_j \geq 0, \quad \text{for } j = 1,2,\ldots\ldots n$$

Where c_j, a_{ij}, b_i are random variables and p_i's are prespecified probabilities. For simplicity, it is assumed that the decision variables, x_j, are deterministic and all random variables are normally distributed with known mean and standard deviations. The detailed theoretical foundations of the following results may be found in Charness and Cooper [130] and Rao [80].

<u>When only</u> b_i are random variables :

Let $\overline{b}_i$ and Var(b_i) denote the mean and the variance of the normally distributed random variable b_i . E_i represents the value of the standard normal variate at which $\Phi(E_i) = 1 - p_i$ (E_i is non-negative). In this case, the objective function remains the same. Each constraint row takes the following deterministic form which also turns out to be linear :

$$\sum_{j=1}^{n} a_{ij}\, x_j - \overline{b}_i - E_i \sqrt{\mathrm{Var}(b_i)} \leq 0, \text{ for } i = 1,2,...m. \tag{A.3}$$

<u>When only</u> a_{ij} are random variables :

Let a_{ij} and $\mathrm{Var}(a_{ij}) = \sigma^2_{a_{i,j}}$. Assume that [V] is the variance covariance matrix of multivariate distribution of a_{ij} and X is a column vector of decision variables x. Let $\Phi(x)$ represent the cumulative distribution function of the standard normal distribution evaluated at x and $\Phi(e_i) = p_i$. This case also does not cause any change in the form of the objective function. Each constraint takes the following deterministic, but highly nonlinear form :

$$\sum_{j=1}^{n} \overline{a}_{ij}\, x_j + e_i \sqrt{X^T V_i X} - b_i \leq 0 \quad \text{for } i = 1,2,....m. \tag{A.4}$$

The nonlinearity of the this constraint expression is reduced if stochastic coefficients, a_{ij} 's, are independent and, thereby, the covariance terms of the matrix V are all zero. The simplified, though still nonlinear, form is :

$$\sum_{j=1}^{n} \overline{a}_{ij} + e_i \sqrt{\sum_{j=1}^{n} \mathrm{Var}(a_{ij})\, x_j^2} - b_i \leq 0 \text{ for } i = 1,2......m. \tag{A.5}$$

When only c_j's are random variables :

If c_j's are normally distributed random variables, the objective function, $F(X)$ will also be a normally distributed random variable (note : the distribution of the value of the optimum value is not likely to be normally distributed). Let $\bar{c}_j$ denote the mean of each c_j and V the variance-covariance matrix of all c_j's. The deterministic (and of course nonlinear) form of the previously stochastic objective function is :

$$F(X) = k_1 \sum_{j=1}^{n} \bar{c}_j x_j + k_2 \sqrt{X^T V X} \tag{A.6}$$

and if the cost coefficients, c_j's, are independent, the square root section of the objective function takes the form of : $k_2 \sqrt{\sum_{j=1}^{n} \mathrm{Var}(c_j)\, x_j^2}$ where k_1 and k_2 are non-negative coefficients whose values indicate the relative importance of the mean and the standard deviation of the distribution of the objective function. For example, $k_1 = k_2 = 1$ indicates equal importance for the minimization of the mean as well as the standard deviation of the distribution of F(X).

When c_j, a_{ij}, and, b_i are all random variables:

This is the most general case in which all LP components follow a normal distribution. The resulting deterministic equivalent form reflects the stochastic nature of the initial problem for the desired level of probability for each constraint. The objective function has the same form as above (independent case) when only c_j's were normal variables. Each constraint takes the following deterministic (and nonlinear) form :

$$\bar{h}_i + e_i \sqrt{\mathrm{Var}(h_i)} \leq 0 \text{ for } i = 1,2,\ldots m \quad \text{where} \quad \bar{h}_i = \sum_{j=1}^{n} \bar{a}_{ij} x_j - \bar{b}_i \quad \text{for all } i. \tag{A.7}$$

Appendix B. Available Solution Methods for Deterministic Equivalent Form of Chance Constrained Programming Problems

It is possible to solve the resulting nonlinear form by using some general nonlinear programming solution strategies such as convex programming and other feasible direction methods. Such methods, however, will become intractable as the number of decision variables grows. The literature provides two clear-cut and easy to implement methods for linearizing the nonlinear constraints of any deterministic equivalent form resulting from normally and independently distributed a_{ij} and b_j coefficients.

Chance-Constrained Programming Algorithm (CHAPS) [88,89]:

Consider following deterministic equivalent form :

$$\text{Minimize} \sum_{j \in J} c_j \, x_j \tag{A.8}$$

$$\text{Subject to} \quad \sum_{j \in J} e_{ij} x_j + \psi(\alpha_i)\,[\, d_{i0}^2 + \sum_{j \in} d_{ij}^2 x_j^2 \,]^{1/2} \leq e_{i0} \quad \text{for all } i \in I \tag{A.9}$$

$x_j \geq 0$. Indices I and J represent the constraint and variable sets.

$e_{ij} = E(a_{ij})$, $d_{ij}^2 = V(a_{ij})$, for $i \in I$, $j \in J$ $\quad e_{i0} = E(b_i)$, and $\quad d_{i0}^2 = V(b_i)$. $i \in I$

The set of feasible solutions is enlarged by introducing a new slack variable for each constraint. The separated form of the above constraint (A.9) is written as :

$$\sum_{j \in J} e_{ij} x_j + \psi(\alpha_i)\, y_{in} \leq e_{i0} \quad i \in I \tag{A.10}$$

$$y_{ij} \geq (y_{i,j-1}^2 + d_{ij}^2 x_j^2)^{1/2} \quad i \in I,\ j \in J \tag{A.11}$$

$$y_{i0} = d_{i0} \quad \text{and} \quad x_j \geq 0 \quad i \in I,\ j \in J \tag{A.12}$$

where n is the largest index number in set J and y_{ij} 's are new non-negative decision variables. All constraints of type A.11 above are replaced by linear approximate constraints of :

$$-\, y_{ij} + r_{ijk}\, y_{i,j-1} + s_{ijk}\, x_j \leq 0, \quad i \in I,\ j \in J,\ k = 1 \ldots p \tag{A.13}$$

The index p is the degree of linearization or fineness and r_{ijk} and s_{ijk} are constants whose formulas are given in references [88] and [89]. The authors state that $p = 6$ to 8 is sufficient to reach optimality in most problems. Approximate estimation of the size of the resulting linear programming problem is :

$$\text{number of variables} = r + n \tag{A.14}$$

$$\text{number of rows} = 6r + m \tag{A.15}$$

where r, n, and m are the number of random variables, number of decision variables, and the number of rows of the original Chance Constrained Programming model. CHAPS algorithm does not handle the case in which the objective function has nonlinear terms.

2) Naslund's Approximation [74]

The nonlinear square root portion of each constraint of the deterministic equivalent is converted into an approximate linear form and then added to the rest of the constraint. If the objective function has any nonlinear (square root) terms due to stochastic c_{ij} coefficients, this approximation, shown below, can also be used to linearize the objective function.

$$\{ \sum_{m=1}^{M} V_m X_m \}^{1/2} \leq \{ \sum_{m=1}^{M} V_m \}^{1/2} - \sum_{n=1}^{M} \{ (1 - X_n) [(\sum_{m=1}^{M} V_m)^{1/2} - (\sum_{m=1}^{M} V_m - V_n)^{1/2}] \} \tag{A.16}$$

V_m is the coefficient of each decision variable X_m in the square root section (V_m then is the corresponding variance term). At the end of the approximation process, a constant is obtained and it is carried over to the right hand side of the overall constraint after changing its sign. This approximation is included in STEP2 FORTRAN code as two separate subroutines, one for each environment, in order to linearize terms such as (A.5) and (A.6) of Appendix A.

Appendix C. Examples for Applications of Linearization Techniques

Three examples, one from literature, are solved to justify the selection of Naslund's approximation to linearize non-linear terms encountered in Chapters three and four.

Example 1 : 0/1 Product Selection Problem:

This example illustrates the selection set of jobs which yield the maximum profit when all a_{ij} and b_j coefficients are normally and independently distributed random variables.

$$\text{Max } [\, 10X_1 + 15X_2 + 20X_3 + 14X_4 \,]$$

Subject to :

$$(100;5)\,X_1 + (150;6)\,X_2 + (215;8)\,X_3 + (85;3)\,X_4 \leq (500;15) \quad \text{Machine A constraint}$$

$$(25;2)\,X_1 + (15;2)\,X_2 + (10;2)\,X_3 + (35;3)\,X_4 \leq (74;4) \quad \text{Machine B constraint}$$

$$(40;3)\,X_1 + (0.5;0.1)\,X_2 + (20;2)\,X_3 + (5;1)\,X_4 \leq (60;5) \quad \text{Machine C constraint}$$

Where all X 's are 0/1 decision variables and $X_i = 1$ indicates that job i will be produced and sold. The parameters in parenthesises indicate the mean and the standard deviation of each coefficient. If the variations are ignored, the resulting deterministic 0/1 problem has the solution of 0-1-1-1 with the objective function of $49. If the management, for example, requires that each constraint should have at least ninety-nine percent probability of not being violated, then the 0/1 problem shown above takes the following deterministic equivalent, but nonlinear form :

$$\text{Max } [\, 10X_1 + 15X_2 + 20X_3 + 14X_4 \,]$$

Subject to :

$$100X_1 + 150X_2 + 215X_3 + 85X_4 + 2.33\sqrt{25X_1^2 + 36X_2^2 + 64X_3^2 + 9X_4^2 + 225} \le 500$$

$$25X_1 + 15X_2 + 10X_3 + 34X_4 + 2.33\sqrt{4X_1^2 + 4X_2^2 + 4X_3^2 + 9X_4^2 + 16} \le 74$$

$$40X_1 + 0.5X_2 + 20X_3 + 5X_4 + 2.33\sqrt{9X_1^2 + 0.01X_2^2 + 4X_3^2 + X_4^2 + 25} \le 60$$

There are $2^4 = 16$ possible combinations from which the optimum must be selected. Enumeration process has shown that combination of $X_1 = 0$ and $X_2 = X_3 = X_4 = 1$ is still the optimal one with maximum profit of $49.

Naslund's approximation has been applied to above nonlinear model to get the following linearized form (objective function is the same):

$$101.56\,X_1 + 152.27\,X_2 + 219.13\,X_3 + 85.56\,X_4 \le 464.37$$

$$25.79\,X_1 + 15.79\,X_2 + 10.79\,X_3 + 36.84\,X_4 \le 64.03$$

$$41.79\,X_1 + 0.50\,X_2 + 20.77\,X_3 + 5.19\,X_4 \leq 48.19$$

The above model can be solved via various tools including MPSIII and LINDO.

The deterministic equivalent form of this example has also been solved by using CHAPS algorithm (details of CHAPS solution are too long to include here). Table 60 compares the performances of both solution methods :

Table 60. Comparison of Two Solution Methods for Chance Constrained Programming Problems.

Criteria	Chaps Algorithm	Naslund's Approximation
Number of Variables	18	4
Number of Constraints	54	3
Continuous Optimum	$48.45	$49.01
Integer Optimum	$35 (0-1-1-0)	$49 (0-1-1-1)
Number of Iterations	53	6

In this example, Naslund's approximation (IP which results after using this approximation and its solution) appears better than CHAPS algorithm with respect to computation time, problem size and the optimum value found. The lower objective function value (inferior) of CHAPS algorithm may be explained with use of a linearization factor of only four in the example since CHAPS algorithm will reach to optimality in continuous case with the use of higher linearization levels. The authors of CHAPS algorithm do not discuss the performance of their algorithm when some or all of the decision variables are integers.

Example 2 : Cattle feed problem with continuous variables:

Minimum cost cattle feed problem under probabilistic protein constraint was formulated as a chance constrained programming problem in [95] and solved by CHAPS algorithm. To test its performance against CHAPS and the feasible direction algorithm of Zoutendijk's (its solution also reported in [89]), Naslund's approximation has been applied to the same problem. Table 61 on page 245 contains the results showing the performances of three methods of solving for this Chance Constrained Programming with linear objective function.

Table 61. Comparison of Three Solution Methods for the Cattle Feed Problem

Method	x_1	x_2	x_3	x_4	Z
Zoutendijk's	0.6359	0	0.31270	0.0515	29.8924
CHAPS	0.635875	0	0.31266	0.051459	29.8888
Naslund's	0.60926	0	0.31538	0.07536	30.3093

Although Naslund's approximation yields a minimum cost which is 1.405 percent worse than the other two algorithms, it must remembered that Naslund's approximation does not require any additional variables or constraints as is the case with CHAPS or any kind of searching technique necessary when using a nonlinear programming algorithm such as Zoutendijk's.

Example 3 : Linearization of Square Root of Sum of 0/1 Variables:

The purpose of this example is to demonstrate the accuracy of Naslund's approximation in linearizing a typical nonlinear expression often encountered in this research. Consider the expression,

$$(103.7\,X_1^2 + 112.5\,X_2^2 + 68.5\,X_3^2 + 76\,X_4^2 + 40\,X_5^2 + 102\,X_6^2 + 61\,X_7^2 + 75\,X_8^2 + 14X_9^2 + 36\,X_{10}^2)^{1/2} \quad (A.17)$$

where $X_1 \ldots X_{10} \in [0,1]$. Application of Naslund's approximation to nonlinear expression of (A.17) results in the following linear form :

$$2.05\,X_1 + 2.24\,X_2 + 1.34\,X_3 + 1.49\,X_4 + 0.77\,X_5 + 2.02\,X_6 + 1.19\,X_7 + 1.47\,X_8 + 0.26\,X_9 + 0.69\,X_{10} + 12.72 \quad (A.18)$$

The constant, 12.72, has to be ignored if (A.18) is a part of an objective function and carried over to the right hand side if (A.18) is part of a constraint. A small code was used in comparing the actual values of A.17 with that of (A.18) for all 1024 combinations of the ten zero one variables : The average amount of error is 8.9 percent over all combinations, but the error rate falls rapidly as the number of one's in a given combination is increased. For example,

- The average error rate is 7.93 percent if there are at least two one's.
- The average error rate is 3.30 percent if there are at least five one's.
- The average error rate is 2.00 percent if there are at least seven one's.

If, in machine mapping and capacity assignment/allocation problems like those considered in Chapter three, the size of the job mix is similar to the size of the machine mix, the accuracy of such approximations should be good since similar sizes would make the corresponding matrices less sparse (more 1's). While these errors are somewhat significant, they will be equally applicable to decision proceses for both functional and cellular environments.

Conclusion: Naslund's approximation appears to be a very useful tool in solving chance constrained programming problems quickly. The results of Table 60 on page 244, Table 61 on page 245, and example three can not be generalized, but, for heuristic applications, Naslund's approximation is a good tool for linearizing certain non-linear terms.

Appendix D. Sample Data for Problem Sets :

Table 62. Job-Class Data

Class	Job A	Job B	Job C	Job D	Job E	Job F	Job H	Job Q	Job R	Job S	Job U	Job V
C1	1	1	1	0	1	1	1	1	1	0	0	0
C2	0	1	1	1	0	0	1	0	1	1	1	1
C3	1	0	0	1	1	1	0	1	1	0	0	1
C4	1	0	1	0	0	0	1	0	0	1	1	1
C5	1	1	0	0	0	1	1	1	1	0	0	0
C6	0	0	1	1	1	1	1	0	1	1	1	0
C7	0	1	0	0	0	1	0	1	0	1	0	1

Table 63. Machine-Class Data

Class	Machine P	Machine J	Machine K	Machine N	Machine W	Machine Z	Machine T	Machine Y
C1	1	1	0	0	0	1	0	0
C2	1	0	0	0	1	0	0	1
C3	0	0	1	1	1	0	0	0
C4	0	1	0	0	1	0	0	0
C5	0	0	1	1	0	0	1	0
C6	0	0	0	1	0	1	0	0
C7	1	0	0	0	0	1	1	0

Legend: Job B (above) needs at least one operation from operation classes of 1,2,5, and 7. Machine J is able to perform operation classes of 1 and 4 (below).

Table 64. Variable Cost and Processing Time Data

Machines

Ope.	P	J	K	N	W	Z
1	1.7 min $2.0	1.5 min $2.3				1.8 min $1.70
2	2.3 min $2.4	2.1 min $2.5				2.5 min $1.95
3	3.1 min $2.7	2.8 min $2.9				3.2 min $2.20
4	2.0 min $1.7				2.1 min $1.6	
5	2.3 min $1.9				2.5 min $1.7	
6	2.8 min $2.5				3.1 min $1.9	
7			3.1 min $2.6	3.3 min $2.4	3.4 min $2.4	
8			3.4 min $2.9	3.7 min $2.7	3.6 min $2.6	
9			4.1 min $3.3	4.5 min $3.1	4.4 min $2.9	
10			4.9 min $3.4	5.3 min $3.2	5.3 min $3.1	
11		2.1 min $1.4			2.5 min $1.2	
12		3.2 min $1.7			3.7 min $1.05	
13			6.1 min $1.3	6.6 min $1.4		
14			6.5 min $1.5	7.1 min $1.55		
15			7.0 min $1.6	7.3 min $1.7		
16				2.1 min $3.3		2.0 min $3.0
17				2.7 min $3.6		2.5 min $3.2
18				3.1 min $3.7		3.0 min $3.6
19				3.6 min $4.2		3.4 min $3.9
20	3.2 min $2.7					3.1 min $2.5

Legend: Each operation No.7 takes 3.1 minutes on machine K and incurs a total variable cost of $2.6/part. $VC^3_{K,7}$ = $2.6/part and $t^3_{K,7}$ = 3.1 (actually a random variable) minutes.

Class 1 includes operations { 1,2,3 }. Similarly, Class 2 = { 4,5,6 }, Class 3 = { 7,8,9,10 }, Class 4 = { 11,12 }, Class 5 = { 13,14,15 }, Class 6 = { 16,17,18,19 }, and Class 7 = { 20 }.

Variable Cost and Processing Time Data Continued

Machines

Ope.	T	Y
1		
2		
3		
4		2.7 min $1.0
5		2.9 min $1.2
6		3.2 min $1.7
7		
8		
9		
10		
11		
12		
13	5.7 min $1.1	
14	6.3 min $1.4	
15	6.8 min $1.5	
16		
17		
18		
19		
20	2.7 min $2.9	

Table 65. Machine Data on Costs, Needs, Capabilities, and Limitations.

	Machine P	Machine J	Machine K	Machine N	Machine W	Machine Z
IC_i	$97K	$61K	$75K	$80K	$83K	$101K
MA_i	56	40	48	55	60	65
$\overline{U}_i$	0.90	0.95	0.95	0.92	0.96	0.93
$Var(U_i)$	.0003	.0005	.0004	.0006	.0003	.0004
C_i	{1,2,7}	{1,4}	{3,5}	{3,5,6}	{2,3,4}	{1,6,7}
RS_i	20	25	25	20	18	15
MS_i	2	3	3	4	3	2
SC_i	$1.35/min	$1.55/min	$1.11/min	$1.55/min	$0.94/min	$1.56/min

Legend: Machine P costs $97000 in investment cost and it requires 56 ft^2 of area. It has a normally distributed uptime ratio or reliability with mean of 0.90 and a variance of 0.0003. This machine can perform operation classes of 1,2, and 7 (or operations 1,2,3,4,5,6, and 20) and needs to be reset after processing maximum of items parts of any kind. Such resetting takes only 2 minutes if the next batch of parts are the same as the ones processed before stopping for this resetting or minor set up. Major setup cost of machine P is $1.35/min regardless of which of the feasible operation classes for which machine P is being prepared.

For problem set No.4, the following rows should be appended to Table 65 (as columns) for machines T and Y:

T : $89K, 37, 0.96, .0005, {5,7}, 23, 4, $1.40

Y : $53K, 33, 0.99, .0003, {2}, 28, 5, $0.69

Table 66. Job Data for Demand and Operation Requirements

	Job A	Job B	Job C	Job D	Job E	Job F	Job H
$\overline{D}_k$	104	180	140	187	165	114	120
$\sigma_k^2(D_k)$	18	24	17	12	34	26	20
LSC_k	$34	$56	$23	$28	$13	$24	$14
BHC_k	$0.15	$0.20	$0.17	$0.21	$0.33	$0.24	$0.30
MNK_k	11	12	8	10	6	9	5
N_{nk}	#2,#8 #11,#14	#1,#13 #20,#4	#12,#3 #4,#18	#9,#17 #5	#1,#8 #16	#8,#18,#13 #3,#20	#5,#2,#11 #14,#18

Legend: The daily demand for job B is normally distributed with a mean of 180 and a variance of 24. It costs $0.20/ft to transport each Job B. The firm loses $56 for each job B item that can not be delivered at the end of the production period. $56 reflects lost revenue and intangible factors such as damaged goodwill of the firm. A maximum of 12 items of job B can be transported by one mover (unit load) at one time. Job B needs operations No. 1,13,20, and 4 (in precedence order) which belong to operation classes of 1,2,5, and 7.

	Job Q	Job R	Job S	Job U	Job V
$\overline{D}_k$	95	65	50	218	245
$\sigma_k^2(D_k)$	6	2	5	55	70
LSC_k	$35	$42	$67	$ 6	$ 9
BHC_k	$0.05	$0.14	$0.25	$0.11	$0.08
MNK_k	5	4	6	13	17
N_{nk}	#2,#7 #20,#14	#2,#4#15 #18,#9	#12,#17 #4,#20	#18#11 #6	#9,#12 #20,#5

Table 67. Set-up Time Data for Each Machine

Class	Machine P	Machine J	Machine K	Machine N	Machine W	Machine Z
C1	30 min	15 min				22 min
C2	24 min				17 min	
C3			24 min	32 min	15 min	
C4		19 min			34 min	
C5			12 min	28 min		
C6				18 min		26 min
C7	29 min					28 min

Legend: If two totally dissimilar unit loads of jobs follow each other on machine K for any class 3 operation, it will take 24 minutes of set up time. That is, ST^{2}_{P} = 24 minutes.

For machine T, C5 : 14 minutes C7 : 16 minutes and for machine Y, C2 : 10 minutes.

Table 68. Job-Design Similarity Data for all Twelve Jobs.

Job	Job A	Job B	Job C	Job D	Job E	Job F	Job H	Job Q	Job R	Job S	Job U	Job V
A	1.00	0.60	0.41	0.30	0.22	0.65	0.71	0.64	0.27	0.53	0.10	0.38
B		1.00	0.38	0.34	0.41	0.58	0.63	0.59	0.44	0.80	0.60	0.22
C			1.00	0.75	0.82	0.39	0.41	0.66	0.10	0.71	0.77	0.80
D				1.00	0.74	0.42	0.29	0.55	0.10	0.11	0.71	0.29
E					1.00	0.35	0.31	0.27	0.77	0.93	0.55	0.46
F						1.00	0.57	0.86	0.92	0.27	0.05	0.49
H							1.00	0.39	0.15	0.48	0.70	0.13
Q								1.00	0.23	0.55	0.62	0.29
R									1.00	0.11	0.87	0.32
S										1.00	0.26	0.82
U											1.00	0.46
V												1.00

Legend: Jobs or parts B and C have 0.38 design/shape similarity, that is, $SM^{d}_{B,C}$ = 0.38. If these two jobs follow each other on machine K for a class 3 operation, the setup (Table 67 shows full set up time is 19 minutes for this combination) time will be (1 - 0.38)*24 = 15 minutes. All entries above have been chosen randomly.

Table 69. Job Similarity Data based on Process Plans (Twelve Jobs).

Job	Job A	Job B	Job C	Job D	Job E	Job F	Job H	Job Q	Job R	Job S	Job U	Job V
A	1.00	0.33	0.33	0.17	0.40	0.50	0.50	0.60	0.50	0.14	0.20	0.33
B		1.00	0.33	0.17	0.17	0.50	0.50	0.50	0.50	0.33	0.00	0.33
C			1.00	0.40	0.40	0.29	0.80	0.14	0.50	0.60	0.50	0.33
D				1.00	0.50	0.33	0.33	0.17	0.60	0.40	0.25	0.40
E					1.00	0.60	0.33	0.40	0.60	0.40	0.25	0.17
F						1.00	0.43	0.80	0.67	0.29	0.17	0.29
H							1.00	0.29	0.67	0.50	0.40	0.29
Q								1.00	0.50	0.14	0.00	0.33
R									1.00	0.29	0.17	0.29
S										1.00	0.50	0.60
U											1.00	0.20
V												1.00

Similarity values shown above were calculated using the method explained in Chapter three.

Table 70. Weighted Job Similarity Data (Twelve Jobs).

Job	Job A	Job B	Job C	Job D	Job E	Job F	Job H	Job Q	Job R	Job S	Job U	Job V
A	1.00	0.47	0.37	0.24	0.31	0.58	0.61	0.62	0.39	0.34	0.15	0.36
B		1.00	0.36	0.26	0.29	0.54	0.57	0.55	0.46	0.57	0.30	0.28
C			1.00	0.58	0.61	0.34	0.61	0.40	0.30	0.66	0.61	0.57
D				1.00	0.62	0.38	0.31	0.36	0.35	0.26	0.48	0.35
E					1.00	0.48	0.32	0.34	0.69	0.67	0.40	0.32
F						1.00	0.50	0.84	0.80	0.28	0.11	0.39
H							1.00	0.34	0.41	0.49	0.55	0.21
Q								1.00	0.37	0.35	0.31	0.31
R									1.00	0.20	0.52	0.31
S										1.00	0.38	0.71
U											1.00	0.33
V												1.00

Weighted similarity values shown above were calculated by taking the average of the entries shown in Table 68 on page 253 and Table 69 above.

Appendix E. Input Files and Data Requirements of Hierarchical Comparison Computations

Hierarchical step calculations are carried out using a mixture of manual and semi-manual data preparation steps using computer programming and the available computer packages. WATFIV compiler was used for FORTRAN programming. The WATFIV EXEC file defines the locations of the data files used in all programs.

WATFIV EXEC File (for all steps with mainframe computer programming)

```
&TRACE OFF
FILEDEF 30 DISK STEP1 NUMBERS
FILEDEF 31 DISK MACHINE CHRS
FILEDEF 34 DISK JOB CHRS
FILEDEF 36 DISK STEP1 TIMES
FILEDEF 37 DISK JOBOPE MATRIX
FILEDEF 40 DISK STEP2 DATA
FILEDEF 41 DISK MACH2 DATA
FILEDEF 44 DISK JOB2 DATA
FILEDEF 46 DISK STEP1 TIMES
FILEDEF 47 DISK VARIABLE COSTS
FILEDEF 48 DISK JOBOPE MATRIX
FILEDEF 49 DISK OPECLASS MATRIX
FILEDEF 50 DISK MACCLS MATRIX
FILEDEF 51 DISK JOBCLS MATRIX
FILEDEF 52 DISK JOBCLL MATRIX
FILEDEF 70 DISK STEP5 NUMBERS
FILEDEF 74 DISK STEP5 MACHINE
FILEDEF 75 DISK JOBCHR MATRIX
```

```
FILEDEF 76 DISK MACDEP MATRIX
FILEDEF 77 DISK JDPVST MATRIX
FILEDEF 78 DISK ICLMCO MATRIX
FILEDEF 80 DISK UNIT TIMES
FILEDEF 81 DISK ULOAD CONSTANTS
FILEDEF 82 DISK JOBCLS4 MATRIX
FILEDEF 83 DISK MACCLS4 MATRIX
FILEDEF 84 DISK JOBOPE4 MATRIX
FILEDEF 85 DISK TIMES4 MATRIX
FILEDEF 86 DISK MACHINE LOADSPCS
FILEDEF 87 DISK JOB LOADSPCS
FILEDEF 89 DISK SETUP TIMES
FILEDEF 90 DISK FUNCTION SETS
FILEDEF 91 DISK CELLULAR INDEX
FILEDEF 92 DISK CELLULAR SETS
FILEDEF 08 DISK XXXXX CNTL A (LRECL 80 RECFM F
WATFIV XXXXX (xxxxx = file name)
```

Input Requirements of STEP1 FORTRAN Code (Problem Set No.1):

STEP1 numbers showing initial parameters

4,20,4,40,1350,1100,20000

MACHINE CHRS showing machine name, cost, area, and reliability

'P',97,56,.9,.0003,
'J',61,40,.95,.0005,
'K',75,48,.95,.0004,
'N',80,55,.92,.0006

JOB2 DATA showing job name, daily demand, variance, and number of operations

'A',104,18,4,
'B',180,24,4,
'C',140,17,4,
'D',187,12,3

OPECLASS MATRIX showing operation(rows) membership in 7 operation classes

1,0,0,0,0,0,0,
1,0,0,0,0,0,0,
1,0,0,0,0,0,0,
0,1,0,0,0,0,0,
0,1,0,0,0,0,0,
0,1,0,0,0,0,0,
0,0,1,0,0,0,0,
0,0,1,0,0,0,0,
0,0,1,0,0,0,0,
0,0,1,0,0,0,0,
0,0,0,1,0,0,0,

0,0,0,1,0,0,0,
0,0,0,0,1,0,0,
0,0,0,0,1,0,0,
0,0,0,0,1,0,0,
0,0,0,0,0,1,0,
0,0,0,0,0,1,0,
0,0,0,0,0,1,0,
0,0,0,0,0,1,0,
0,0,0,0,0,0,1

MACCLS MATRIX showing machine(rows) capability for 7 operation classes

1,1,0,0,
1,0,0,0,
0,0,1,1,
0,1,0,0,
0,0,1,1,
0,0,0,1,
1,0,0,0

JOBCLS MATRIX showing job operation class(rows) needs of four jobs

1,1,1,0,
0,1,1,1,
1,0,0,1,
1,0,1,0,
1,1,0,0,
0,0,1,1,
0,1,0,0

JOBOPE MATRIX showing operation needs(columns) of four jobs

0,1,0,0,
1,0,0,0,
0,0,1,0,
0,1,1,0,
0,0,0,1,
0,0,0,0,
0,0,0,0,
1,0,0,0,
0,0,0,1,
0,0,0,0,
1,0,0,0,
0,0,1,0,
0,1,0,0,
1,0,0,0,
0,0,0,0,
0,0,0,0,
0,0,0,1,
0,0,1,0,
0,0,0,0,
0,1,0,0

STEP1 TIMES showing operation times of 20 operations on 4 machines

1.7,1.5,0,0,
2.3,2.1,0,0,
3.1,2.8,0,0,
2.0,0,0,0,
2.3,0,0,0,
2.8,0,0,0,
0,0,3.1,3.3,
0,0,3.4,3.7,
0,0,4.1,4.5,
0,0,4.9,5.3,
0,2.1,0,0,
0,3.2,0,0,
0,0,6.1,6.6,
0,0,6.5,7.1,
0,0,7,7.3,
0,0,0,2.1,
0,0,0,2.7,
0,0,0,3.1,
0,0,0,3.6,
3.2,0,0,0

Input Requirements of STEP2 FORTRAN Code (Problem Set No.1) :

This data is needed in addition to most of the data above.

STEP2 DATA

4,20,4,40,7,2,2,1,1,10000.,2.33,0,0,0

MACH2 DATA showing machine name and suggested availability from step 1

'P',5,
'J',3,
'K',7,
'N',3

JOBCLL MATRIX showing job (columns) assignments to cells (rows) in binary

1,1,0,0,
0,0,1,1

VARIABLE COSTS showing variable costs of 20 operations on 4 machines

2,2.3,0,0,
2.4,2.5,0,0,
2.7,2.9,0,0,
1.7,0,0,0,
1.9,0,0,0,
2.5,0,0,0,
0,0,2.6,2.4,
0,0,2.9,2.7,

0,0,3.3,3.1,
0,0,3.4,3.2,
0,1.4,0,0,
0,1.7,0,0,
0,0,1.3,1.4,
0,0,1.5,1.55,
0,0,1.6,1.7,
0,0,0,3.3,
0,0,0,3.6,
0,0,0,3.7,
0,0,0,4.2,
2.7,0,0,0

Input Requirements of UNIT FORTRAN Code (for all problem sets):

Input Matrices of MACCLS4, JOBCLS4, JOBOPE4, and TIMES4 are all problem set No.4 versions of problem set No.1 explained above.

ULOAD CONSTANTS showing parameters

4,8,12,7,20,19

FUNCTION SETS showing number of jobs, machines, and average setup factors

4,4,0.54,
6,7,0.51,
6,10,0.52,
8,12,0.53

CELLULAR INDEX showing cell-set membership, number of jobs, and setup factor

1,1,2,0.40,
1,2,2,0.25,
2,1,4,0.38,
2,2,3,0.23,
2,3,3,0.39,
2,4,2,0.59,
2,5,2,0.26,
3,1,5,0.45,
3,2,5,0.39,
3,3,4,0.35,
3,4,3,0.47,
3,5,3,0.46,
4,1,4,0.52,
4,2,4,0.22,
4,3,4,0.53,
4,4,3,0.35,
4,5,3,0.22,

4,6,3,0.46,
4,7,3,0.49

CELLULAR SETS showing job names (number) in each of nineteen distinct cells

1,2,
3,4,
1,2,6,7,
3,4,5,
1,2,6,
3,7,
4,5,
1,2,6,7,9,
3,4,5,8,10,
1,2,6,8,
3,7,10,
4,5,9,
1,2,4,7,
3,5,10,12,
6,8,9,11,
1,2,7,
3,10,12,
4,5,9,
6,8,11

MACHINE LOADSPCS showing machine names, reset limits, and reset times

'P',20,2,
'J',25,3,
'K',25,3,
'N',20,4,
'W',18,3,
'Z',15,2,
'T',23,4,
'Y',28,5

JOB LOADSPCS showing job names, demand, and unit load size

'A',104,11,
'B',180,12,
'C',140,8,
'D',187,10,
'E',165,6,
'F',114,9,
'H',120,5,
'Q',95,5,
'R',65,4,
'S',50,6,
'U',218,13,
'V',245,17

SETUP TIMES showing setup times of each machine for feasible classes

30,15,0,0,0,22,0,0,
24,0,0,0,17,0,0,10,
0,0,24,32,15,0,0,0,
0,19,0,0,34,0,0,0,
0,0,12,28,0,0,14,0,
0,0,0,18,0,26,0,0,
29,0,0,0,0,28,16,0

Input requirements of STEP5 FORTRAN Code (Problem Set No.1, Functional Case)

STEP5 NUMBERS showing parameters

4,20,4,7,0,0,0,0,0

JOBCHR MATRIX showing demand, lotsize, and operation class data

'A',104,10,11,34,1,4,
'B',180,15,12,56,1,4,
'C',140,18,8,23,1,4,
'D',187,19,10,28,2,3

STEP5 MACHINE showing available machine names and amounts after Step 4 process.

'P',4/'J',3/'K',4/'N',3 (in short matrix form)

MACDEP, JDPVST matrices and ICLMCO Data (ICLJOB and MCOUNT arrays)

1,1,0,0,
2,0,0,0,
0,0,1,1,
0,2,0,0,
0,0,3,0,
0,0,0,2,
1,0,0,0
JDPVST :
1,1,0,0/0,1,1,0/1,0,0,1/0,1,1,1/1,0,0,1 (in short matrix form)
ICLMCO data
2,3/2,2/2,3/3,2/2,2/ (in short matrix form)

UNIT TIMES showing unit load times for feasible combinations

Extreme care is necessary in entering this data : Each n rows correspond to available operation classes or departments in an ascending order (n = number of visits to department X distinct number of machines left in the department after Step 4). For problem set No.1, jobs

A,B, and C visit department No.1 to use machine P or J, then first 6 rows (3 X 2) below are all for class No.1 operations. If there were 2 machine P's and 2 machine J's, only first 6 rows would still be needed. Each row below has a length equal to the maximum number of batches of job which belongs to row combination.

```
41.5,67.9,93.2,119.6,114.9,171.2,196.5,222.9,248.2,260.8,
  (Class 1, machine P, Job A or 1,P,A)
36.6,58.1,78.5,100.0,121.4,141.8,163.3,183.7,205.2,226.7,247.1,268.6,289.0,310
41.0,65.8,91.7,116.5,142.4,192.0,217.8,242.6,268.5,293.3,318.1,344.0,368.8,394.
7,419.5,444.3,457.8, (1,P,C)
31.2,54.3,79.0,102.1,126.8,149.9,174.7,197.8,220.9,233.0, (2,P,B)
26.1,44.1,63.7,81.7,101.3,119.3,139.0,157.0,176.6,194.6,214.2,232.2,251.8,269.8
,289.4,  (1,J,B)
30.5,52.9,75.3,99.3,121.7,144.1,168.1,190.5,212.9,237.0,259.4,281.8,305.8,328.2
,350.6,374.6,397.0,408.2,  (1,J,C)
37,62,86,111.1,136.2,160.2,185.3,209.3,234.4,259.4,283.4,308.5,332.5,357.6,382.
7,  (2,P,B)
29,45,62,78,95.1,111.1,127.1,144.2,160.2,177.3,193.3,209.3,226.4,242.4,259.4,27
5.4,291.4,300.5, (2,P,C)
36,60,83,107.1,130.1,154.4,177.2,201.3,224.3,248.4,271.4,295.4,318.4,342.5,365.
5,389.6,412.6,436.7,452.8, (2,P,D)
50.4,87.8,126.8,164.2,203.2,240.6,279.6,317,354.4,373, (3,K,A)
54,95,137.6,178.6,221.2,262.6,303.2,345.8,386.8,429.4,470.4,511.4,554.1,595.1,6
37.7,678.7,719.7,762.3,791, (3,K,D)
58,100.8,141.5,184.4,225.1,268,308.7,351.5,392.2,412.9, (3,N,A)
62.3,109.4,154.4,201.6,246.6,293.8,338.8,385.9,430.9,478.1,523.1,570.2,615.2,66
2.4,707.4,754.6,799.6,846.7,878.2,  (3,N,D)
33.4,56.5,81.2,104.3,129,152.1,176.8,199.9,223,235.1, (4,J,A)
35.9,61.5,87.1,114.3,139.9,165.5,192.7,218.3,243.9,271.1,296.7,322.3,349.5,375.
1,400.7,428.7,428,453.6,466.4, (4,J,C)
78,149.5,222.6,294.1,367.2,438.7,511.8,583.3,654.8,689, (5,K,A)
79.7,152.9,227.7,300.9,375.7,448.9,523.7,596.9,671.8,745,819.8,893,967.8,1041,1
115.8, (5,K,B)
34.5,59.3,86.3,111.1,138,162.8,187.6,214.6,239.4,266.4,291.2,316,342.9,367.7,39
4.7,419.5,444.3,458.8,  (6,N,C)
36.7,65.9,92.9,122,149,178.2,205.2,234.4,261.4,290.5,317.5,346.7,373.7,402.8,42
9.8,459,486,515.2,534.1,   (6,N,D)
54.1,93.5,131.9,171.4,210.9,249.3,288.8,327.2,366.7,406.1,444.5,484,522.4,561.9
,601.4   (7,P,B)
```

Normally, unit load times must be input in one entry per line fashion by running UNIT FORTRAN after making the necessary format changes so that there is no manual input effort. STEP5 FORTRAN code should also be modified so that unit load times are read as one entry in each input row rather than the above format.

Appendix F. Problem Sizes and Expanded Forms of Mathematical Models

Models of Chapter three and their modified forms in Chapter four may contain hundreds of zero-one assignment variables and dozens of integer or fractional decision variables. Total number of variables and the constraints depend on the densities of input matrices of job-class, job-cell, job-operation, machine-class, and distinct number of jobs and available machine types. Chapter five contains results for various data sizes. Following expanded models are written out for problem set No.1.

Notation for the assignment variables: Following example illustrates the notational differences in the modelling of the two environments :

$X^1_{p,a}$: is 1 if class 1 operation requirement of job A is assigned to machine P in Step 2F.

$X^1_{p,a,2}$: is one if operation No.2 of Job A (pre assigned to cell 1) is assigned to machine P in Step 2C.

$$\text{Minimize } 97M_P + 61M_J + 75M_K + 80M_N + BM(AA^x + EC^x)$$

Subject to :

Deterministic Equivalents of Machine Capacity Constraints :

1) $208.7\, M_{p,a,2} + 228.57\, M_{j,a,2} \geq 113.89$

2) $141.18\, M_{k,a,8} + 129.73\, M_{n,a,8} \geq 113.89$

3) $228.57\, M_{j,a,11} \geq 113.89$

4) $73.85\, M_{k,a,14} + 67.61 M_{n,a,14} \geq 113.89$

5) $282.35\, M_{p,b,1} + 320\, M_{j,b,1} \geq 191.41$

6) $240\, M_{p,b,4} \geq 191.41$

7) $78.79\, M_{k,b,13} + 72.73\, M_{n,b,13} \geq 191.41$

8) $150\, M_{m,b,20} \geq 191.41$

9) $154.84\, M_{p,c,3} + 171.43\, M_{j,c,3} \geq 149.61$

10) $240\, M_{p,c,4} \geq 149.61$

11) $150\, M_{j,c,12} \geq 149.61$

12) $154.84\, M_{n,c,18} \geq 149.61$

13) $208.70\, M_{p,d,5} \geq 195.07$

14) $117.07\, M_{k,d,9} + 106.67\, M_{n,d,9} \geq 195.07$

15) $177.78\, M_{n,d,17} \geq 195.07$

Constraints of Equation 3.1.2 of Step 1 :

16) $M_{p,a,2} + M_{p,b,4} + M_{p,b,20} + M_{p,c,3} + M_{p,c,4} + M_{p,d,5} = 0.9\, M_P$

17) $M_{j,a,2} + M_{j,a,11} + M_{j,b,1} + M_{j,c,3} + M_{j,c,12} = 0.95\, M_J$

18) $M_{k,a,8} + M_{k,a,14} + M_{k,b,13} + M_{k,d,9} = 0.95\, M_K$

19) $M_{n,a,8} + M_{n,a,14} + M_{n,b,13} + M_{n,c,18} + M_{n,d,9} + M_{n,d,17} = 0.92\, M_N$

Plant Area and Budget Constraints :

20) $M_P + M_J + M_K + M_N \leq TA + AA^x$

21) $M_P + M_J + M_K + M_N \leq C + EC^x$

Integrality and Nonnegativity Constraints :

$M_P,\ M_J,\ M_K,\ M_N \geq$ and integer

$M_{p,a,2},\ M_{j,a,2},\ \ldots\ldots\ldots M_{n,d,17} \geq 0$

$AA,\ EC \geq 0$

Figure 41. Example of Expanded Form of Step 1 Model

Minimize Z

$$249.60\,X^1_{p,a} + 360\,X^1_{p,b} + 378\,X^1_{j,a} + 260\,X^1_{j,b} + \ldots\ldots + 486\,X^7_{p,b}$$

$$+ BM\,(AC^p_p + \ldots\ldots AC^p_n) +$$

$$+ \sqrt{103.68\,(X^1_{p,a})^2 + 96\,(X^1_{p,b})^2 + \ldots\ldots + 40.50\,(X^5_{k,a})^2 + \ldots + 174.96\,(X^7_{p,b})^2}$$

Subject to :

Deterministic Equivalents of Machine Capacity Constraints of type 3.2.1 :

$$1)\ 239.2\,X^1_{p,a} + 306\,X^1_{p,b} + 434\,X^1_{p,c} + 2.33\sqrt{95.22\,(X^1_{p,a})^2 + \ldots + 163.37\,(X^1_{p,c})^2} \le 480\,M_{P,1}$$

$$2)\ 218.4\,X^1_{j,a} + 270\,X^1_{j,b} + 392\,X^1_{j,c} + 2.33\sqrt{79.38\,(X^1_{j,a})^2 + \ldots\ldots + 133.28\,(X^1_{j,c})^2} \le 480\,M_{J,1}$$

....

....

$$9)\ 434\,X^6_{n,c} + 504.9\,X^6_{n,d} + 2.33\sqrt{163.37\,(X^6_{n,c})^2 + 87.48\,(X^6_{n,d})^2} \le 480\,M_{N,6}$$

....

Job, class, machine assignment constraints of type 3.2.2. :

$$11)\ X^1_{p,a} + X^1_{j,a} = 1$$

....

....

$$18)\ X^3_{k,d} + X^3_{n,d} = 1$$

....

....

$$22)\ X^5_{k,b} + X^5_{n,b} = 1$$

....

Machine allocation constraints of type 3.2.3. :

26) $M_{P,1} + M_{P,2} + M_{P,7} \le M_P$ (input from step 1) $1 + AC^p_p$

27) $M_{J,1} + M_{J,4} \le M_J$ (input from step 1) $1 + AC^p_j$

28) $M_{K,3} + M_{K,5} \le M_K$ (input from step 1) $1 + AC^p_k$

29) $M_{N,3} + M_{N,5} + M_{N,6} \le M_N$ (input from step 1) $1 + AC^p_n$

Integrality and Nonnegativity Constraints :

$M_{P,1}, \ldots M_{N,6} \ge 0$ and integer, $AC^p_p, \ldots AC^p_n \ge 0$

$X^1_{p,a},\ X^1_{p,b} \ldots\ldots X^7_{p,b} \in [0,1]$

Figure 42. Deterministic Equivalent of Model of Step 2F

Minimize Z

$$250.71\, X^1_{p,a,2} + 361.03\, X^1_{p,b,1} + 306.74\, X^1_{p,b,4} + \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 674.98\, X^2_{n,d,17}$$

$$+ \ BM\,(AC^p_p + \ldots\ldots\ AC^p_n) \ +$$

$$+ \sqrt{nn\,(X^1_{p,a})^2 + nn\,(X^1_{p,b})^2 + \ldots\ldots\ldots + nn\,(X^5_{k,a})^2 + \ldots\ldots + nn\,(X^7_{p,b})^2}$$

Subject to :

Deterministic Equivalents of Machine Capacity Constraints of type 3.3.1 :

$$1) \ldots X^1_{p,a,1} + X^1_{p,b,1} + X^1_{p,b,4} + \ldots X^1_{p,b,20}\ 2.33 + \sqrt{\ldots (X^1_{p,a,2})^2 + \ldots + (X^1_{p,b,20})^2} \leq 480\, M_{P,1}$$

....

....

$$8)\ nn\,X^2_{n,c,18} + nn\,X^2_{n,d,9} + nn\,X^2_{n,d,17}\ 2.33 + \sqrt{cc\,(X^1_{n,c,18})^2 + \ldots + cc\,(X^2_{n,d,17})^2} \leq 480\, M_{N,2}$$

....

Job, class, machine assignment constraints of type 3.3.2. :

$$9)\ X^1_{p,a,1} + X^1_{j,a,1} = 1$$

....

..... (nn and cc refer to numerical coefficients)

$$15)\ X^1_{k,b,13} + X^1_{n,b,13} = 1$$

....

....

$$22)\ X^2_{k,d,9} + X^2_{n,d,9} = 1$$

....

Machine allocation constraints of type 3.2.3. :

$$24)\ M_{P,1} + M_{P,2} + \ \leq M_P \text{ (input from step 1) } 1 + AC^p_p$$

$$25)\ M_{J,1} + M_{J,2} \leq M_J \text{ (input from step 1) } + 1 + AC^p_j$$

$$26)\ M_{K,1} + M_{K,2} \leq M_K \text{ (input from step 1) } + 1 + AC^p_k$$

$$27)\ M_{N,1} + M_{N,2}\, M_N \text{ (input from step 1) } + 1 + AC^p_n$$

Integrality and Nonnegativity Constraints :

$$M_{P,1}, \ldots M_{N,2} \geq 0 \text{ and integer, } AC^p_p, \ldots AC^p_n \geq 0$$

$$X^1_{p,a,1}, X^1_{p,b,1} \ldots\ldots X^2_{n,d,17} \in [0,1]$$

Figure 43. Deterministic Equivalent of Model of Step 2C

(*) : The remaining constraints are the same as in deterministic equivalent form shown in Figure 42 on page 265.

Minimize Z

$$250.71\, X^{1}_{p,a} + 361.03\, X^{1}_{p,b} + 379.33\, X^{1}_{p,c} + 261.21\, X^{1}_{j,a} + \ldots\ldots\ldots\ldots\ldots\ldots + 487.9\, X^{7}_{p,b}$$

$$+\ BM\,(\, AC^{p}_{p} + \ldots\ldots\ldots + AC^{p}_{n}\,)$$

subject to :

1) $245.85\, X^{1}_{p,a} + 310.73\, X^{1}_{p,b} + 446\, X^{1}_{p,c} \leq 480\, M_{P,1}$

....

9) $449.11\, X^{6}_{n,c} + 512.02\, X^{6}_{n,d} \leq 480\, M_{N,6}$

(*)

Figure 44. Linearized Form of Deterministic Equivalent of Step 2F

Appendix G. Description of MPSIII Package for Solution of Mathematical Models

Often, as in this research, users may have to develop their own codes to generate the proper input data since a typical input data may easily be in the order of thousands of lines. Manual data creation is only possible for very small problems and subject to errors as the problem size grows. A typical input file contains following major components :

- Sections showing the sign of each constraint.
- Columns section showing the location of each variable in objective function and the constraint and Right hand side values section.
- Bounds section with upper bounds for all variables except for 0/1 variables.

Figure 45 on page 269 summarizes file organization and the format requirements when using MPSIII in batch mode. MPSIII along with the other similar packages such as MPSX/370 and LINDO has its own matrix generation capability, but this option was found too complicated and impractical to use. Appendix H shows sample MPSIII input files generated by various FORTRAN codes in this research.

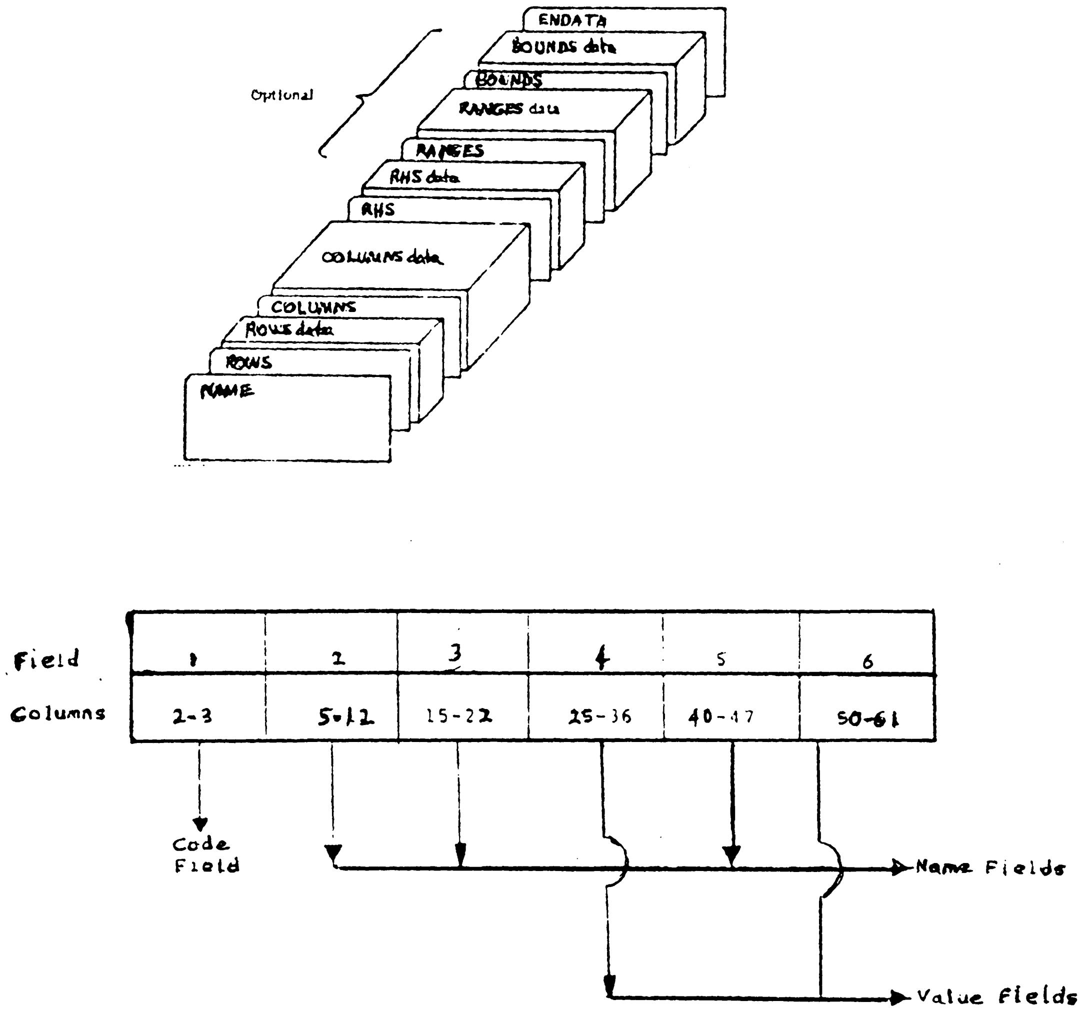

Figure 45. File Organization and Format Requirements of MPSIII Package

Appendix H. MPSIII File Example (Command and Input Sections)

Command Section:

This section is normally the same in all problem sets.

```
//A223HS   JOB  53646,SARPER,REGION=2048K,TIME=(0,59)
/*PRIORITY STANDARD
/*JOBPARM CARDS=1000,LINES=100
/*ROUTE PRINT VTVM1.MENDERES
// EXEC  $IPIII,TIME=1,REGION=800K
//EXEC.SYSIN DD *
NAME        MIPIII
*
*      DECK IS SET UP TO RUN FROM CONVERT DECK
*      TO RUN DATAFORM, REMOVE CONVERT ROW AND THE
*      ASTERISK(*) ON THE CMPMAT ROW IN THE SYSTEM TABLE.
*
             T:....TEGY = BP
             PRINT     = 0
             NODES      = 200
             Z:..STEM = NN, OPTION
             CONVERT  = TEST1
             MATRIX   = MATRIX
             OBJ     = Z
             RHS     = RH
             BOUND    = BOUD
             PICTURE
             CONTSOL
             SOLUTION = ACTIVE
ENDATA
```

STEP1C CNTL for Problem Set No.1 (Created by STEP1 FORTRAN) :

STEP1F CNTL is not shown, but it is similar.

```
NAME        TEST1    FREE
ROWS
 N  Z
 G  R1
 G  R2
 G  R3
 .....
 .....
 G  R15
 E  R16
 ......
 E  R19
 L  R20
 L  R21
COLUMNS
   DEBE     'MARKER'              'INTORG'
   MP       Z          97.0      R16       -0.90
   MP       R20          56.0     R21         97.0
   MJ       Z          61.0      R17       -0.95
   MJ       R20          40.0     R21         61.0
   MK       Z          75.0      R18       -0.95
   MK       R20          48.0     R21         75.0
   MN       Z          80.0      R19       -0.92
   MN       R20          55.0     R21         80.0
   FINE     'MARKER'              'INTEND'
   AA       Z          20000.     R20         -1.0
   EC       Z          20000.     R21         -1.0
   MPA2      R1           208.70     R16          1.0
   MJA2      R1           228.57     R17          1.0
   MKA8      R2           141.18     R18          1.0
   ................................................
   ................................................
   MND9      R14          106.67     R19          1.0
   MND17     R15          177.78     R19          1.0
RHS
   RH       R1          113.89
   RH       R2          113.89
   ...........................
   ...........................
   RH       R15          195.07
   RH       R16              0.
   RH       R17              0.
   RH       R18              0.
   RH       R19              0.
   RH       R20           1350.
   RH       R21           1100.
BOUNDS
 UP BOUD      MP            40.0
 ..............................
 UP BOUD      MPC4              40.0
 ..................................
```

```
 UP BOUD     MND17          40.0
ENDATA
```

STEP2F CNTL for Problem Set No.1 (Created by STEP2F FORTRAN) :

STEP2C CNTL is not shown, but it is similar.

```
NAME        TEST1    FREE
ROWS
 N  Z
 L  R1
 L  R2
 .
 .
 L  R10
 E  R11
 E  R12
 .
 .
 E  R20
 E  R24
 E  R25
 L  R26
 L  R27
 L  R28
 L  R29
COLUMNS
    DEBE     'MARKER'              'INTORG'
    MPC1     R1        -480.      R26          1.
    MJC1     R2        -480.      R27          1.
    MPC2     R3        -480.      R26          1.
    MKC3     R4        -480.      R28          1.
    MNC3     R5        -480.      R29          1.
    MJC4     R6        -480.      R27          1.
    MKC5     R7        -480.      R28          1.
    MNC5     R8        -480.      R29          1.
    MNC6     R9        -480.      R29          1.
    MPC7     R10       -480.      R26          1.
    XC1PA    Z         250.71     R1           245.85
    XC1PA    R11       1.
    XC1PB    Z         361.03     R1           310.73
    XC1PB    R12       1.
    XC1PC    Z         379.33     R1           446.30
    XC1PC    R13       1.
    XC1JA    Z         261.21     R2           224.56
    XC1JA    R11       1.
    XC1JB    Z         415.37     R2           274.07
    XC1JB    R12       1.
    XC1JC    Z         407.54     R2           403.14
    XC1JC    R13       1.
    XC2PB    Z         306.74     R3           368.43
    XC2PB    R14       1.
    XC2PC    Z         238.52     R3           285.72
    XC2PC    R15       1.
    XC2PD    Z         355.76     R3           435.40
```

```
    XC2PD     R16        1.
    XC3KA     Z           303.24    R4          367.67
    XC3KA     R17        1.
    XC3KD     Z           618.51    R4          780.26
    XC3KD     R18        1.
    XC3NA     Z           282.21    R5          400.02
    XC3NA     R17        1.
    XC3ND     Z           580.94    R5          856.47
    XC3ND     R18        1.
    XC4JA     Z           145.98    R6          224.75
    XC4JA     R19        1.
    XC4JC     Z           238.52    R6          464.33
    XC4JC     R20        1.
    XC5KA     Z           156.43    R7          701.12
    XC5KA     R21        1.
    XC5KB     Z           234.43    R7          1128.49
    XC5KB     R22        1.
    XC5NA     Z           161.66    R8          766.03
    XC5NA     R21        1.
    XC5NB     Z           252.50    R8          1220.78
    XC5NB     R22        1.
    XC6NC     Z           520.54    R9          449.11
    XC6NC     R23        1.
    XC6ND     Z           674.88    R9          512.02
    XC6ND     R24        1.
    XC7PB     Z           487.90    R10         612.53
    XC7PB     R25        1.
    FINE    'MARKER'              'INTEND'
    ACP     Z          10000.     R26        -5.0
    ACJ     Z          10000.     R27        -3.0
    ACK     Z          10000.     R28        -7.0
    ACN     Z          10000.     R29        -3.0
RHS
    RH      R1         -18.51
    RH      R2         -16.68
    RH      R3         -15.70
    RH      R4         -19.54
    RH      R5         -21.35
    RH      R6         -14.41
    RH      R7         -39.14
    RH      R8         -42.56
    RH      R9         -14.67
    RH      R10          0.00
    RH      R11             1.
    RH      R12             1.
    .....
    .....
    RH      R23             1.
    RH      R24             1.
    RH      R25             1.
    RH      R26             5.0
    RH      R27             3.0
    RH      R28             7.0
    RH      R29             3.0
BOUNDS
 UP BOUD     MPC1            40.0
```

```
UP BOUD    MPC2        40.0
UP BOUD    MPC7        40.0
UP BOUD    MJC1        40.0
UP BOUD    MJC4        40.0
UP BOUD    MKC3        40.0
UP BOUD    MKC5        40.0
UP BOUD    MNC3        40.0
UP BOUD    MNC5        40.0
UP BOUD    MNC6        40.0
UP BOUD    ACP         40.0
UP BOUD    ACJ         40.0
UP BOUD    ACK         40.0
UP BOUD    ACN         40.0
ENDATA
```

STEP5F CNTL for Problem Set No.1 :
(Created by STEP5 FORTRAN and sorted)

STEP5C CNTL is not shown, but it is similar.

```
NAME        TEST1    FREE
ROWS
 N  Z
 L  R1
 L  R2
 .  ..
 .  ..
 .  ..
 L  R31
 E  R32
 .  ...
 .  ...
 E  R46
 L  R47
 .  ...
 L  R60
COLUMNS
   DEBE      'MARKER'              'INTORG'
   Q1AJ1U1   R2           1.     R32         11.
   Q1AJ1U1   R48          31.2
   Q1AJ1U1   R36          11.
   Q1AJ1U10  R2           1.     R32         104.
   Q1AJ1U10  R48          233.0
   Q1AJ1U10  R36          104.
   ...............................................
   ...............................................
   Q1AJ1U2   R36          22.
   Q6DN2U11  R59          317.5
   Q6DN2U11  R46          -110.
   ...............................
RHS
   RH        R1           1.
   RH        R2           1.
   .............................
   .............................
   RH        R5           1.
```

```
   RH        R6            1.
   RH        R7            1.
   RH        R33       180.0
   RH        R34       140.0
   .............................
   RH        R41           0.
   RH        R42           0.
   .............................
   RH        R46           0.
   RH        R47         480.
   .............................
   RH        R60         480.
BOUNDS
 UP BOUD     UDA              104.
 UP BOUD     UDB              180.
 UP BOUD     UDC              140.
 UP BOUD     UDD              187.
ENDATA
```

Appendix I. Sequence Selection Methodology for Functional Production Environment (Step 3F)

This section describes an optimal sequence selection method when there are far too many jobs assigned to a given machine in each department of the functional facility. An alternative heuristic method was in used in Chapters three and four to determine the contribution of set-up requirements in capacity planning and production costs of the two environments. Following inputs are used in step 3 and some of them (identified with *) are the outputs of steps 1 and 2F.

SC_i^c	Set-up cost for each class c operation on machine i ($/min).
JA_{ia}^c	Set of at least two jobs assigned to use a[th] machine i in process class area c. (*)
$JA_{ia}^{c,0}$	The same set including dummy job 0. (*)
MA_c	Set of machines with at least two jobs assigned to process class area c. (*)
a_i	Number of type i machines in set MA_c .(*)
ST_i^c	Set-up time required to prepare machine i for any class c operation when the precedeing and following jobs have zero design similarity.
SC_{in}^c	Set-up cost for operation $n \in c$ on machine i ($/min).

JA^{j}_{nia} Set of at least two jobs whose certain operations have been assigned to the a^{th} machine type i in cell j. (*)

$JA^{j,0}_{nia}$ The same set including the dummy job 0. (*)

Decision Variables :

SQ^{c}_{lmia} 1 if job l immediately preceedes job m on the a^{th} machine i in process area c, 0 otherwise.

TST^{c}_{ia} Total set-up time needed on the a^{th} machine type i in process area c.

AC^{s}_{i} Additional machine i capacity needed due to set-up requirements over all facility. (as percentage over M_{ic} or M_{ij})

SQ^{j}_{lmia} 1 if job l immediately precedes job m on the a^{th} machine of type i in cell j, 0 otherwise.

TST^{j}_{ia} Total set-up time needed on the a^{th} type i machine in cell j.

Step 3F (Functional Facility Case): Step 2F determines the assignment of jobs to machines in operation class areas or departments. Such assignments, however, indicate only the jobs that should be assigned to a machine groups (if there are at least two of each) of identical machines. In some cases, it is possible that the distinct number of jobs assigned to each department can exceed the number of assignable machines available or the reverse may be true. The goal of overall loading is as follows :

- Balance the load among the identical machines in the machine group.
- Determine which job(s) should be assigned to each one of the identical machines in the machine group.
- Sequence jobs so that the total set-up time and cost is the minimum (Step 3)

Possible Cases Resulting from Step 2F :

Following notation is defined by considering the job set assigned to each process class, c, area and each machine type assigned for that job set and processing area.

N_i^c : Number of machine type i available in class area c.

JA_i^c : Set of jobs assigned to use machine type i in class area c.

NJA_i^c : Number of different jobs in set JA_i^c .

<u>1) $NJA_i^c = N_i^c$:</u>

This is a trivial case and each job gets assigned to each available machine (one to one case).

<u>2) $NJA_i^c < N_i^c$:</u>

Here, two further possibilities exist :

2-A) If $\left(\frac{N_i^c}{NJA_i^c}\right)$ is integer :

This is also a trivial case and each job is equally assigned to the number machines that can be allocated to that job.

2-B) If the above ratio is not an integer :

First, each job is fully assigned to one machine and the remaining number of machines, RM_i^c , is calculated by taking the difference between N_i^c and NJA_i^c . If $RM_i^c = 1$, the remaining capacity needed for the jobs will have to be met from this one machine.

If $RM_i^c > 1$, remaining capacity required for the jobs is ranked from highest to the lowest and the jobs are assigned to the remaining machines by the rank order.

3) If $NJA_i^c > N_i^c$:

In this case, the remaining number of jobs, RJ_i^c, is calculated by taking the difference between NJA_i^c and N_i^c. Next, available number of machines are first loaded by N_i^c jobs that require higher capacities than the other jobs. Once, these jobs are loaded, the remaining capacity on each of the machines is found and loaded by splitting the unassigned jobs while trying to balance the load levels of all machines. Step 2F will yield certain process area, c, and unique machine combinations in which two or more jobs or job fractions will have to be processed. This information needs to be carried over to Step 3 for sequencing of such jobs on each machine

Step 3F (Functional Facility Case): The goal of this step is to find an optimal sequence for processing of two or more jobs assigned to each machine type in Step 2 under the following assumptions :

1. Once sequenced, the jobs will be continuously processed until assigned number of parts receive the necessary operation in each class area.
2. There are set-up time and cost incurred as machine use changes from one job to another. The set-up times are usually different for each sequence of any two job.
3. It is necessary to consider an additional dummy job, 0, to account for the initial set-up needed before the first job is processed.

Mathematical Model for Sequence Selection for Functional Facility: The model shown in Figure 46 on page 281 receives the complete job machine operation assignment decisions for each operation class area or department and seeks the best or a good sequence before each machine or machine group. Then, the goals (objective function) are summarized as : 1) Incur minimum setup cost over all operation class areas or the entire shop and 2) Determine additional machine capacities that must be acquired due to the setup times. Figure 46 on page 281 shows the model which captures the desired details.

Explanation of the Constraints

I1 & I2 : Assure unique sequences.

I3. : Finds total setup time on each machine.

I4.: Tells how much excess machine capacity will be needed due to the setup times.

Discussion of Step 3C (Cellular Facility Case):

Step 2C of cellular manufacturing layout assignment procedure gives more detail than the step 2 of process layout assignment procedure by indicating to which machine each operation of each job should be assigned. Since a job is to receive all of its operations in the same cell, it is likely that several operations of a job will be assigned to the same machine in that cell. This, however, does not necessarily mean savings in set-up and handling costs because, due to operation precedence requirements, it may not be feasible to keep the same job on the same machine for the next assigned operation by postponing another operation assigned to a different machine

$$\min \Big[\sum_{c} \sum_{i \in MA_c} SC_i^c \sum_{a_i} \sum_{m \in JA_{ia}^c} \sum_{\substack{l \in JA_{ia}^{c,0} \\ l \neq m}} SM_{lm}\ SQ_{lmia}^c\ ST_i^c + BM \sum_{i} AC_i^s \Big]$$

Subject to :

$$\sum_{\substack{l \in JA_i^{c,0} \\ l \neq m}} SQ_{lmia}^c = 1 \qquad \text{for all } c,\ i \in MA_c,\ a_i,\ m \in JA_{ia}^c \qquad (I.1)$$

$$\sum_{l \in JA_{ia}^c} SQ_{0lla}^c = 1 \qquad \text{for all } c,\ a_i,\ i \in MA_c \qquad (I.2)$$

$$TST_{ia}^c = \sum_{m \in JA_{ia}^c} \sum_{\substack{l \in JA_{ia}^{c,0} \\ l \neq m}} SM_{lm}\ SQ_{lmia}^c\ ST_{lml}^c \qquad \text{for all } c,\ a_i,\ i \in MA_c \qquad (I.3)$$

$$\sum_{c} TST_{ia}^c \leq T\,(1 + AC_i^s) \qquad \text{for all } a_i,\ i \in MA_c \qquad (I.4)$$

$$SQ_{lmia}^c = 0,1, \quad TST_{ia}^c \text{ and } AC_i^s \geq 0$$

Figure 46. Sequencing Model for Functional Facility (Step 3F)

Appendix J. Lists of the Computer Codes Used in Stage One

This appendix contains listings of four programs : STEP1, 2, 5 and UNIT FORTRAN codes. In order to provide easy future reference with a line number before each executable statement, WATFIV compiled form, instead of the source form, is given below. **STEP1 FORTRAN listing :**

```
      C$JOB
      C          STAGE 1 STEP 1 INPUT GENERATION
      C              FOR BOTH ALTERNATIVES
      C  ****************************************************************
      C  THE PURPOSE OF THIS PROGRAM IS TO CREATE THE VARIABLE PORTION
      C  OR THE MAIN INPUT NEEDED TO RUN MPSIII PACKAGE.  THIS CODE
      C  CREATES THE NECESSARY INPUT FOR ANY DIMENSIONAL SIZE.
      C
1          IMPLICIT REAL(A-H,O-Z)
2          DIMENSION IC(10),IAREA(10),DEMAND(10),DVAR(10)
3          DIMENSION E(10),U(10),VAR(10),IOPPRJ(10),JOBOPE(20,10)
4          REAL TIMES(20,10)
5          CHARACTER*1 MAKH(10),NAME(10)
      C
      C   IC,IAREA,U : DENOTE INITIAL COST, AREA NEED, AND THE RELIABILITY
      C            OF EACH OF NUMMAC MACHINE TYPES AVAILABLE.
      C   DEMAND,DVAR,
      C   E,IOPPRJ   : DAILY DEMAND & ITS VARIANCE, NORMAL VARIATE VALUE FOR
      C            THE CHANCE CONSTRAINT, AND THE NUMBER OF DIFFERENT
      C            OPERATIONS FOR EACH OF NUMJOB JOBS.
```

```
C    MAKH,NAME  : CHARACTER **ARRAYS CONTAINING MACHINE & JOB NAMES.
C    BM         : HIGH PENALTY COST.
C    TOTARE,
C    TOTCAP     : TOTAL AVAILABLE AREA AND CAPITAL AT PLANNING TIME.
C    JOBOPE,    : 0/1 MATRIX SHOWING JOB/OPERATION NEEDS.
C    TIMES      : MATRIX SHOWING FEASIBLE OPERATION TIMES ON MACHINES.
C
      CALL INPUT(NUMMAC,NUMOP,NUMJOB,MAXMAC,TIMES,E,U,VAR,IOPPRJ,
     *  JOBOPE,IC,IAREA,DEMAND,DVAR,MAKH,NAME,TOTARE,TOTCAP,BM)
C
C    CALCULATE THE NUMBER ROWS WITH > = SIGN
C
      NSECT1 = 0
      NSECT2 = 0
            DO 1000 IOP = 1,NUMOP
              DO 1100 IJOB = 1,NUMJOB
C
        IF(JOBOPE(IOP,IJOB).GT.0) NSECT1 = NSECT1 + 1
 1100   CONTINUE
 1000   CONTINUE
        NSECT2 = NSECT1 + NUMMAC
      CALL RSIGN(NSECT1,NSECT2)
      CALL ROWLC(NSECT1,NSECT2,U,IC,IAREA,NUMMAC,MAKH)
      CALL ROWCF(NSECT1,NUMMAC,NUMOP,NUMJOB,TIMES,JOBOPE,IOPPRJ,MAKH,
     *      NSECT2,NAME,BM)
      CALL RGTHSD(NSECT1,NUMMAC,NUMJOB,DEMAND,DVAR,IOPPRJ,E,TOTARE,TOTCA
     *       P)
      CALL BOUNDS(NUMJOB,NUMOP,NUMMAC,MAXMAC,MAKH,NAME,JOBOPE,TIMES)
C
      STOP
      END
C
C *****************************************************************
C THIS UNIT RECEIVES ALL COST, TIME, AND JOB/OPER/MACHINE RELATED DATA
C
      SUBROUTINE INPUT(NUMMAC,NUMOP,NUMJOB,MAXMAC,TIMES,E,U,VAR,IOPPRJ,
     *      JOBOPE,IC,IAREA,DEMAND,DVAR,MAKH,NAME,TOTARE,TOTCAP,BM)
C
      IMPLICIT REAL(A-H,O-Z)
      DIMENSION IC(10),IAREA(10),DEMAND(10),DVAR(10),
     *      E(10),U(10),VAR(10),IOPPRJ(10),JOBOPE(20,10)
      REAL TIMES(20,10)
      CHARACTER*1 MAKH(10),NAME(10)
C
      READ(30,*) NUMMAC,NUMOP,NUMJOB,MAXMAC,TOTARE,TOTCAP,BM
C
         DO 1000 MACH = 1,NUMMAC
          READ(31,*) MAKH(MACH),IC(MACH),IAREA(MACH),U(MACH),VAR(MACH)
 1000   CONTINUE
C
C
      DO 1200 IJOB = 1,NUMJOB
      READ(34,*) NAME(IJOB),DEMAND(IJOB),DVAR(IJOB),E(IJOB),IOPPRJ(IJOB)
 1200   CONTINUE
C
       DO 1300 IOP = 1,NUMOP
```

```
      READ(36,*) (TIMES(IOP,MACH),MACH = 1,NUMMAC)
      READ(37,*) (JOBOPE(IOP,IJOB),IJOB = 1,NUMJOB)
C
 1300   CONTINUE
        RETURN
        END
C
C  ********************************************************************
C  THIS UNIT WRITES OUT THE SIGN AND THE ROW NUMBER OF EACH
C  OF THE CONSTRAINTS OF ** STEP1 **. E.G. G R1, L R11
C
      SUBROUTINE RSIGN(NSECT1,NSECT2)
C
      CHARACTER SIGN*1,QT*1,SP*10
      QT = ''''
      SP ='          '
C
      WRITE(7,1900)
      WRITE(8,1900)
 1900 FORMAT('NAME          TEST1    FREE',/'ROWS    ')
      WRITE(8,2000)
 2000 FORMAT(1X,'N',2X,'Z')
C
      ITOT = NSECT2 + 2
C
      DO 1000 ICONST = 1,ITOT
           SIGN = 'E'
           IF (ICONST.LE.NSECT1) SIGN = 'G'
           IF (ICONST.GT.NSECT2) SIGN = 'L'
             IF (ICONST.GE.10) GOTO 1200
           WRITE(8,1100) SIGN,ICONST
 1100        FORMAT(1X,A1,2X,'R',I1)
           GO TO 1000
 1200        WRITE(8,1300) SIGN,ICONST
 1300        FORMAT(1X,A1,2X,'R',I2)
 1000        CONTINUE
C
      WRITE(7,2140)SP,SP
      WRITE(8,2140)
 2140 FORMAT('COLUMNS    ',2A10)
      WRITE(8,351)
 351  FORMAT('    DEBE      ''MARKER''                 ''INTORG''')
       RETURN
      END
C
C*****************************************************
C THIS UNIT DETERMINES AND WRITES OUT ROW LOCATIONS AND VALUES OF
C EACH M(I) VARIABLES IN THE MIP FORM OF THE TOTAL MPSIII INPUT.
C
      SUBROUTINE ROWLC(NSECT1,NSECT2,U,IC,IAREA,NUMMAC,MAKH)
C
      CHARACTER*1 MAKH(10),MN
      DIMENSION IAREA(10),IC(10),U(10)
C
      ILAST1 = NSECT2 + 1
      ILAST2 = ILAST1 + 1
```

```
      IROW = NSECT1 + 1
          DO 1000 MACH   = 1,NUMMAC
              MN = MAKH(MACH)
              U(MACH) = - U(MACH)
          IF ( IROW.GT.9) GO TO 1150
          WRITE(8,1100) MN,IC(MACH),IROW,U(MACH)
 1100       FORMAT('    M',A1,8X,'Z',10X,I2,'.0',T40,'R',I1,9X,F5.2)
          GO TO 1250
 1150      WRITE(8,1200) MN,IC(MACH),IROW,U(MACH)
 1200      FORMAT('    M',A1,8X,'Z',10X,I2,'.0',T40,'R',I2,8X,F5.2)
 1250      IROW = IROW + 1
C
       WRITE(8,1020) MN,ILAST1,IAREA(MACH),ILAST2,IC(MACH)
 1020 FORMAT('    M',A1,8X,'R',I2,10X,I3,'.0',7X,'R',I2,10X,I2,'.0')
 1000      CONTINUE
C
      WRITE(8,350)
 350 FORMAT('   FINE     ''MARKER''              ''INTEND''')
        RETURN
        END
C *************************************************************************
C THIS UNIT DETERMINES THE COEFFICIENTS AND THE ROW LOCATIONS
C OF ALL M(IKN) VARIABLES
C
       SUBROUTINE ROWCF(NSECT1,NUMMAC,NUMOP,NUMJOB,TIMES,JOBOPE,IOPPRJ,
     *MAKH,NSECT2,NAME,BM)
C
         REAL TIMES(20,10),TIME(20,10,10)
         DIMENSION JOBOPE(20,10),IOPPRJ(10),ILINE2(10)
         CHARACTER*1 MAKH(10),NAME(10),MN,MK
C
          MARKOP = 0
          ILINE1 = 1
          ILAST1 = NSECT2 + 1
          ILAST2 = ILAST1 + 1
C PRINTING THE LOCATIONS OF ADDITIONAL AREA AND $ NEED VARIABLES : AA/AC
             WRITE(8,1000) BM,ILAST1
 1000          FORMAT('    AA',8X,'Z',10X,F6.0,8X,'R',I2,10X,'-1.0')
             WRITE(8,1050) BM,ILAST2
 1050          FORMAT('    EC',8X,'Z',10X,F6.0,8X,'R',I2,10X,'-1.0')
C
             DO 1100 IJOB = 1,NUMJOB
               DO 1200 IOP = 1,NUMOP
                IF( JOBOPE(IOP,IJOB).EQ.0) GOTO 1200
                         DO 1300 MACH = 1,NUMMAC
                ILINE2(MACH) = NSECT1 + MACH
               IF(TIMES(IOP,MACH).EQ.0) GOTO 1300
                TIME(IOP,MACH,IJOB) = 480.0/TIMES(IOP,MACH)
                MARKOP = IOP
                MN = NAME(IJOB)
                MK = MAKH(MACH)
C  REPEATING SAME WRITE/FORMAT STATEMENTS BY CHANGING FIELDS FROM I2 TO
C  I1 AS NEEDED TO AVOID IMPROPER GAPS SUCH AS R 8 OR MPA 2 IN THE FINAL
C  MPSIII SOURCE FILE.
       IF (MARKOP.GT.9) GOTO 1380
           IF(ILINE1.GT.9) GOTO 1350
```

```
      WRITE(8,1310) MK,MN,MARKOP,ILINE1,TIME(IOP,MACH,IJOB),ILINE2(MACH)
 1310 FORMAT('    M',2A1,I1,6X,'R',I1,10X,F6.2,7X,'R',I2,10X,'1.0')
            GOTO 1300
 1350 WRITE(8,1315) MK,MN,MARKOP,ILINE1,TIME(IOP,MACH,IJOB),ILINE2(MACH)
 1315 FORMAT('    M',2A1,I1,6X,'R',I2,9X,F6.2,7X,'R',I2,10X,'1.0')
            GOTO 1300
 1380       IF(ILINE1.GT.9) GOTO 1355
      WRITE(8,1325) MK,MN,MARKOP,ILINE1,TIME(IOP,MACH,IJOB),ILINE2(MACH)
 1325 FORMAT('    M',2A1,I2,5X,'R',I1,10X,F6.2,7X,'R',I2,10X,'1.0')
            GOTO 1300
 1355 WRITE(8,1345) MK,MN,MARKOP,ILINE1,TIME(IOP,MACH,IJOB),ILINE2(MACH)
 1345 FORMAT('    M',2A1,I2,5X,'R',I2,9X,F6.2,7X,'R',I2,10X,'1.0')
 1300       CONTINUE
C
            ILINE1 = ILINE1 + 1
 1200       CONTINUE
 1100       CONTINUE
C
       WRITE(8,3000)
 3000  FORMAT('RHS')
       RETURN
       END
C*********************************************************************
C THIS UNIT LIST ALL CONSTRAINTS IN ORDER AND WRITES THE CORRECT RHS
C VALUE
0      SUBROUTINE RGTHSD(NSECT1,NUMMAC,NUMJOB,DEMAND,DVAR,IOPPRJ,E,
     *TOTARE,TOTCAP)
C
            DIMENSION DEMAND(10),DVAR(10),IOPPRJ(10),E(10)
C
C  CALCULATION OF NEW RHS VALUES DUE TO NORMALLY DISTRIBUTED DEMANDS
C
            ILINE = 0
            ILAST1 = 0
            ILAST2 = 0
         DO 1000 IJOB = 1,NUMJOB
              IVAL = IOPPRJ(IJOB)
        DEMAND(IJOB) = DEMAND(IJOB)+( E(IJOB) * SQRT(DVAR(IJOB)) )
        DO 1100 ICOUNT = 1,IVAL
              ILINE = ILINE + 1
               IF (ILINE.GT.9) GOTO 1150
              WRITE(8,1190) ILINE,DEMAND(IJOB)
 1190          FORMAT(4X,'RH',8X,'R',I1,3X,F14.2)
               GOTO 1100
 1150          WRITE(8,1200) ILINE,DEMAND(IJOB)
 1200          FORMAT(4X,'RH',8X,'R',I2,2X,F15.2)
 1100    CONTINUE
1 1000   CONTINUE
         DO 1400 ICOUNT = 1,NUMMAC
          ILINE = ILINE + 1
           WRITE(8,1500) ILINE
 1500       FORMAT(4X,'RH',8X,'R',I2,18X,'0.')
 1400    CONTINUE
           ILAST1 = NSECT1+NUMMAC+1
           ILAST2 = ILAST1+ 1
           WRITE(8,1600) ILAST1,TOTARE
```

```
            WRITE(8,1650) ILAST2,TOTCAP
1600          FORMAT(4X,'RH',8X,'R',I2,F18.0)
1650          FORMAT(4X,'RH',8X,'R',I2,F18.0)
        WRITE(7,1800)
        WRITE(8,1800)
1800 FORMAT('BOUNDS                                              ',
     *'                ')
       RETURN
       END
C
C**********************************************************************
C THIS UNIT LISTS ALL POSSIBLE/FEASIBLE M(I) AND M(IKN) COMBINATIONS
C AND PLACES SOME HIGH BOUND ON EACH ONE TO CONFORM WITH MPSIII FORMAT
C
       SUBROUTINE BOUNDS(NUMJOB,NUMOP,NUMMAC,MAXMAC,MAKH,NAME,JOBOPE,
     *             TIMES)
C
       CHARACTER*1 MAKH(10),MN,MK,QT,STAR,SLASH,NAME(10)
       DIMENSION MACCLS(10,10),JOBOPE(20,10)
       REAL TIMES(20,10)
C
       QT=''''
       STAR='*'
       SLASH='/'
         DO 1000 MACH = 1,NUMMAC
                MN = MAKH(MACH)
                WRITE(8,1200) MN,MAXMAC
1200              FORMAT(' UP',1X,'BOUD',6X,'M',A1,12X,I2,'.0')
1000      CONTINUE
               DO 1400 IJOB = 1,NUMJOB
                 DO 1500 IOP = 1,NUMOP
                  IF( JOBOPE(IOP,IJOB).EQ.0) GOTO 1500
                        DO 1600 MACH = 1,NUMMAC
                IF(TIMES(IOP,MACH).EQ.0) GOTO 1600
                  MARKOP = IOP
                  MN = NAME(IJOB)
                  MK = MAKH(MACH)
              IF (MARKOP.GT.9) GOTO 1550
                WRITE(8,1690) MK,MN,MARKOP,MAXMAC
1690             FORMAT(' UP',1X,'BOUD',6X,'M',2A1,I1,14X,I2,'.0')
              GOTO 1600
1550             WRITE(8,1710) MK,MN,MARKOP,MAXMAC
1710             FORMAT(' UP',1X,'BOUD',6X,'M',2A1,I2,13X,I2,'.0')
1600          CONTINUE
1500          CONTINUE
1400          CONTINUE
       WRITE(7,3300)
       WRITE(8,3300)
3300 FORMAT('ENDATA                                              ',
     *'                ')
       WRITE(8,6000) SLASH,STAR
6000 FORMAT(2A1)
       WRITE(8,8000) SLASH,SLASH
8000 FORMAT(2A1)
          RETURN
```

```
      END
C$ENTRY
```

STEP2 FORTRAN listing :

```
C$JOB
C            STAGE 1 STEP 2 INPUT GENERATION
C                FOR BOTH ALTERNATIVES
C    ***********************************************************
C  THE PURPOSE OF THIS PROGRAM IS TO CREATE THE VARIABLE PORTION
C  OR THE MAIN INPUT NEEDED TO RUN MPSIII PACKAGE.  THIS CODE
C  CREATES THE NECESSARY INPUT FOR ANY DIMENSIONAL SIZE.
C
C     VALUE OF ISLECT INSTRUCTS THIS CODE TO PRODUCE AN INPUT
C     FOR FUNCTIONAL (1) OR CELLULAR (2) FORMATIONS IN ACCORDANCE
C     FIGURES 9 AND 10. IN EITHER CASE, THE PROGRAMS CALL UPON
C     SUBROUTINES * FNAPPR & CMAPPR * TO LINEARIZE ALL NONLINEAR TERMS
C     USING ** NASLUND'S ** APPROXIMATION.  THE RESULTING INPUT
C     FILES INCLUDE ALL ALGEBRAIC MANIPULATIONS.
C SUBROUTINES STARTING WITH LETTERS FN PERFORM FUNCTIONAL FORMATION
C CALCULATIONS ( CM FOR CELLULAR FORMATION )
C    SUBROUTINES RSIGN & RHS ARE USED BY BOTH FORMATIONS
      IMPLICIT REAL(A-H,O-Z)
      DIMENSION DEMAND(12),DVAR(12),JOBCLS(10,12),IFUNCT(9,9,12,20)
      DIMENSION IOPPRJ(12),JOBOPE(20,12),MACCLS(10,10),IOPCLS(20,10)
      DIMENSION ICLFEA(9,9,12,20),ZCOST(9,9,12,20),VCCOST(20,10)
      DIMENSION TIMES(20,10),ZVAR(9,9,12,20),RWTIME(9,9,12,20)
      DIMENSION RWVAR(9,9,12,20),RVARSM(10,10),ISTEP1(12),RIGHHS(10,10)
      DIMENSION ICLCLS(5,7),MACOKY(10,10),JOBCLL(5,20)
      CHARACTER*1 MAKH(12),NAME(12)
C
C           :
C
C   ISTEP1    : ARRAY OF NUMBER OF MACHINES OF EACH TYPE FROM STEP 1
C   NUMMAC,NUMOP
C   RIGHHS,K1,K2 : NUMBER OF MACHINES, OPERATIONS, RHS VECTOR, AND
C              COEFFICIENTS OF LINEARIZATION OF OBJECTIVE FUNCTION
C   ZCOST, ZVAR   :  THE MEAN AND VARIANCE OF Z TERMS
C   RWTIME, RWVAR :  THE SAME FOR ROW TERMS
C   NSECT2, NSECT3:NUMBER OF CONSTRAINTS OF EACH TYPE IN FUNCTIONAL CAS
C   ISECT1,(2),(3) THE SAME IN CELLULAR CASE
C   DEMAND,DVAR,
C   EVAR,       DAILY DEMAND & ITS VARIANCE, NORMAL VARIATE VALUE FOR
C   IOPPRJ       THE CHANCE CONSTRAINT, AND THE NUMBER OF DIFFERENT
C              OPERATIONS FOR EACH OF NUMJOB JOBS.
C   MAKH,NAME  : CHARACTER ARRAYS CONTAINING MACHINE & JOB NAMES.
C   MACCLS,
C   JOBCLS     : 0/1 MATRICES SHOWING FEASIBILITIES BETWEEN VARIOUS
C              MACHINE/OPERATION CLASS AND JOB/OPERATION CLASS NEEDS.
C   IOPCLS     : 0/1 MATRICE SHOWING THE NUMBERS OF EACH OPERATION
C              WHICH BELONG TO A GIVEN GENERAL OPERATION CLASS.
C   JOBOPE,    : 0/1 MATRIX SHOWING JOB/OPERATION NEEDS.
C   TIMES      : MATRIX SHOWING FEASIBLE OPERATION TIMES ON MACHINES.
C   JOBCLL     : 0/1 MATRIX SHOWING JOB CELL ASSIGNMENTS
C   ICLCLS     : 0/1 MATRIX SHOWING IF A GIVEN OPE. CLASS IS NEEDED IN
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```
C              : CELL J
C   ICLFEA,IFUNCT : 0/1 FEASIBILITY INDICATORS FOR JOB/CELL FORMATIONS
C   MACOKY      : 0/1 MATRIX SHOWING POSSIBLE MACHINE/CELL COMBINATIONS
C
       CALL INPUT(NUMMAC,NUMOP,NUMJOB,MAXMAC,TIMES,EVAR,IOPPRJ,VCCOST,
     *JOBOPE,IOPCLS,DEMAND,DVAR,MAKH,NAME,MACCLS,JOBCLS,BM,NUMCLS,
     *NUMCLL,K1,K2,ISTEP1,NSECT2,NSECT3,IFUNCT,ISLECT,JOBCLL,ISECT1,
     *ISECT2,ICLFEA,ICLCLS,MACOKY,ZCOST,ZVAR,RWTIME,RWVAR,RVARSM,RIGHHS)
C   BRANCHING ACCORDING TO THE VALUE OF ISLECT
        IF (ISLECT.GT.1) GOTO 1000
      CALL FNFEAS(NUMMAC,NUMOP,NUMJOB,NUMCLS,TIMES,JOBOPE,IOPCLS,MAKH,
     *       NAME,DEMAND,DVAR,MACCLS,JOBCLS,IFUNCT,ZCOST,VCCOST,ZVAR,
     *       RWTIME,RWVAR)
      CALL RSIGN(NSECT2,NSECT3,NUMMAC)
      CALL FNAPPR(K1,K2,ZCOST,ZVAR,RWTIME,RWVAR,EVAR,IFUNCT,RVARSM,
     *        MACCLS,RIGHHS,NUMCLS,NUMMAC,NUMCEL,NUMJOB,NUMOP)
      CALL FNASSG(IFUNCT,NSECT2,NSECT3,NUMCLS,NUMJOB,NUMOPE,NUMMAC,BM,
     *        NUMOP,MACCLS,JOBCLS,ISTEP1,MAKH,NAME,ZCOST,RWTIME)
      CALL RHS(NSECT2,NSECT3,NUMCLS,NUMMAC,MACCLS,ISTEP1,RIGHHS)
      CALL FNBOUD(MAXMAC,NUMMAC,NUMCLS,MAKH,MACCLS)
      GOTO 1500
C             CALLS FOR CELLULAR FORMATION :
 1000 CONTINUE
      CALL RSIGN(ISECT1,ISECT2,NUMMAC)
      CALL CMFEAS(NUMMAC,NUMOP,NUMJOB,NUMCLS,TIMES,JOBOPE,IOPCLS,MAKH,
     *       NAME,DEMAND,DVAR,MACCLS,JOBCLS,ICLFEA,ZCOST,VCCOST,ZVAR,
     *       RWTIME,RWVAR,JOBCLL,ICLCLS,NUMCLL)
      CALL CMAPPR(K1,K2,ZCOST,ZVAR,RWTIME,RWVAR,EVAR,ICLFEA,
     *   RVARSM,MACOKY,RIGHHS,NUMCLS,NUMMAC,NUMCLL,NUMJOB,NUMOP)
      CALL CMASSG(ICLFEA,ISECT1,ISECT2,NUMCLS,NUMJOB,NUMOPE,NUMMAC
     *        ,BM,NUMOP,MACCLS,JOBOPE,ISTEP1,MAKH,NAME,ZCOST,RWTIME,
     *        JOBCLL,ICLCLS,MACOKY,NUMCLL)
      CALL RHS(ISECT1,ISECT2,NUMCLL,NUMMAC,MACOKY,ISTEP1,RIGHHS)
      CALL CMBOUD(MAXMAC,NUMMAC,NUMCLS,MAKH,MACOKY,NUMCLL)
 1500 STOP
      END
C ****************************************************************
C ****************************************************************
C THIS UNIT RECEIVES ALL COST, TIME, AND JOB/OPER/MACHINE RELATED DATA
C
      SUBROUTINE INPUT(NUMMAC,NUMOP,NUMJOB,MAXMAC,TIMES,EVAR,IOPPRJ,VCCO
     *ST,JOBOPE,IOPCLS,DEMAND,DVAR,MAKH,NAME,MACCLS,JOBCLS,BM,NUMCLS,
     *NUMCLL,K1,K2,ISTEP1,NSECT2,NSECT3,IFUNCT,ISLECT,JOBCLL,ISECT1,
     *ISECT2,ICLFEA,ICLCLS,MACOKY,ZCOST,ZVAR,RWTIME,RWVAR,RVARSM,RIGHHS)
C
      IMPLICIT REAL(A-H,O-Z)
      DIMENSION DEMAND(12),DVAR(12),JOBCLS(10,12),IFUNCT(9,9,12,20)
      DIMENSION IOPPRJ(12),JOBOPE(20,12),MACCLS(10,10),RIGHHS(10,10)
      DIMENSION ICLFEA(9,9,12,20),ZCOST(9,9,12,20),VCCOST(20,10)
      DIMENSION TIMES(20,10),ZVAR(9,9,12,20),RWTIME(9,9,12,20)
      DIMENSION RWVAR(9,9,12,20),RVARSM(10,10),ISTEP1(12),IOPCLS(20,10)
      DIMENSION JOBCLL(5,20),ICLCLS(5,7),MACOKY(10,10)
      CHARACTER*1 MAKH(12),NAME(12)
      READ(40,*) NUMMAC,NUMOP,NUMJOB,MAXMAC,NUMCLS,NUMCLL,ISLECT,
     *       K1,K2,BM,EVAR,NSECT2,NSECT3,ISECT1
        DO 1000 MACH = 1,NUMMAC
```

```
          READ(41,*) MAKH(MACH),ISTEP1(MACH)
 1000   CONTINUE
          DO 1100 ICLASS = 1,NUMCLS
           DO 1100 MACH = 1,NUMMAC
             DO 1100 IJOB = 1,NUMJOB
               DO 1100 IOP = 1,NUMOP
                RVARSM(ICLASS,MACH) =        0
                RIGHHS(ICLASS,MACH) =        0
                ZCOST(ICLASS,MACH,IJOB,IOP) =  0
                ZVAR(ICLASS,MACH,IJOB,IOP) =  0
                RWTIME(ICLASS,MACH,IJOB,IOP) = 0
                RWVAR(ICLASS,MACH,IJOB,IOP) =  0
                IFUNCT(ICLASS,MACH,IJOB,IOP) = 0
                ICLFEA(ICLASS,MACH,IJOB,IOP) = 0
 1100      CONTINUE
           DO 1150 ICELL = 1,NUMCLL
           DO 1155 MACH = 1,NUMMAC
 1155         MACOKY(ICELL,MACH) = 0
            DO 1150 ICLASS = 1,NUMCLS
 1150        ICLCLS(ICELL,ICLASS) = 0
      DO 1200 IJOB = 1,NUMJOB
      READ(44,*) NAME(IJOB),DEMAND(IJOB),DVAR(IJOB),IOPPRJ(IJOB)
 1200   CONTINUE
       DO 1300 IOP = 1,NUMOP
       READ(46,*) (TIMES(IOP,MACH),MACH = 1,NUMMAC)
       READ(47,*) (VCCOST(IOP,MACH),MACH = 1,NUMMAC)
       READ(48,*) (JOBOPE(IOP,IJOB),IJOB = 1,NUMJOB)
       READ(49,*) (IOPCLS(IOP,ICLASS),ICLASS = 1,NUMCLS)
 1300    CONTINUE
         DO 1400 ICLASS = 1,NUMCLS
         READ(50,*) (MACCLS(ICLASS,MACH),MACH = 1,NUMMAC)
         READ(51,*) (JOBCLS(ICLASS,IJOB),IJOB = 1,NUMJOB)
 1400    CONTINUE
         DO 1500 ICLASS = 1,NUMCLS
           DO 1600 IJOB = 1,NUMJOB
C  COUNTING THE NUMBER OF ROWS OF CONSTRAINT TYPE 3.2.2 IN STEP 2F
          IF (JOBCLS(ICLASS,IJOB).EQ.1 ) NSECT3 = NSECT3 + 1
 1600    CONTINUE
C COUNTING THE NUM. OF ASSIGNMENT CONSTRAINTS IN CELLULAR FORMATION
         ISECT2 = NSECT3
           DO 1700 MACH = 1,NUMMAC
C COUNTING THE NUMBER OF ROWS OF CONSTRAINT TYPE 3.2.1 IN STEP 2F
          IF (MACCLS(ICLASS,MACH).EQ.1 ) NSECT2 = NSECT2 + 1
 1700    CONTINUE
 1500    CONTINUE
         DO 1800 ICELL = 1,NUMCLL
 1800     READ(52,*) (JOBCLL(ICELL,IJOB),IJOB = 1,NUMJOB)
C          DETERMINATION OF OPERATION CLASSES NEEDED IN EACH CELL
               DO 5000 ICELL = 1,NUMCLL
                 DO 5100 IJOB = 1,NUMJOB
          IF ( JOBCLL(ICELL,IJOB).NE.1) GOTO 5100
                DO 5200 ICLASS = 1,NUMCLS
           IF (JOBCLS(ICLASS,IJOB).NE.1)  GOTO 5200
              ICLCLS(ICELL,ICLASS) = 1
 5200     CONTINUE
 5100     CONTINUE
```

```
 5000    CONTINUE
           DO 6000 ICELL = 1,NUMCLL
            DO 6100 ICLASS = 1,NUMCLS
             IF(ICLCLS(ICELL,ICLASS).NE.1) GOTO 6100
               DO 6200 MACH = 1,NUMMAC
         IF (MACCLS(ICLASS,MACH).EQ.1) MACOKY(ICELL,MACH) = 1
 6200   CONTINUE
 6100   CONTINUE
 6000   CONTINUE
              DO 7000 ICELL = 1,NUMCLL
                 DO 7100 MACH = 1,NUMMAC
C  COUNTING THE NUM. OF CAPACITY CONSTRAINTS IN CELLULAR FORMATION
                   ISECT1 = ISECT1 + MACOKY(ICELL,MACH)
 7100    CONTINUE
 7000    CONTINUE
         RETURN
         END
1 C
  C  *****************************************************************
  C  THIS UNIT WRITES OUT THE SIGN AND THE ROW NUMBER OF EACH
  C  OF THE CONSTRAINTS IN ** BOTH MODELS **. E.G. G R1, L R11
  C
0         SUBROUTINE RSIGN(NSECT2,NSECT3,NUMMAC)
  C
        CHARACTER SIGN*1,QT*1,SP*10
        QT = ''''
        SP ='          '
        WRITE(7,1900)
        WRITE(8,1900)
 1900 FORMAT('NAME         TEST1     FREE',/'ROWS     ')
        WRITE(8,2000)
 2000 FORMAT(1X,'N',2X,'Z')
        ITOT = NSECT2 + NSECT3 + NUMMAC
        DO 1000 ICONST = 1,ITOT
             SIGN = 'E'
             IF (ICONST.LE.NSECT2) SIGN = 'L'
             IF (ICONST.GT.(NSECT2 + NSECT3) ) SIGN = 'L'
               IF (ICONST.GE.10) GOTO 1200
             WRITE(8,1100) SIGN,ICONST
 1100          FORMAT(1X,A1,2X,'R',I1)
             GO TO 1000
 1200          WRITE(8,1300) SIGN,ICONST
 1300          FORMAT(1X,A1,2X,'R',I2)
 1000          CONTINUE
  C
        WRITE(7,2140)SP,SP
        WRITE(8,2140)
 2140 FORMAT('COLUMNS    ',2A10)
        WRITE(8,351)
 351  FORMAT('    DEBE      ''MARKER''                ''INTORG''')
         RETURN
         END
  C
  C*****************************************************************
  C THIS UNIT CALCULATES ALL FEASIBLE Z AND CONSTRAINT COEFFICIENTS
```

```
      C AND THEIR VARIANCES.
            SUBROUTINE FNFEAS(NUMMAC,NUMOP,NUMJOB,NUMCLS,TIMES,JOBOPE,
           *          IOPCLS,MAKH,NAME,DEMAND,DVAR,MACCLS,JOBCLS,IFUNCT
           *          ,ZCOST,VCCOST,ZVAR,RWTIME,RWVAR)
      C
            IMPLICIT REAL(A-H,O-Z)
            DIMENSION DEMAND(12),DVAR(12),JOBCLS(10,12),IFUNCT(9,9,12,20)
            DIMENSION JOBOPE(20,12),MACCLS(10,10),IOPCLS(20,10)
            DIMENSION ZCOST(9,9,12,20),VCCOST(20,10),RWVAR(9,9,12,20)
            DIMENSION TIMES(20,10),ZVAR(9,9,12,20),RWTIME(9,9,12,20)
            CHARACTER*1 MAKH(12),NAME(12)
      C  THIS UNIT DETERMINES ALL FEASIBLE CLASS,MACHINE,JOB, AND OPERATION
      C  COMBINATIONS FOR FUNCTIONAL FORMATION AND THEN CALCULATES THE MEAN
      C  AND THE STD DEVIATION OF EACH STOCHASTIC COEFFICIENT FOR BOTH
      C  OBJECTIVE FUNCTION AND CONSTRAINT TERMS.
      C
                 DO 5000 ICLASS = 1,NUMCLS
                  DO 5100 MACH = 1,NUMMAC
                     DO 5200 IJOB = 1,NUMJOB
                        DO 5300 IOP = 1,NUMOP
               IF (MACCLS(ICLASS,MACH).NE.1) GOTO 5100
                 IF (JOBCLS(ICLASS,IJOB).NE.1) GOTO 5200
                   IF (JOBOPE(IOP,IJOB).NE.1)  GOTO 5300
                   IF (IOPCLS(IOP,ICLASS).NE.1) GOTO 5300
                  IFUNCT(ICLASS,MACH,IJOB,IOP) = 1
                 ZCOST(ICLASS,MACH,IJOB,IOP) = VCCOST(IOP,MACH)*DEMAND(IJOB)
                 ZVAR(ICLASS,MACH,IJOB,IOP) = DVAR(IJOB)*
           *       VCCOST(IOP,MACH)*VCCOST(IOP,MACH)
                RWTIME(ICLASS,MACH,IJOB,IOP) = TIMES(IOP,MACH)*DEMAND(IJOB)
                RWVAR(ICLASS,MACH,IJOB,IOP) = DVAR(IJOB)*
           *       TIMES(IOP,MACH)*TIMES(IOP,MACH)
              IF(ZCOST(ICLASS,MACH,IJOB,IOP).EQ.0) GOTO 5300
       5300   CONTINUE
       5200   CONTINUE
       5100   CONTINUE
       5000   CONTINUE
             RETURN
             END
      C
      C  ******************************************************************
      C THIS UNIT DETERMINES AND WRITES OUT THE LOCATIONS ( BOTH ROW & Z )
      C OF ALL 0/1 ASSIGNMENT VARIABLES SUCH AS ** XC1PA ** IN STEP 2F
      C
            SUBROUTINE FNASSG(IFUNCT,NSECT2,NSECT3,NUMCLS,NUMJOB,NUMOPE,NUMMAC
           *          ,BM,NUMOP,MACCLS,JOBCLS,ISTEP1,MAKH,NAME,ZCOST,RWTIME)
      C
            IMPLICIT REAL(A-H,O-Z)
            DIMENSION DEMAND(12),DVAR(12),JOBCLS(10,12),IFUNCT(9,9,12,20)
            DIMENSION IOPPRJ(12),JOBOPE(20,12),MACCLS(10,10),ILINE2(12)
            DIMENSION ICELL(9,9,12,20),ZCOST(9,9,12,20),VCCOST(20,10)
            DIMENSION TIMES(20,10),RWTIME(9,9,12,20),ZERONE(10,10,10)
            DIMENSION JBCLS(12),ISTEP1(12)
            CHARACTER*1 MAKH(12),NAME(12)
             ILINE = NSECT2 + NSECT3
                   DO 4000 MACH = 1,NUMMAC
                   ILINE2(MACH) = ILINE + MACH
```

```
4000        CONTINUE
          ILINE1 = 0
        DO 5000 ICLASS = 1,NUMCLS
         DO 5100 MACH = 1,NUMMAC
          IF(MACCLS(ICLASS,MACH).NE.1) GOTO 5100
          ILINE1 = ILINE1 + 1
          IF (ILINE1.GT.9) GOTO 5150
          WRITE(8,5170) MAKH(MACH),ICLASS,ILINE1,ILINE2(MACH)
5170 FORMAT(4X,'M',A1,'C',I1,T15,'R',I1,T28,'-480.',T40,'R',I2,T55,'1.'
  *)
       GOTO 5100
5150        WRITE(8,5200) MAKH(MACH),ICLASS,ILINE1,ILINE2(MACH)
5200 FORMAT(4X,'M',A1,'C',I1,T15,'R',I2,T28,'-480.',T40,'R',I2,T55,'1.'
  *)
5100   CONTINUE
5000   CONTINUE
      INC = 0
C COUNTING THE NUMBER OF 1'S IN JOBCLS TO FIND JBCLS VALUES FOR EACH
C CLASS AFTER SHIFTING ITS LOCATION DOWN BY 1.
      JBCLS(1) = 0
      NUMLSS = NUMCLS - 1
       DO 5300 ICLASS = 1,NUMLSS
       DO 5350 IJOB = 1,NUMJOB
5350     IF ( JOBCLS(ICLASS,IJOB).EQ.1) INC = INC + 1
        II = ICLASS + 1
        JBCLS(II) = INC
5300        CONTINUE
      IMARK = 1
      IROW2 = NSECT2
      DO 6000 ICLASS = 1,NUMCLS
        DO 6100 MACH = 1,NUMMAC
     IF (MACCLS(ICLASS,MACH).EQ.1) IROW2 = NSECT2 + JBCLS(ICLASS)
         DO 6200 IJOB = 1,NUMJOB
           DO 6300 IOP = 1,NUMOP
           IF (IFUNCT(ICLASS,MACH,IJOB,IOP).NE.1) GOTO 6300
           IROW2 = IROW2 + 1
           IF (IMARK.GT.9) GOTO 6350
     WRITE(8,6450) ICLASS,MAKH(MACH),NAME(IJOB),ZCOST(ICLASS,MACH,IJOB
  *,IOP),IMARK,RWTIME(ICLASS,MACH,IJOB,IOP)
6450  FORMAT(4X,'XC',I1,A1,A1,T15,'Z',T28,F8.2,T40,'R',I1,T51,F8.2)
      GOTO 6550
6350 WRITE(8,6500) ICLASS,MAKH(MACH),NAME(IJOB),ZCOST(ICLASS,MACH,IJOB
  *,IOP),IMARK,RWTIME(ICLASS,MACH,IJOB,IOP)
6500  FORMAT(4X,'XC',I1,A1,A1,T15,'Z',T28,F8.2,T40,'R',I2,T51,F8.2)
6550  WRITE(8,6600) ICLASS,MAKH(MACH),NAME(IJOB),IROW2
6600  FORMAT(4X,'XC',I1,2A1,T15,'R',I2,T28,'1.')
6300   CONTINUE
6200   CONTINUE
      IF (MACCLS(ICLASS,MACH).EQ.1 ) IMARK = IMARK + 1
6100   CONTINUE
6000   CONTINUE
     WRITE(8,4500)
4500 FORMAT('   FINE     ''MARKER''              ''INTEND''')
      ICONST = NSECT2 + NSECT3
        DO 9000 MACH = 1,NUMMAC
             ICONST = ICONST + 1
```

```
      WRITE(8,9100) MAKH(MACH),BM,ICONST,ISTEP1(MACH)
 9100  FORMAT(4X,'AC',A1,T15,'Z',T28,F6.0,T40,'R',I2,T55,'-',I1,'.0')
 9000  CONTINUE
      WRITE(8,9200)
 9200  FORMAT('RHS')
       RETURN
       END
C ****************************************************************
C THIS UNIT APPLIES NASLUND'S APPR. FORMULA TO STEP 2F TERMS.
      SUBROUTINE FNAPPR(K1,K2,ZCOST,ZVAR,RWTIME,RWVAR,EVAR,IFUNCT,
     *      RVARSM,MACCLS,RIGHHS,NUMCLS,NUMMAC,NUMCEL,NUMJOB,NUMOP)
C  THIS UNIT PERFORMS NECESSARY LINEARIZATION CALCULATIONS FOR
C  STEP 2F AND USES NASLUND'S APPR. FORMULA FOR STOCHASTIC * Z *
C  AND A(I,J) COEFF. ELEMENTS. NO STOCHASTIC RHS ELEMENTS EXIST HERE.
      IMPLICIT REAL(A-H,O-Z)
      DIMENSION DEMAND(12),DVAR(12),IFUNCT(9,9,12,20),SUMCNT(10,10)
      DIMENSION ICELL(9,9,12,20),ZCOST(9,9,12,20),VCCOST(20,10)
      DIMENSION TIMES(20,10),ZVAR(9,9,12,20),RWTIME(9,9,12,20)
      DIMENSION RWVAR(9,9,12,20),RVARSM(10,10),RIGHHS(10,10)
      DIMENSION MACCLS(10,10)
C FIRST, Z TERMS ARE TRANSFORMED INTO LINEAR FORM AS SHOWN IN APPENDIX
            ZVARSM = 0
        DO 5000 ICLASS = 1,NUMCLS
         DO 5100 MACH = 1,NUMMAC
           DO 5200 IJOB = 1,NUMJOB
            DO 5300 IOP = 1,NUMOP
             SUMCNT(ICLASS,MACH) = 0
       IF (IFUNCT(ICLASS,MACH,IJOB,IOP).EQ.0 ) GOTO 5300
       ZVARSM = ZVARSM + ZVAR(ICLASS,MACH,IJOB,IOP)
 5300   CONTINUE
 5200   CONTINUE
 5100   CONTINUE
 5000   CONTINUE
             ZVART = SQRT(ZVARSM)
        DO 6000 ICLASS = 1,NUMCLS
         DO 6100 MACH = 1,NUMMAC
           DO 6200 IJOB = 1,NUMJOB
            DO 6300 IOP = 1,NUMOP
      IF(IFUNCT(ICLASS,MACH,IJOB,IOP).EQ.0) GOTO 6300
      ZCOST(ICLASS,MACH,IJOB,IOP) = ZCOST(ICLASS,MACH,IJOB,IOP) +
     * ZVART - (SQRT( ZVARSM - ZVAR(ICLASS,MACH,IJOB,IOP)))
 6300   CONTINUE
 6200   CONTINUE
 6100   CONTINUE
 6000   CONTINUE
C  LINEARIZING 3.2.1 TYPE ROW CONSTRAINTS OF STEP 2F
        DO 7000 ICLASS = 1,NUMCLS
         DO 7100 MACH = 1,NUMMAC
           DO 7200 IJOB = 1,NUMJOB
            DO 7300 IOP = 1,NUMOP
         IF ( IFUNCT(ICLASS,MACH,IJOB,IOP).EQ.0 ) GOTO 7300
       RVARSM(ICLASS,MACH) = RVARSM(ICLASS,MACH) + RWVAR(ICLASS,
     *MACH,IJOB,IOP)
 7300   CONTINUE
 7200   CONTINUE
 7100   CONTINUE
```

```
 7000     CONTINUE
           DO 8000 ICLASS = 1,NUMCLS
            DO 8100 MACH = 1,NUMMAC
              DO 8200 IJOB = 1,NUMJOB
                DO 8300 IOP = 1,NUMOP
        IF (IFUNCT(ICLASS,MACH,IJOB,IOP).EQ.0) GOTO 8300
        DIFF = SQRT(RVARSM(ICLASS,MACH)) - SQRT(RVARSM(ICLASS,MACH) -
      * RWVAR(ICLASS,MACH,IJOB,IOP))
        DIFF1 = SQRT( RVARSM(ICLASS,MACH) - RWVAR(ICLASS,MACH,IJOB,IOP))
        SUMCNT(ICLASS,MACH) = SUMCNT(ICLASS,MACH) + DIFF
        RWTIME(ICLASS,MACH,IJOB,IOP) = RWTIME(ICLASS,MACH,IJOB,IOP) +
      &(EVAR *(( SQRT(RVARSM(ICLASS,MACH)))- DIFF1))
 8300     CONTINUE
 8200     CONTINUE
 8100     CONTINUE
 8000     CONTINUE
           DO 9000 ICLASS = 1,NUMCLS
             DO 9100 MACH = 1,NUMMAC
             IF(MACCLS(ICLASS,MACH).EQ.0 ) GOTO 9100
        RIGHHS(ICLASS,MACH) = -EVAR * ( SQRT(RVARSM(ICLASS,MACH)) -
      *SUMCNT(ICLASS,MACH) )
       IF(SQRT(RVARSM(ICLASS,MACH)).EQ.SUMCNT(ICLASS,MACH)) RIGHHS(ICLASS
      *,MACH) = 0
 9100 CONTINUE
 9000 CONTINUE
        RETURN
        END
C
1 C*******************************************************************
C
0       SUBROUTINE RHS(NSECT2,NSECT3,NUMCLS,NUMMAC,MACCLS,ISTEP1,RIGHHS)
C  IN CELLULAR CASE, MATRIX MACOKY AND CONSTANT NUMCLL ARE MAPPED
C  ONTO MATRIX MACCLS AND CONSTANT NUMCLS IS USED IN FUNCTIONAL CASE
       DIMENSION ISTEP1(12),RIGHHS(10,10),MACCLS(10,10)
       ILINE = 0
       ISUM = NSECT2 + NSECT3
       DO 1000 ICLASS = 1,NUMCLS
         DO 1020 MACH = 1,NUMMAC
          IF(MACCLS(ICLASS,MACH).EQ.0) GOTO 1020
          ILINE = ILINE + 1
          IF (ILINE.GT.9) GOTO 1040
          WRITE(8,1030) ILINE,RIGHHS(ICLASS,MACH)
 1030    FORMAT(4X,'RH',T15,'R',I1,T27,F8.2)
          GOTO 1020
 1040    WRITE(8,1050) ILINE,RIGHHS(ICLASS,MACH)
 1050    FORMAT(4X,'RH',T15,'R',I2,T27,F8.2)
 1020 CONTINUE
 1000 CONTINUE
             IBEGIN = NSECT2 + 1
             DO 1200 ICOUNT = IBEGIN,ISUM
               IF ( ICOUNT.GT.9) GOTO 1140
             WRITE(8,1160) ICOUNT
 1160          FORMAT(4X,'RH',T15,'R',I1,T35,'1.')
                   GOTO 1200
 1140          WRITE(8,1250) ICOUNT
 1250          FORMAT(4X,'RH',T15,'R',I2,T35,'1.')
```

```
1200       CONTINUE
      ISUBTO = NSECT2 + NSECT3
         DO 1300 MACH = 1,NUMMAC
           ICONST = ISUBTO + MACH
           WRITE(8,1400) ICONST, ISTEP1(MACH)
1400         FORMAT(4X,'RH',T15,'R',I2,T33,I2,'.0')
1300         CONTINUE
      WRITE(7,1800)
      WRITE(8,1800)
1800 FORMAT('BOUNDS                                          ',
    *'                ')
     RETURN
     END
C
C*********************************************************************
C THIS UNIT LISTS ALL POSSIBLE/FEASIBLE M(I) AND M(IKN) COMBINATIONS
C AND PLACES SOME HIGH BOUND ON EACH ONE TO CONFORM WITH MPSIII FORMAT
C
      SUBROUTINE FNBOUD(MAXMAC,NUMMAC,NUMCLS,MAKH,MACCLS)
C
     CHARACTER*1 MAKH(12),QT,STAR,SLASH
     DIMENSION MACCLS(10,10)
     QT=''''
     STAR='*'
     SLASH='/'
     DO 1000 MACH = 1,NUMMAC
      DO 1100 ICLASS = 1,NUMCLS
        IF( MACCLS(ICLASS,MACH).NE.1) GOTO 1100
        WRITE(8,1200) MAKH(MACH),ICLASS,MAXMAC
1200    FORMAT(' UP',1X,'BOUD',T15,'M',A1,'C',I1,T32,I2,'.0')
1100    CONTINUE
1000    CONTINUE
        DO 1300 MACH = 1,NUMMAC
              WRITE(8,1400) MAKH(MACH),MAXMAC
1400            FORMAT(' UP',1X,'BOUD',T15,'AC',A1,T32,I2,'.0')
1300    CONTINUE
     WRITE(7,3300)
     WRITE(8,3300)
3300 FORMAT('ENDATA                                          ',
    *'                ')
     WRITE(8,6000) SLASH,STAR
6000 FORMAT(2A1)
     WRITE(8,8000) SLASH,SLASH
8000 FORMAT(2A1)
        RETURN
        END
C*******************************************************
C*******************************************************
C    CELLULAR ENVIRONMENT OPTION SUBROUTINES
C*********************************************************
C *********************************************************
C  THIS UNIT WRITES OUT THE SIGN AND THE ROW NUMBER OF EACH
C  OF THE CONSTRAINTS OF ** STEP 2C **. E.G. G R1, L R11
C
C
C*********************************************************
```

```
C THIS UNIT CALCULATES ALL FEASIBLE Z AND CONSTRAINT COEFFICIENTS
C AND THEIR VARIANCES FOR CELLULAR FORMATION
      SUBROUTINE CMFEAS(NUMMAC,NUMOP,NUMJOB,NUMCLS,TIMES,JOBOPE,
     *        IOPCLS,MAKH,NAME,DEMAND,DVAR,MACCLS,JOBCLS,ICLFEA,
     *        ZCOST,VCCOST,ZVAR,RWTIME,RWVAR,JOBCLL,ICLCLS,NUMCLL)
      IMPLICIT REAL(A-H,O-Z)
      DIMENSION DEMAND(12),DVAR(12),JOBCLS(10,12),ICLFEA(9,9,12,20)
      DIMENSION JOBOPE(20,12),MACCLS(10,10),IOPCLS(20,10),JOBCLL(5,20)
      DIMENSION ZCOST(9,9,12,20),VCCOST(20,10),RWVAR(9,9,12,20)
      DIMENSION TIMES(20,10),ZVAR(9,9,12,20),RWTIME(9,9,12,20)
      DIMENSION ICLCLS(5,7)
      CHARACTER*1 MAKH(12),NAME(12)
C  THIS UNIT DETERMINES ALL FEASIBLE CLASS,MACHINE,JOB, AND OPERATION
C  COMBINATIONS FOR CELLULAR FORMATION AND THEN CALCULATES THE MEAN
C  AND THE STD DEVIATION OF EACH STOCHASTIC COEFFICIENT FOR BOTH
C  OBJECTIVE FUNCTION AND CONSTRAINT TERMS.
        DO 4900 ICELL = 1,NUMCLL
          DO 5000 ICLASS = 1,NUMCLS
           DO 5100 MACH = 1,NUMMAC
             DO 5200 IJOB = 1,NUMJOB
               DO 5300 IOP = 1,NUMOP
        IF (ICLCLS(ICELL,ICLASS).NE.1) GOTO 5000
        IF (MACCLS(ICLASS,MACH).NE.1) GOTO 5100
          IF (JOBCLS(ICLASS,IJOB).NE.1) GOTO 5200
            IF (JOBCLL(ICELL,IJOB).NE.1) GOTO 5200
            IF (JOBOPE(IOP,IJOB).NE.1)  GOTO 5300
            IF (IOPCLS(IOP,ICLASS).NE.1) GOTO 5300
           ICLFEA(ICELL,MACH,IJOB,IOP) = 1
          ZCOST(ICELL,MACH,IJOB,IOP) = VCCOST(IOP,MACH)*DEMAND(IJOB)
          ZVAR(ICELL,MACH,IJOB,IOP) = DVAR(IJOB)*
     *     VCCOST(IOP,MACH)*VCCOST(IOP,MACH)
         RWTIME(ICELL,MACH,IJOB,IOP) = TIMES(IOP,MACH)*DEMAND(IJOB)
         RWVAR(ICELL,MACH,IJOB,IOP) = DVAR(IJOB)*
     *     TIMES(IOP,MACH)*TIMES(IOP,MACH)
 5300  CONTINUE
 5200  CONTINUE
 5100  CONTINUE
 5000  CONTINUE
 4900  CONTINUE
         DO 9000 ICELL = 1,NUMCLS
          DO 9100 MACH = 1,NUMMAC
            DO 9200 IJOB = 1,NUMJOB
              DO 9300 IOP = 1,NUMOP
       IF(ZCOST(ICELL,MACH,IJOB,IOP).EQ.0) GOTO 9300
 9300  CONTINUE
 9200  CONTINUE
 9100  CONTINUE
 9000  CONTINUE
       RETURN
       END
C  ******************************************************************
C ***************************************************************
C THIS UNIT APPLIES NASLUND'S APPR. FORMULA TO STEP 2C TERMS.
      SUBROUTINE CMAPPR(K1,K2,ZCOST,ZVAR,RWTIME,RWVAR,EVAR,ICLFEA,
     *        RVARSM,MACOKY,RIGHHS,NUMCLS,NUMMAC,NUMCLL,NUMJOB,NUMOP)
C   THIS UNIT PERFORMS NECESSARY LINEARIZATION CALCULATIONS FOR
```

```
C   STEP 2C AND USES NASLUND'S APPR. FORMULA FOR STOCHASTIC * Z *
C   AND A(I,J) COEFF. ELEMENTS. NO STOCHASTIC RHS ELEMENT EXIST HERE.
      IMPLICIT REAL(A-H,O-Z)
      DIMENSION DEMAND(12),DVAR(12),ICLFEA(9,9,12,20),SUMCNT(10,10)
      DIMENSION ZCOST(9,9,12,20),VCCOST(20,10),MACOKY(10,10)
      DIMENSION TIMES(20,10),ZVAR(9,9,12,20),RWTIME(9,9,12,20)
      DIMENSION RWVAR(9,9,12,20),RVARSM(10,10),RIGHHS(10,10)
C FIRST, Z TERMS ARE TRANSFORMED INTO LINEAR FORM AS SHOWN IN APPENDIX
                ZVARSM = 0
           DO 5000 ICELL = 1,NUMCLL
            DO 5100 MACH = 1,NUMMAC
              DO 5200 IJOB = 1,NUMJOB
                DO 5300 IOP = 1,NUMOP
                  SUMCNT(ICELL,MACH) = 0
        IF (ICLFEA(ICELL,MACH,IJOB,IOP).NE.1 ) GOTO 5300
        ZVARSM = ZVARSM + ZVAR(ICELL,MACH,IJOB,IOP)
 5300     CONTINUE
 5200     CONTINUE
 5100     CONTINUE
 5000     CONTINUE
                ZVART = SQRT(ZVARSM)
           DO 6000 ICELL = 1,NUMCLL
            DO 6100 MACH = 1,NUMMAC
              DO 6200 IJOB = 1,NUMJOB
                DO 6300 IOP = 1,NUMOP
      IF(ICLFEA(ICELL,MACH,IJOB,IOP).EQ.0) GOTO 6300
      ZCOST(ICELL,MACH,IJOB,IOP) = ZCOST(ICELL,MACH,IJOB,IOP) +
     * ZVART - (SQRT( ZVARSM - ZVAR(ICELL,MACH,IJOB,IOP)))
 6300     CONTINUE
 6200     CONTINUE
 6100     CONTINUE
 6000     CONTINUE
   LINEARIZING 3.2.1 TYPE ROW CONSTRAINTS OF STEP 2CM
           DO 7000 ICELL = 1,NUMCLL
            DO 7100 MACH = 1,NUMMAC
              DO 7200 IJOB = 1,NUMJOB
                DO 7300 IOP = 1,NUMOP
      IF (ICLFEA(ICELL,MACH,IJOB,IOP).NE.1) GOTO 7300
       RVARSM(ICELL,MACH) = RVARSM(ICELL,MACH) + RWVAR(ICELL,
     *MACH,IJOB,IOP)
 7300     CONTINUE
 7200     CONTINUE
 7100     CONTINUE
 7000     CONTINUE
           DO 8000 ICELL = 1,NUMCLL
            DO 8100 MACH = 1,NUMMAC
              DO 8200 IJOB = 1,NUMJOB
                DO 8300 IOP = 1,NUMOP
      IF (ICLFEA(ICELL,MACH,IJOB,IOP).NE.1) GOTO 8300
      DIFF = SQRT(RVARSM(ICELL,MACH)) - SQRT(RVARSM(ICELL,MACH) -
     * RWVAR(ICELL,MACH,IJOB,IOP))
      DIFF1 = SQRT( RVARSM(ICELL,MACH) - RWVAR(ICELL,MACH,IJOB,IOP))
      SUMCNT(ICELL,MACH) = SUMCNT(ICELL,MACH) + DIFF
      RWTIME(ICELL,MACH,IJOB,IOP) = RWTIME(ICELL,MACH,IJOB,IOP) +
     &(EVAR *(( SQRT(RVARSM(ICELL,MACH)))- DIFF1))
 8300    CONTINUE
```

```
8200    CONTINUE
8100    CONTINUE
8000    CONTINUE
        DO 9000 ICELL = 1,NUMCLL
          DO 9100 MACH = 1,NUMMAC
          IF(MACOKY(ICELL,MACH).NE.1 ) GOTO 9100
     RIGHHS(ICELL,MACH) = -EVAR * ( SQRT(RVARSM(ICELL,MACH)) -
    *SUMCNT(ICELL,MACH) )
     IF(SQRT(RVARSM(ICELL,MACH)).EQ.SUMCNT(ICELL,MACH)) RIGHHS(ICELL
    *,MACH) = 0
9100  CONTINUE
9000  CONTINUE
      RETURN
      END
C
C*********************************************************************
C**********************************************************************
C THIS UNIT DETERMINES AND WRITES OUT THE LOCATIONS AND COEFFICIENTS
C OF ALL 0/1 ASSIGNMENT VARIABLES SUCH AS ** XA2P ** AND MACHINE
C NUMBERS, MP1, IN STEP 2CM.
C
      SUBROUTINE CMASSG(ICLFEA,ISECT1,ISECT2,NUMCLS,NUMJOB,NUMOPE,NUMMAC
     *       ,BM,NUMOP,MACCLS,JOBOPE,ISTEP1,MAKH,NAME,ZCOST,RWTIME,
     *       JOBCLL,ICLCLS,MACOKY,NUMCLL)
      IMPLICIT REAL(A-H,O-Z)
      DIMENSION DEMAND(12),DVAR(12),JOBCLS(10,12),ICLFEA(9,9,12,20)
      DIMENSION IOPPRJ(12),JOBOPE(20,12),MACCLS(10,10),ILINE2(5,10)
      DIMENSION IROW1(9,9,12,20),ZCOST(9,9,12,20),VCCOST(20,10)
      DIMENSION ISTEP1(12),TIMES(20,10),RWTIME(9,9,12,20)
      DIMENSION ICLCLS(5,7),JOBCLL(5,20),MACOKY(10,10),IROW2(9,9,12,20)
      CHARACTER*1 MAKH(12),NAME(12)
       ILINE = ISECT1 + ISECT2
           DO 3000 ICELL = 1,NUMCLL
            DO 3100 MACH = 1,NUMMAC
              ILINE2(ICELL,MACH) = 0
              IF ( MACOKY(ICELL,MACH).NE.1) GOTO 3100
                ILINE2(ICELL,MACH) = ILINE + MACH
3100         CONTINUE
3000         CONTINUE
            ILINE1 = 0
        DO 5000 ICELL = 1,NUMCLL
         DO 5100 MACH = 1,NUMMAC
           IF(MACOKY(ICELL,MACH).NE.1) GOTO 5100
           ILINE1 = ILINE1 + 1
           IF (ILINE1.GT.9) GOTO 5150
           WRITE(8,5170) MAKH(MACH),ICELL,ILINE1,ILINE2(ICELL,MACH)
5170 FORMAT(4X,'M',A1,'C',I1,T15,'R',I1,T28,'-480.',T40,'R',I2,T55,'1.'
    *)
       GOTO 5100
5150        WRITE(8,5200) MAKH(MACH),ICELL,ILINE1,ILINE2(ICELL,MACH)
5200 FORMAT(4X,'M',A1,'C',I1,T15,'R',I2,T28,'-480.',T40,'R',I2,T55,'1.'
    *)
5100   CONTINUE
5000   CONTINUE
C   FINDING THE LOCATION AND COEFF. OF THE 0/1 ASSIGNMENT VARIABLES
        IMARK1 = 0
```

```
      IMARK2 = ISECT1 + 1
        DO 5300 ICELL = 1,NUMCLL
          DO 5300 MACH = 1,NUMMAC
     IF( MACOKY(ICELL,MACH).EQ.1 ) IMARK1 = IMARK1 + 1
            DO 5300 IJOB = 1,NUMJOB
              DO 5300 IOP = 1,NUMOP
      IROW1(ICELL,MACH,IJOB,IOP) = 0
      IF (ICLFEA(ICELL,MACH,IJOB,IOP).NE.1 ) GOTO 5300
      IROW1(ICELL,MACH,IJOB,IOP) = IMARK1
5300          CONTINUE
        DO 6100 ICELL = 1,NUMCLL
          DO 6200 IJOB = 1,NUMJOB
          IF (JOBCLL(ICELL,IJOB).NE.1) GOTO 6200
            DO 6300 IOP = 1,NUMOP
              DO 6400 MACH = 1,NUMMAC
       IROW2(ICELL,MACH,IJOB,IOP) = 0
       IF (ICLFEA(ICELL,MACH,IJOB,IOP).NE.1) GOTO 6400
       IROW2(ICELL,MACH,IJOB,IOP) = IMARK2
6400    CONTINUE
        IF (JOBOPE(IOP,IJOB).EQ.1) IMARK2 = IMARK2 + 1
6300      CONTINUE
6200      CONTINUE
6100      CONTINUE
        DO 7600 ICELL = 1,NUMCLL
          DO 7600 MACH = 1,NUMMAC
            DO 7600 IJOB = 1,NUMJOB
              DO 7600 IOP = 1,NUMOP
          IF (ICLFEA(ICELL,MACH,IJOB,IOP).NE.1) GOTO 7600
C REPEATED PRINTS MADE TO AVOID ANY GAPS BETWEEN THE DIGITS
       IF (IOP.GT.9) THEN DO
          IF (IROW1(ICELL,MACH,IJOB,IOP).GT.9) THEN DO
   WRITE(8,6450) ICELL,MAKH(MACH),NAME(IJOB),IOP,ZCOST(ICELL,MACH,IJO
  *B,IOP),IROW1(ICELL,MACH,IJOB,IOP),RWTIME(ICELL,MACH,IJOB,IOP)
6450  FORMAT(4X,'X',I1,A1,A1,I2,T15,'Z',T28,F8.2,T40,'R',I2,T51,F8.2)
                ELSE
   WRITE(8,6451) ICELL,MAKH(MACH),NAME(IJOB),IOP,ZCOST(ICELL,MACH,IJO
  *B,IOP),IROW1(ICELL,MACH,IJOB,IOP),RWTIME(ICELL,MACH,IJOB,IOP)
6451  FORMAT(4X,'X',I1,2A1,I2,T15,'Z',T28,F8.2,T40,'R',I1,T51,F8.2)
                          END IF
                ELSE DO
          IF (IROW1(ICELL,MACH,IJOB,IOP).GT.9) THEN DO
   WRITE(8,6452) ICELL,MAKH(MACH),NAME(IJOB),IOP,ZCOST(ICELL,MACH,IJO
  *B,IOP),IROW1(ICELL,MACH,IJOB,IOP),RWTIME(ICELL,MACH,IJOB,IOP)
6452  FORMAT(4X,'X',I1,2A1,I1,T15,'Z',T28,F8.2,T40,'R',I2,T51,F8.2)
                ELSE
   WRITE(8,6453) ICELL,MAKH(MACH),NAME(IJOB),IOP,ZCOST(ICELL,MACH,IJO
  *B,IOP),IROW1(ICELL,MACH,IJOB,IOP),RWTIME(ICELL,MACH,IJOB,IOP)
6453  FORMAT(4X,'X',I1,2A1,I1,T15,'Z',T28,F8.2,T40,'R',I1,T51,F8.2)
                          END IF
                   END IF
       IF (IOP.GT.9) THEN DO
          IF (IROW2(ICELL,MACH,IJOB,IOP).GT.9) THEN DO
   WRITE(8,6550) ICELL,MAKH(MACH),NAME(IJOB),IOP,IROW2(ICELL,MACH,IJO
  *B,IOP)
6550 FORMAT(4X,'X',I1,2A1,I2,T15,'R',I2,T28,'1.')
                ELSE
```

```
      WRITE(8,6551) ICELL,MAKH(MACH),NAME(IJOB),IOP,IROW2(ICELL,MACH,IJO
     *B,IOP)
6551 FORMAT(4X,'X',I1,2A1,I2,T15,'R',I1,T28,'1.')
                                        END IF
                              ELSE DO
                  IF (IROW2(ICELL,MACH,IJOB,IOP).GT.9) THEN DO
      WRITE(8,6552) ICELL,MAKH(MACH),NAME(IJOB),IOP,IROW2(ICELL,MACH,IJO
     *B,IOP)
6552 FORMAT(4X,'X',I1,2A1,I1,T15,'R',I2,T28,'1.')
                              ELSE
      WRITE(8,6553) ICELL,MAKH(MACH),NAME(IJOB),IOP,IROW2(ICELL,MACH,IJO
     *B,IOP)
6553 FORMAT(4X,'X',I1,2A1,I1,T15,'R',I1,T28,'1.')
                                         END IF
                                 END IF
7600 CONTINUE
      WRITE(8,4500)
4500 FORMAT('    FINE      ''MARKER''                ''INTEND''')
         ICONST = ISECT1 + ISECT2
           DO 9000 MACH = 1,NUMMAC
               ICONST = ICONST + 1
        WRITE(8,9100) MAKH(MACH),BM,ICONST,ISTEP1(MACH)
9100   FORMAT(4X,'AC',A1,T15,'Z',T28,F6.0,T40,'R',I2,T55,'-',I1,'.0')
9000   CONTINUE
        WRITE(8,9200)
9200   FORMAT('RHS')
         RETURN
         END
C *****************************************************************
C
C*****************************************************************
C THIS UNIT LISTS ALL POSSIBLE/FEASIBLE M(I) AND M(IKN) COMBINATIONS
C AND PLACES SOME HIGH BOUND ON EACH ONE TO CONFORM WITH MPSIII FORMAT
C
      SUBROUTINE CMBOUD(MAXMAC,NUMMAC,NUMCLS,MAKH,MACOKY,NUMCLL)
C
      CHARACTER*1 MAKH(12),QT,STAR,SLASH
      DIMENSION MACOKY(10,10)
      QT=''''
      STAR='*'
      SLASH='/'
      DO 1000 MACH = 1,NUMMAC
       DO 1100 ICELL = 1,NUMCLL
         IF( MACOKY(ICELL,MACH).NE.1) GOTO 1100
         WRITE(8,1200) MAKH(MACH),ICELL,MAXMAC
1200    FORMAT(' UP',1X,'BOUD',T15,'M',A1,'C',I1,T32,I2,'.0')
1100    CONTINUE
1000   CONTINUE
         DO 1300 MACH = 1,NUMMAC
              WRITE(8,1400) MAKH(MACH),MAXMAC
1400          FORMAT(' UP',1X,'BOUD',T15,'AC',A1,T32,I2,'.0')
1300   CONTINUE
      WRITE(7,3300)
      WRITE(8,3300)
3300 FORMAT('ENDATA                                    ',
     *'                ')
```

```
  579        WRITE(8,6000) SLASH,STAR
  580    6000 FORMAT(2A1)
  581        WRITE(8,8000) SLASH,SLASH
  582    8000 FORMAT(2A1)
  583            RETURN
  584            END
        C***********************************************************
        C
0       C$ENTRY
0STATEMENTS EXECUTED=  293583
0COMPILE TIME=     0.32 SEC,EXECUTION TIME=      1.65 SEC,     19.55.52
-       C$STOP
```

UNIT FORTRAN listing :

```
1       C$JOB
        C                UNIT FORTRAN
        C  **********************************************************
        C  THE PURPOSE OF THIS PROGRAM IS TO CALCULATE UNIT LOAD TIMES
        C  OF JOBS ON DIFFERENT FEASIBLE MACHINES IN ALL PROBLEM SETS.
    1       IMPLICIT REAL(A-H,O-Z)
    2       DIMENSION DEMAND(12),JOBCLS(7,12),SETUP(7,8),LOCSET(20),
         *        JOBOPE(20,12),MACCLS(7,8),TIMES(20,8),ILIMIT(8),
         *        ASFC(19),IOPCLS(20,7),NUMLOD(12),MNLAST(12),IEVEN(12),
         *        MACTOT(4),JOBTOT(4),ASFF(4),ICELNO(20),JOBMEM(20),
         *        JOBNUM(19,5),MNK(12),RTIME(8)
    3       CHARACTER*1 MAKH(10),NAME(12)
        C
        C           :
        C
        C   NSETS     : NUMBER OF PROBLEM SETS (4)
        C   NCELLS    : NUMBER OF DISTINCT CELLULAR FORMATIONS IN ALL SETS(19)
        C   SETUP     : MATRIX OF FULL SETUP TIMES ON EACH MACHINE.
        C   JOBMEM     : *ARRAY OF NUMBER OF JOBS IN EACH CELLULAR FORMATION.
        C   LOCSET    : *ARRAY INDICATING PROBLEM SET MEMBERSHIP OF EACH FORM.
        C   ASFF      : AVERAGE SETUP SIMILARITY FACTOR FOR EACH FUNCTIONAL
        C             PROBLEM SET.
        C   ASFC      : THE SAME FOR EACH OF NCELL CELLULAR FORMATIONS.
        C   JOBOPE    : 0/1 MATRIX SHOWING JOB/OPERATION NEEDS.
        C   IOPCLS    : 0/1 MATRIX SHOWING OPERATION/CLASS MEMBERSHIPS.
        C   TIMES     : MATRIX SHOWING FEASIBLE OPERATION TIMES ON MACHINES.
        C ***************************************************************
        C  ULT  : UNIT LOAD TIME FOR IUNIT ITEMS OF JOB IJOB ON MACHINE MACH
        C        FOR CLASS OPERATION OF ICLASS IN A GIVEN PROBLEM SET OR
        C        CELLULAR FORMATION.
        C  UCLT : SAME FOR EACH OF NCELLS CELLULAR FORMATIONS.
        C  MNK       : NUMBER JOBS OF EACH TYPE THAT MAKE UP A UNIT LOAD
        C  ILIMIT    : NUMBER OF JOBS EACH MACHINE CAN PROCESS BEFORE A
        C             MINOR SETUP BECOMES NECESSARY
        C  RTIME     : DURATION OF SUCH SETUP.
        C  MACTOT     : NUMBER MACHINE TYPES AVAILABLE IN EACH PROBLEM SET
        C  JOBTOT     : SAME FOR JOB TYPES (E.G. 4 MACHINES, 4 JOBS IN SET 1)
        C  ICELNO     : POSITION OF CELLULAR FORMATION IN LOCSET
        C  IEVEN      : *ARRAY SHOWING JOBS WITH PARTIAL LAST UNIT LOADS (0)
```

```
C              AFTER MEAN DEMAND IS DIVIDED BY MNK
C   TOT1,2,3   : SETUP, OPERATION, AND RESET TIMES FOR A LOAD OF GIVEN
C              NUMBER OF UNIT LOADS.
C
C  DATA READ, **ARRAYS INITIALIZED
C
      READ(93,*) NSETS,NUMMAC,NUMJOB,NUMCLS,NUMOP,NCELLS
      DO 1000 IJOB = 1,NUMJOB
        NUMLOD(IJOB) = 0
        MNLAST(IJOB) = 0
        IEVEN(IJOB)  = 0
 1000 READ(87,*) NAME(IJOB),DEMAND(IJOB),MNK(IJOB)
       DO 1200 IOP = 1,NUMOP
       READ(85,*) (TIMES(IOP,MACH),MACH = 1,NUMMAC)
       READ(84,*) (JOBOPE(IOP,IJOB),IJOB = 1,NUMJOB)
       READ(49,*) (IOPCLS(IOP,ICLASS),ICLASS = 1,NUMCLS)
 1200   CONTINUE
        DO 1300 ICLASS = 1,NUMCLS
        READ(83,*) (MACCLS(ICLASS,MACH),MACH = 1,NUMMAC)
        READ(82,*) (JOBCLS(ICLASS,IJOB),IJOB = 1,NUMJOB)
        READ(89,*) (SETUP(ICLASS,MACH),MACH = 1,NUMMAC)
 1300   CONTINUE
        DO 1400 MACH = 1,NUMMAC
 1400     READ(86,*) MAKH(MACH),ILIMIT(MACH),RTIME(MACH)
          DO 1500 ISET = 1,NSETS
 1500      READ(90,*) MACTOT(ISET),JOBTOT(ISET),ASFF(ISET)
       DO 1700 ICELL = 1,NCELLS
       READ(91,*) LOCSET(ICELL),ICELNO(ICELL),JOBMEM(ICELL),ASFC(ICELL)
                N = JOBMEM(ICELL)
            READ(92,*) (JOBNUM(ICELL,IJOB),IJOB = 1,N)
 1700       CONTINUE
C
C   DISTINCT NUMBER OF UNIT LOADS OF EACH TYPE IS FOUND :
C
        DO 3000 IJOB = 1,NUMJOB
C  DETERMINING NUMBER OF UNIT LOADS
          PALLET = DEMAND(IJOB)/MNK(IJOB)
          IPALLT = INT(PALLET)
C  IF THE DIVISION IS AN INTEGER, THEN LAST LOAD IS A FULL ONE.
           IF (PALLET.EQ.IPALLT)  THEN DO
               IEVEN(IJOB)  = 0
               NUMLOD(IJOB) = IPALLT
               MNLAST(IJOB) = MNK(IJOB)
                      ELSE DO
               NUMLOD(IJOB) = IPALLT + 1
               MNLAST(IJOB) = DEMAND(IJOB) - IPALLT * MNK(IJOB)
                               END IF
 3000     CONTINUE
C   INDICATING THE PROBLEM SET FOR WHICH FUNCTIONAL UNIT
C   LOAD TIMES ARE TO BE CALCULATED.
               ISET = 4
           IJ = JOBTOT(ISET)
           IM = MACTOT(ISET)
          DO 5100 ICLASS = 1,NUMCLS
           DO 5200 MACH = 1,IM
            DO 5300 IJOB = 1,IJ
```

```
              IF(MACCLS(ICLASS,MACH).NE.1) GOTO 5200
              IF(JOBCLS(ICLASS,IJOB).NE.1) GOTO 5300
                 ILDS = NUMLOD(IJOB)
                   DO 5400 IOP = 1,NUMOP
                IF(JOBOPE(IOP,IJOB).NE.1) GOTO 5400
                IF(IOPCLS(IOP,ICLASS).NE.1) GOTO 5400
                    DURATN = TIMES(IOP,MACH)
                    IRESET = 0
               DO 5800 IUNIT = 1,ILDS
C INITIAL SETUP, OP., AND RESET TIMES FOUND AND STORED IN TOT1,2,3
                TOT1 = SETUP(ICLASS,MACH)*ASFF(ISET)
C  HANDLING INCOMPLETE LAST UNIT LOAD CASES :
             IF (IUNIT.LT.ILDS) GOTO 5817
               IF(IEVEN(IJOB).EQ.1) THEN DO
                TOT2 = IUNIT * MNK(IJOB) * DURATN
                                  ELSE DO
                TOT2 = ( ( (IUNIT-1)*MNK(IJOB)) + MNLAST(IJOB)) * DURATN
                                  END IF
                                  GOTO 5819
  5817            TOT2 = IUNIT * MNK(IJOB) * DURATN
  5819              IRESET = (IUNIT * MNK(IJOB) ) / ILIMIT(MACH)
                TOT3 = RTIME(MACH) * ASFF(ISET)* IRESET
           ULT=TOT1 + TOT2 + TOT3
C
C     WRITE(8,7010) ISET,ICLASS,MAKH(MACH),NAME(IJOB),IUNIT,ULT
C7010   FORMAT(3X,'SET ',I1,' CLASS ',I1,' MACH ',A1,' JOB ',A1,
C    *'  UNIT ',I2,' TIME = ',F8.1,' MINUTES')
  5800     CONTINUE
  5400     CONTINUE
  5300     CONTINUE
  5200     CONTINUE
  5100     CONTINUE
  5000     CONTINUE
C SIMILAR OPERATIONS ARE REPEATED FOR CELLULAR CASE
C ********************************************************************
C AGAIN, TO AVOID LONG OUTPUTS, DESIRED PORTION IS SPECIFIED
          DO 8000 ICELL = 1,2
               IS = LOCSET(ICELL)
               INUM = ICELNO(ICELL)
               IJ = JOBMEM(ICELL)
             DO 8010 ICLASS = 1,NUMCLS
               IM = MACTOT(IS)
              DO 8020 MACH = 1,IM
              IF(MACCLS(ICLASS,MACH).NE.1) GOTO 8020
               DO 8030 IJB = 1,IJ
                   IJOB = JOBNUM(ICELL,IJB)
              IF(JOBCLS(ICLASS,IJOB).NE.1) GOTO 8030
                 ILDS = NUMLOD(IJOB)
                   DO 8040 IOP = 1,NUMOP
                IF(JOBOPE(IOP,IJOB).NE.1) GOTO 8040
                IF(IOPCLS(IOP,ICLASS).NE.1) GOTO 8040
                    DURATN = TIMES(IOP,MACH)
                    IRESET = 0
               DO 8050 IUNIT = 1,ILDS
                TOT1 = SETUP(ICLASS,MACH)*ASFC(ICELL)
C  HANDLING INCOMPLETE LAST UNIT LOAD CASES :
```

```
93              IF (IUNIT.LT.ILDS) GOTO 6817
94                IF(IEVEN(IJOB).EQ.1) THEN DO
95                TOT2 = IUNIT * MNK(IJOB) * DURATN
96                               ELSE DO
97                TOT2 = ( ( (IUNIT-1)*MNK(IJOB)) + MNLAST(IJOB)) * DURATN
98                               END IF
99                               GOTO 6819
100   6817          TOT2 = IUNIT * MNK(IJOB) * DURATN
101   6819            IRESET = (IUNIT * MNK(IJOB) ) / ILIMIT(MACH)
102                 TOT3 = RTIME(MACH) * ASFC(ICELL)* IRESET
103                 UCLT = TOT1 + TOT2 + TOT3
     C
104       WRITE(8,7011) IS,INUM,ICLASS,MAKH(MACH),NAME(IJOB),IUNIT,
         *UCLT
105   7011 FORMAT(3X,'SET ',I1,' CELL ',I2,' CLASS ',I1,' MAC ',A1,' JOB ',A1
         *,' UNIT ',I2,' UNIT TIME = ',F8.1)
106   8050     CONTINUE
107   8040     CONTINUE
108   8030     CONTINUE
109   8020     CONTINUE
110   8010     CONTINUE
111   8000     CONTINUE
112               STOP
113               END
0        C$ENTRY
```

STEP5 FORTRAN listing :

```
1        C$JOB
         C            STAGE ONE-STEP 5 INPUT GENERATION
         C   ************************************************************
         C   THE PURPOSE OF THIS PROGRAM IS TO CREATE THE VARIABLE PORTION
         C   OR THE MAIN INPUT NEEDED TO RUN MPSIII PACKAGE.  THIS CODE
         C   CREATES THE NECESSARY INPUT FOR ANY DIMENSIONAL SIZE.
         C
         C     THIS PROGRAM DOES NOT PRODUCE THE INPUT IN THE FORMAT
         C     FULLY COMPATIBLE WITH MPSIII PACKAGE.  AFTER RUNNING,
         C     COLUMNS SECTION MUST BE SORTED IN ASCENDING ORDER.
         C     THIS MODIFICATION IS MADE MANUALLY USING CMS/XEDIT
         C     COMMAND OF ** SORT /MARKER/ A 5 12 ** ON LINE RIGHT
         C     AFTER INPUT FILE STEP5 CNTL IS CREATED WITH THIS PROGRAM.
         C
         C    ALSO, SOME OF THE I3 FORMAT FIELDS MAY RESULT IN TERMS SUCH AS R 42
         C    IN THE OUTPUT FILE.  SUCH ENTRIES MUST FIXED BY REMOVING BLANKS
         C    AFTER THE LETTER R WHENEVER A ROW LOCATION IS INDICATED.
         C     IF NOT, MPSIII PACKAGE WILL PRODUCE ERROR MESSEGAS AND HALT.
         C
   1          DIMENSION ICLJOB(10),JOBNED(10),MACDEP(10,10),MCOUNT(10),
           *      JDPVST(10,10),MTYPE(10),DEMAND(12),DVAR(12),MAXLOD(12),
           *      LSCOST(12),MNK(12),IFIRST(12),UTIME(12,12,12,30)
   2          CHARACTER*1 MAKH(10),NAME(12)
         C
         C    ISEG1,2,3,4 : NUMBER OF CONSTRAINTS WITH RHS VALUES OF
         C               1,DEMAND,0, AND T (USUALLY 480 MINUTES)
         C    ICLJOB(ICLASS) :ARRAY OF NUMBER OF DISTINCT JOBS VISITING EACH DEPT
         C    JOBNED(IJOB)   :ARRAY OF NUMBER OF DEPTS EACH JOB VISITS
```

```
C   MACDEP(ICLASS,MACH) :MATRIX SHOWING NUMBER OF EACH OF THE MACHINE
C                  TYPES REMAINING IN EACH DEPT. AFTER STEP 4
C   JDPVST(ICLASS,IJOB) :MATRIX (BINARY) SHOWING VISIT NEED OF JOBS TO
C                  A GIVEN DEPT OR OPERATION CLASS AREA.
C                  (SAME AS **JOBCLS** MATRIX USED IN OTHER CODES)
C   MAKH,NAME  : CHARACTER ARRAYS CONTAINING MACHINE & JOB NAMES.
C   UTIL :(MACH) : RELIABILITY/UPTIME OF EACH MACHINE TYPE
C   MCOUNT(ICLASS) : NUMBER OF MACHINES IN EACH CLASS AREA.
C   MTYPE(MACH)    : NUMBER OF EACH MACHINE TYPE IN THE ENTIRE FACILITY
C   UTIME(ICLASS,MACH,IJOB,IUNIT) :   MATRIX SHOWING
C                        UNIT LOAD TIMES
C  LSCOST(IJOB) : LOST SALES COST FOR EACH JOB TYPE
C  MNK(IJOB)    : UNIT LOAD SIZE OF EACH JOB TYPE
C  MAXLOD(IJOB) : MAXIUMUM NUMBER OF UNIT LOADS OF EACH TYPE
C  IFIRST(IJOB) : VERY FIRST OPERATION CLASS NUMBER OF EACH JOB TYPE
C  JOBORD(IJOB,IORDER) : MATRIX SHOWING CLASS NEEDS IN CONSECUTIVE
C                  ORDER WITHOUT ANY NO-NEED (0) TERMS.
C  MEMBER(IJOB,IRW,1 OR 2) : OPERATION CLASS MEMBERS OF EACH JOB
C                    BALANCE EQUATION CONTRAINT. E.G., FOR
C                    JOB A:#1 & #3 FOR ROW1, #3 & #5 FOR ROW2
C
      CALL INPUT(NUMMAC,NUMOP,NUMJOB,NUMCLS,MAXMAC,UTIME,LSCOST,
     *        DEMAND,ICLJOB,JOBNED,MACDEP,JDPVST,MTYPE,MCOUNT,
     *        MAKH,NAME,ISEG1,ISEG2,ISEG3,ISEG4,MAXLOD,MNK,
     *        IFIRST)
      CALL RSIGN(ISEG1,ISEG2,ISEG3,ISEG4)
      CALL ASSIGN(ISEG1,ISEG2,ISEG3,ISEG4,MAKH,NAME,UTIME,MAXLOD,DEMAND,
     *        LSCOST,NUMJOB,NUMMAC,NUMCLS,MACDEP,JDPVST,MCOUNT,MNK,
     *        IFIRST,JOBNED)
      CALL RHS(ISEG1,ISEG2,ISEG3,ISEG4,DEMAND)
      CALL BOUNDS(NUMJOB,NAME,DEMAND)
 1500 STOP
      END
C *****************************************************************
       SUBROUTINE INPUT(NUMMAC,NUMOP,NUMJOB,NUMCLS,MAXMAC,UTIME,
     *     LSCOST,DEMAND,ICLJOB,JOBNED,MACDEP,JDPVST,MTYPE,MCOUNT
     *     ,MAKH,NAME,ISEG1,ISEG2,ISEG3,ISEG4,MAXLOD,MNK,IFIRST)
       DIMENSION ICLJOB(10),JOBNED(10),UTIL(10),MACDEP(10,10),MCOUNT(10),
     *        JDPVST(10,10),MTYPE(10),DEMAND(12),DVAR(12),MAXLOD(12),
     *        LSCOST(12),MNK(12),IFIRST(12),UTIME(12,12,12,30)
       CHARACTER*1 MAKH(10),NAME(12)
       READ(70,*) NUMMAC,NUMOP,NUMJOB,NUMCLS,ISEG1,ISEG2,
     *          ISEG3,ISEG3X,ISEG4
          DO 1000  MACH = 1,NUMMAC
 1000       READ(74,*) MAKH(MACH),MTYPE(MACH)
            DO 1005 IJOB = 1,NUMJOB
 1005       READ(75,*) NAME(IJOB),DEMAND(IJOB),
     *   MAXLOD(IJOB),MNK(IJOB),LSCOST(IJOB),IFIRST(IJOB),JOBNED(IJOB)
         DO 1010 ICLASS = 1,NUMCLS
            READ(76,*) (MACDEP(ICLASS,MACH),MACH = 1,NUMMAC)
            READ(77,*) (JDPVST(ICLASS,IJOB),IJOB = 1,NUMJOB)
            READ(78,*) ICLJOB(ICLASS),MCOUNT(ICLASS)
 1010        CONTINUE
C
C
C
```

```
C      CALCULATION OF ISEG1....ISEG4
C
          DO 3000 ICLASS = 1,NUMCLS
 3000       ISEG1 = ISEG1 + ( ICLJOB(ICLASS)*MCOUNT(ICLASS))
          DO 3010 IJOB = 1,NUMJOB
 3010       ISEG3X = ISEG3X + JOBNED(IJOB)
              ISEG3 = ISEG3X - NUMJOB
              ISEG2 = NUMJOB
          DO 3020 MACH = 1,NUMMAC
 3020      ISEG4 = ISEG4 + MTYPE(MACH)
C
C
        DO 2000 ICLASS = 1,NUMCLS
         DO 2010 MACH = 1,NUMMAC
          IF (MACDEP(ICLASS,MACH).LT.1) GOTO 2010
           DO 2020 IJOB = 1,NUMJOB
           IF (JDPVST(ICLASS,IJOB).NE.1) GOTO 2020
                NUMUNT = MAXLOD(IJOB)
            DO 2021 IUNIT = 1,NUMUNT
C  READING FROM A SINGLE COLUMN FILE GENERATED BY UNIT FORTRAN FOR
C  DIRECT DATA INPUT TO STEP5 FORTRAN, AVOIDING MANUAL ENTRY OF
C  THOUSANDS OF UNIT TIME AMOUNTS.
          READ(80,*) UTIME(ICLASS,MACH,IJOB,IUNIT)
 2021 CONTINUE
 2020 CONTINUE
 2010 CONTINUE
 2000 CONTINUE
C
          RETURN
          END
C
C  *******************************************************************
1  C  THIS UNIT WRITES OUT THE SIGN AND THE ROW NUMBER OF EACH
   C  OF THE CONSTRAINTS OF ** BOTH MODELS **. E.G. G R1, L R11
   C
0        SUBROUTINE RSIGN(ISEG1,ISEG2,ISEG3,ISEG4)
C
       CHARACTER SIGN*1,QT*1,SP*10
       QT = ''''
       SP ='          '
       WRITE(7,1900)
       WRITE(8,1900)
 1900 FORMAT('NAME          TEST1     FREE',/'ROWS     ')
       WRITE(8,2000)
 2000 FORMAT(1X,'N',2X,'Z')
C
        ITOT = ISEG1 + ISEG2 + ISEG3 + ISEG4
        ITOT1 = ISEG1 + ISEG2
        ITOT2 = ITOT1 + ISEG3
              DO 3000 ICONST = 1,ITOT
                IF (ICONST.LE.ISEG1) SIGN = 'L'
                IF (ICONST.GT.ITOT2) SIGN = 'L'
                IF (ICONST.GT.ISEG1.AND.ICONST.LE.ITOT1) SIGN = 'E'
                IF (ICONST.GT.ITOT1.AND.ICONST.LE.ITOT2) SIGN = 'E'
 2700 IF (ICONST.GE.10) GOTO 2800
       WRITE(8,2750) SIGN,ICONST
```

```
2750 FORMAT(1X,A1,2X,'R',I1)
      GOTO 3000
2800          IF (ICONST.GT.99) GOTO 2850
    WRITE(8,2770) SIGN,ICONST
2770 FORMAT(1X,A1,2X,'R',I2)
         GOTO 3000
2850 WRITE(8,2771) SIGN,ICONST
2771 FORMAT(1X,A1,2X,'R',I3)
3000 CONTINUE
    WRITE(7,2140)SP,SP
    WRITE(8,2140)
2140 FORMAT('COLUMNS    ',2A10)
    WRITE(8,351)
351  FORMAT('   DEBE     ''MARKER''            ''INTORG''')
     RETURN
     END
C ****************************************************************
C   THIS SUBROUTINE DETERMINES THE LOCATIONS OF ALL DECISION VARIABLES
C
       SUBROUTINE ASSIGN(ISEG1,ISEG2,ISEG3,ISEG4,MAKH,NAME,UTIME,MAXLOD,
     *       DEMAND,LSCOST,NUMJOB,NUMMAC,NUMCLS,MACDEP,JDPVST,MCOUNT,
     *       MNK,IFIRST,JOBNED)
C
       DIMENSION DEMAND(12),LSCOST(12),MAXLOD(12),UTIME(12,12,12,30),
     *       MACDEP(10,10),JDPVST(10,10),MCOUNT(10),MNK(12),JOBROW(12)
     *       ,IFIRST(12),IROW4(10),JOBNED(10),JOBORD(10,7),MEMBER(10,7
     *       ,2)
       CHARACTER*1 NAME(10),MAKH(10),MN,MK
C      WRITING OUT LOCATIONS OF UD(K) VARIABLES (CONSTR. TYPE 3.4.2)
       ITOT = ISEG1 + ISEG2
       ITOT1 = ISEG1 + 1
       IROW1 = 0
C   DETERMINING BEGINNING ROWS OF EACH CONSTRAINT OF TYPE 3.4.4
          DO 1025 ICLASS = 1,NUMCLS
           IF (ICLASS.EQ.1) IROW4(ICLASS) = ISEG1 + ISEG2 + ISEG3
           IF (ICLASS.EQ.1) GOTO 1025
             IROW4(ICLASS) = IROW4(ICLASS - 1) + MCOUNT(ICLASS - 1)
1025           CONTINUE
           DO 2000 IJOB = 1,NUMJOB
              IROWUD = IJOB + ISEG1
              JOBROW(IJOB) = IROWUD
              MN = NAME(IJOB)
           IF (IROWUD.LE.99) GOTO 2018
              WRITE(8,2099) MN,LSCOST(IJOB),IROWUD
2099 FORMAT(4X,'UD',A1,T15,'Z',T26,I8,T40,'R',I3,T55,'1.')
          GOTO 2000
2018           WRITE(8,2100) MN,LSCOST(IJOB),IROWUD
2100 FORMAT(4X,'UD',A1,T15,'Z',T26,I8,T40,'R',I2,T55,'1.')
2000 CONTINUE
C WRITING OUT THE LOCATIONS OF 0/1 VARIABLES
        DO 1000 ICLASS = 1,NUMCLS
          DO 1010 IJOB = 1,NUMJOB
             ISET = IROW4(ICLASS)
          IF (JDPVST(ICLASS,IJOB).NE.1) GOTO 1010
        DO 1020 MACH = 1,NUMMAC
         IF (MACDEP(ICLASS,MACH).LT.1) GOTO 1020
```

```
              NUMUNT = MAXLOD(IJOB)
              MACDUP = MACDEP(ICLASS,MACH)
C
C
          DO 1500 IDP = 1,MACDUP
             IROW1 = IROW1 + 1
            DO 1510 IUN = 1,NUMUNT
             IF (ICLASS.NE.IFIRST(IJOB)) GOTO 1480
C  CHECK IF THE CURRENT BATCH IS THE LAST ONE, IF SO IT MAY NOT BE FULL
      IF(IUN.LT.NUMUNT)  ILLOD = IUN*MNK(IJOB)
C  IF LAST ONE, THEN THE COEFF. OF ITS 0/1 VARIABLE IS EQUAL TO DEMAND
      IF(IUN.EQ.NUMUNT)  ILLOD = DEMAND(IJOB)
      IF (IROW1.GT.9) GOTO 1455
      IF(IUN.GT.9) GOTO 2222
      WRITE(8,1460) ICLASS,NAME(IJOB),MAKH(MACH),IDP,IUN,IROW1,
     *            JOBROW(IJOB),ILLOD
 1460  FORMAT(4X,'Q',I1,2A1,I1,'U',I1,T15,'R',I1,T32,'1.',T40,'R',I3
     *,T52,I4,'.')
               GOTO 2223
 2222  WRITE(8,1433) ICLASS,NAME(IJOB),MAKH(MACH),IDP,IUN,IROW1,
     *            JOBROW(IJOB),ILLOD
 1433  FORMAT(4X,'Q',I1,2A1,I1,'U',I2,T15,'R',I1,T32,'1.',T40,'R',I3
     *,T52,I4,'.')
 2223           GOTO 1510
 1455            IF(IUN.GT.9) GOTO 1466
      WRITE(8,1462) ICLASS,NAME(IJOB),MAKH(MACH),IDP,IUN,IROW1,
     *            JOBROW(IJOB),ILLOD
 1462  FORMAT(4X,'Q',I1,2A1,I1,'U',I1,T15,'R',I2,T32,'1.',T40,'R',I3
     *,T52,I4,'.')
                GOTO 1492
 1466  WRITE(8,1481) ICLASS,NAME(IJOB),MAKH(MACH),IDP,IUN,IROW1,
     *            JOBROW(IJOB),ILLOD
 1481  FORMAT(4X,'Q',I1,2A1,I1,'U',I2,T15,'R',I2,T32,'1.',T40,'R',I3
     *,T52,I4,'.')
 1492          GOTO 1510
 1480 IF(IROW1.LT.10) GOTO 1485
            IF (IUN.GT.9) GOTO 1538
      WRITE(8,1550) ICLASS,NAME(IJOB),MAKH(MACH),IDP,IUN,IROW1
 1550        FORMAT(4X,'Q',I1,2A1,I1,'U',I1,T15,'R',I2,T32,'1.')
             GOTO 1594
 1538  WRITE(8,1551) ICLASS,NAME(IJOB),MAKH(MACH),IDP,IUN,IROW1
 1551        FORMAT(4X,'Q',I1,2A1,I1,'U',I2,T15,'R',I2,T32,'1.')
 1594        GOTO 1510
 1485         IF(IUN.GT.9) GOTO 1603
      WRITE(8,1575) ICLASS,NAME(IJOB),MAKH(MACH),IDP,IUN,IROW1
 1575        FORMAT(4X,'Q',I1,2A1,I1,'U',I1,T15,'R',I1,T32,'1.')
             GOTO 1510
 1603  WRITE(8,1675) ICLASS,NAME(IJOB),MAKH(MACH),IDP,IUN,IROW1
 1675        FORMAT(4X,'Q',I1,2A1,I1,'U',I2,T15,'R',I1,T32,'1.')
 1510        CONTINUE
 1500        CONTINUE
C
C  WRITING OUT THE LOCATION OF 0/1 TERMS IN CAPACITY CONSTRAINTS
             DO 3600 IDP = 1,MACDUP
                IROW4(ICLASS) = IROW4(ICLASS) + 1
                  DO 3700 IUN = 1,NUMUNT
```

```
          IF(IUN.GT.9)  GOTO 3816
        WRITE(8,3750) ICLASS,NAME(IJOB),MAKH(MACH),IDP,IUN,IROW4(ICLASS),
      *UTIME(ICLASS,MACH,IJOB,IUN)
 3750  FORMAT(4X,'Q',I1,2A1,I1,'U',I1,T15,'R',I3,T30,F6.1)
          GOTO 3700
 3816  WRITE(8,3754) ICLASS,NAME(IJOB),MAKH(MACH),IDP,IUN,IROW4(ICLASS),
      *UTIME(ICLASS,MACH,IJOB,IUN)
 3754  FORMAT(4X,'Q',I1,2A1,I1,'U',I2,T15,'R',I3,T30,F6.1)
 3700 CONTINUE
 3600 CONTINUE
C
 1020 CONTINUE
           IROW4(ICLASS) = ISET
 1010 CONTINUE
            IROW4(ICLASS) = IROW4(ICLASS) + 1
 1000 CONTINUE
C  THIS SECTION OF THE ASSIGN SUBROUTINE DETERMINES LOCATIONS OF JOB/CL
C  PAIRS AND THEIR RELATED MACHINE/UNIT LOAD COMBINATIONS.
C  LOCATIONS OF THE 0/1 VARIABLES DETERMINED HERE BELONG TO
C  UNIT LOAD BALANCING CONSTRAINTS OF TYPE 3.4.3 ON FIGURE 8.
C
C        DETERMINING DEPT VISIT NEEDS OF EACH JOB
         IORDER = 1
         DO 8000 IJOB = 1,NUMJOB
            DO 8100 ICLASS = 1,NUMCLS
            IF (JDPVST(ICLASS,IJOB).NE.1) GOTO 8100
               JOBORD(IJOB,IORDER) = ICLASS
               IORDER = IORDER + 1
 8100            CONTINUE
                 IORDER = 1
 8000    CONTINUE
C
C  DETERMINING THE PAIRS
         DO 8600 IJOB = 1,NUMJOB
            IF = 1
            IS = 2
            IROWS = JOBNED(IJOB)-1
            DO 8700 IRW = 1,IROWS
              MEMBER(IJOB,IRW,1) = JOBORD(IJOB,IF)
              MEMBER(IJOB,IRW,2) = JOBORD(IJOB,IS)
                    IF = IS
                    IS = IS + 1
 8700        CONTINUE
 8600        CONTINUE
C  DETERMINE EACH CLASS NUMBER IN THE PAIR FOR A GIVEN ROW NUMBER
      IBEGIN = ISEG1 + ISEG2 + 1
            DO 9000 IJOB = 1,NUMJOB
             IROWS = JOBNED(IJOB) - 1
              DO 9010 IR = 1,IROWS
                ICLAS1 = MEMBER(IJOB,IR,1)
                ICLAS2 = MEMBER(IJOB,IR,2)
C     WRITING OUT EACH 0/1 VARIABLE WITH ITS LOCATION AND COEFFICIENT
                 DO 9040 MACH = 1,NUMMAC
          IF (MACDEP(ICLAS1,MACH).LT.1) GOTO 9040
                 NUMUNT = MAXLOD(IJOB)
                 MACDUP = MACDEP(ICLAS1,MACH)
```

```
                    DO 9015 IDP = 1,MACDUP
                      DO 9015 IUN = 1,NUMUNT
C  CHECK IF THE CURRENT BATCH IS THE LAST ONE, IF SO IT MAY NOT BE FULL
        IF(IUN.LT.NUMUNT)   ILLOD = IUN*MNK(IJOB)
C  IF LAST ONE, THEN THE COEFF. OF ITS 0/1 VARIABLE IS EQUAL TO DEMAND
        IF(IUN.EQ.NUMUNT)   ILLOD = DEMAND(IJOB)
              IF(IUN.GT.9) GOTO 9019
        WRITE(8,9550) ICLAS1,NAME(IJOB),MAKH(MACH),IDP,IUN,IBEGIN,ILLOD
  9550  FORMAT(4X,'Q',I1,2A1,I1,'U',I1,T15,'R',I3,T30,I4,'.')
                   GOTO 9015
  9019  WRITE(8,9558) ICLAS1,NAME(IJOB),MAKH(MACH),IDP,IUN,IBEGIN,ILLOD
  9558  FORMAT(4X,'Q',I1,2A1,I1,'U',I2,T15,'R',I3,T30,I4,'.')
  9015  CONTINUE
  9040  CONTINUE
                  DO 9050 MACH = 1,NUMMAC
C   WRITING ITS CORRESPONDING EQUATION WITH A MINUS SIGN
            IF (MACDEP(ICLAS2,MACH).LT.1) GOTO 9050
                 NUMUNT = MAXLOD(IJOB)
                 MACDUP = MACDEP(ICLAS2,MACH)
                    DO 9016 IDP = 1,MACDUP
                      DO 9016 IUN = 1,NUMUNT
C  CHECK IF THE CURRENT BATCH IS THE LAST ONE, IF SO IT MAY NOT BE FULL
        IF(IUN.LT.NUMUNT)   ILLOD = - IUN*MNK(IJOB)
C  IF LAST ONE, THEN THE COEFF. OF ITS 0/1 VARIABLE IS EQUAL TO DEMAND
        IF(IUN.EQ.NUMUNT)   ILLOD = - DEMAND(IJOB)
              IF(IUN.GT.9) GOTO 9001
        WRITE(8,9551) ICLAS2,NAME(IJOB),MAKH(MACH),IDP,IUN,IBEGIN,ILLOD
  9551  FORMAT(4X,'Q',I1,2A1,I1,'U',I1,T15,'R',I3,T30,I4,'.')
             GOTO 9016
  9001  WRITE(8,9008) ICLAS2,NAME(IJOB),MAKH(MACH),IDP,IUN,IBEGIN,ILLOD
  9008  FORMAT(4X,'Q',I1,2A1,I1,'U',I2,T15,'R',I3,T30,I4,'.')
  9016  CONTINUE
  9050  CONTINUE
C
                IBEGIN = IBEGIN + 1
  9010  CONTINUE
C
  9000   CONTINUE
C
       WRITE(8,4500)
  4500 FORMAT('   FINE "MARKER" "INTEND"')
          WRITE(8,9200)
  9200   FORMAT('RHS')
       RETURN
       END
C   ******************************************************************
        SUBROUTINE RHS(ISEG1,ISEG2,ISEG3,ISEG4,DEMAND)
C
       DIMENSION DEMAND(10),DVAR(10),UTIL(10)
C
       DO 1000 ICONST = 1,ISEG1
            IF (ICONST.GE.10.AND.ICONST.LE.99) GOTO 1200
            IF (ICONST.GT.99) GOTO 1204
            WRITE(8,1100) ICONST
  1100        FORMAT(4X,'RH',T15,'R',I1,T33,'1.')
            GO TO 1000
```

```
1200        WRITE(8,1150) ICONST
1150        FORMAT(4X,'RH',T15,'R',I2,T33,'1.')
           GO TO 1000
1204        WRITE(8,1158) ICONST
1158        FORMAT(4X,'RH',T15,'R',I3,T33,'1.')
1000          CONTINUE
             ITOT1 = ISEG1 + 1
             ITOT2 = ISEG1 + ISEG2
             IJOB = 0
               DO 1300 ICONST = ITOT1,ITOT2
                 IJOB = IJOB + 1
           WRITE(8,1350) ICONST,DEMAND(IJOB)
1350        FORMAT(4X,'RH',T15,'R',I2,T26,F7.1)
1300         CONTINUE
         ITOT3 = ITOT2 + 1
         ITOT4 = ITOT2 + ISEG3
           DO 1400 ICONST = ITOT3,ITOT4
             WRITE(8,1450) ICONST
1450          FORMAT(4X,'RH',T15,'R',I3,T33,'0.')
1400          CONTINUE
              ITOT5 = ITOT4 + 1
              ITOT6 = ISEG1 + ISEG2 + ISEG3 + ISEG4
           DO 1500 ICONST = ITOT5,ITOT6
              IF (ICONST.GT.99) GOTO 1556
             WRITE(8,1550) ICONST
C  NOMINAL MACHINE CAPACITY IS 480 MINUTES.  OUTPUT SHOULD BE
C  ADJUSTED FOR THOSE MACHINES SHARED BY TWO DEPARTMENTS.  THEN,
C  DATA OF THIS PROGRAM SHOULD INCLUDE TWO MACHINES WITH 240 MINUTES
C  OF CAPACITY EACH.
1550          FORMAT(4X,'RH',T15,'R',I2,T30,'480.')
                   GOTO 1500
1556          WRITE(8,1559) ICONST
1559          FORMAT(4X,'RH',T15,'R',I3,T30,'480.')
1500           CONTINUE
        WRITE(7,1800)
        WRITE(8,1800)
1800 FORMAT('BOUNDS                                         ',
    *'                  ')
       RETURN
       END
C
C      ************************************************************
        SUBROUTINE BOUNDS(NUMJOB,NAME,DEMAND)
C
       CHARACTER*1 NAME(10),MN,MK,QT,STAR,SLASH
       DIMENSION DEMAND(12)
C
       QT=''''
       STAR='*'
       SLASH='/'
         DO 1000 IJOB = 1,NUMJOB
             MN = NAME(IJOB)
             WRITE(8,1200) MN,DEMAND(IJOB)
1200          FORMAT(' UP',1X,'BOUD',6X,'UD',A1,12X,F5.0)
1000         CONTINUE
       WRITE(7,3300)
```

```
      WRITE(8,3300)
 3300 FORMAT('ENDATA                                              ',
     *'                 ')
      WRITE(8,6000) SLASH,STAR
 6000 FORMAT(2A1)
      WRITE(8,8000) SLASH,SLASH
 8000 FORMAT(2A1)
         RETURN
         END
0       C$ENTRY
0STATEMENTS EXECUTED=    10890
0CORE USAGE      OBJECT CODE=    14464 BYTES
1DIAGNOSTICS       NUMBER OF ERRORS=       0
0COMPILE TIME=      2.61 SEC,EXECUTION TIME=      1.78 SEC
-       C$STOP
```

Appendix K. Machine Times Needed for Processing Unit Loads

Following data is obtained by running code UNIT FORTRAN shown in Appendix J. Only partial results are given below because complete listings are too long and repetetive.

Problem Set No.1 for Functional Facility:

Full output has 326 records or unique combinations.

```
SET 1 CLASS 1 MACH P JOB A  UNIT  1 TIME =    41.5 MINUTES
SET 1 CLASS 1 MACH P JOB A  UNIT  2 TIME =    67.9 MINUTES
SET 1 CLASS 1 MACH P JOB A  UNIT  3 TIME =    93.2 MINUTES
......................................................
SET 1 CLASS 1 MACH P JOB A  UNIT 10 TIME =   260.8 MINUTES
SET 1 CLASS 1 MACH P JOB B  UNIT  1 TIME =    36.6 MINUTES
SET 1 CLASS 1 MACH P JOB B  UNIT  2 TIME =    58.1 MINUTES
......................................................
SET 1 CLASS 1 MACH P JOB B  UNIT 15 TIME =   331.9 MINUTES
SET 1 CLASS 1 MACH P JOB C  UNIT  1 TIME =    41.0 MINUTES
SET 1 CLASS 1 MACH P JOB C  UNIT  2 TIME =    65.8 MINUTES
......................................................
SET 1 CLASS 1 MACH P JOB C  UNIT 18 TIME =   457.8 MINUTES
SET 1 CLASS 1 MACH J JOB A  UNIT  1 TIME =    31.2 MINUTES
SET 1 CLASS 1 MACH J JOB A  UNIT  2 TIME =    54.3 MINUTES
......................................................
SET 1 CLASS 1 MACH J JOB A  UNIT 10 TIME =   233.0 MINUTES
SET 1 CLASS 1 MACH J JOB B  UNIT  1 TIME =    26.1 MINUTES
......................................................
SET 1 CLASS 1 MACH J JOB B  UNIT 15 TIME =   289.4 MINUTES
```

SET 1 CLASS 1 MACH J JOB C UNIT 1 TIME = 30.5 MINUTES
....
SET 1 CLASS 1 MACH J JOB C UNIT 18 TIME = 408.2 MINUTES
SET 1 CLASS 2 MACH P JOB B UNIT 1 TIME = 37.0 MINUTES
SET 1 CLASS 2 MACH P JOB B UNIT 15 TIME = 382.7 MINUTES
SET 1 CLASS 2 MACH P JOB C UNIT 1 TIME = 29.0 MINUTES
....
SET 1 CLASS 2 MACH P JOB C UNIT 18 TIME = 300.5 MINUTES
SET 1 CLASS 2 MACH P JOB D UNIT 1 TIME = 36.0 MINUTES
SET 1 CLASS 2 MACH P JOB D UNIT 2 TIME = 60.0 MINUTES
SET 1 CLASS 2 MACH P JOB D UNIT 19 TIME = 452.8 MINUTES
SET 1 CLASS 3 MACH K JOB A UNIT 1 TIME = 50.4 MINUTES
....
SET 1 CLASS 3 MACH K JOB A UNIT 10 TIME = 373.0 MINUTES
SET 1 CLASS 3 MACH K JOB D UNIT 1 TIME = 54.0 MINUTES
SET 1 CLASS 3 MACH K JOB D UNIT 2 TIME = 95.0 MINUTES
....
SET 1 CLASS 3 MACH K JOB D UNIT 19 TIME = 791.0 MINUTES
SET 1 CLASS 3 MACH N JOB A UNIT 1 TIME = 58.0 MINUTES
SET 1 CLASS 3 MACH N JOB A UNIT 9 TIME = 392.2 MINUTES
SET 1 CLASS 3 MACH N JOB A UNIT 10 TIME = 412.9 MINUTES
SET 1 CLASS 3 MACH N JOB D UNIT 1 TIME = 62.3 MINUTES
....
SET 1 CLASS 3 MACH N JOB D UNIT 18 TIME = 846.7 MINUTES
SET 1 CLASS 3 MACH N JOB D UNIT 19 TIME = 878.2 MINUTES
SET 1 CLASS 4 MACH J JOB A UNIT 1 TIME = 33.4 MINUTES
SET 1 CLASS 4 MACH J JOB A UNIT 2 TIME = 56.5 MINUTES
....
SET 1 CLASS 4 MACH J JOB A UNIT 9 TIME = 223.0 MINUTES
SET 1 CLASS 4 MACH J JOB A UNIT 10 TIME = 235.1 MINUTES
....
SET 1 CLASS 4 MACH J JOB C UNIT 17 TIME = 453.6 MINUTES
SET 1 CLASS 4 MACH J JOB C UNIT 18 TIME = 466.4 MINUTES
SET 1 CLASS 5 MACH K JOB A UNIT 8 TIME = 583.3 MINUTES
....
SET 1 CLASS 5 MACH K JOB A UNIT 10 TIME = 689.0 MINUTES
SET 1 CLASS 5 MACH K JOB B UNIT 1 TIME = 79.7 MINUTES
....
SET 1 CLASS 5 MACH K JOB B UNIT 15 TIME = 1115.8 MINUTES
SET 1 CLASS 5 MACH N JOB A UNIT 1 TIME = 93.2 MINUTES
....
SET 1 CLASS 5 MACH N JOB A UNIT 9 TIME = 726.7 MINUTES
SET 1 CLASS 5 MACH N JOB A UNIT 10 TIME = 764.3 MINUTES
SET 1 CLASS 5 MACH N JOB B UNIT 1 TIME = 94.3 MINUTES
....
SET 1 CLASS 5 MACH N JOB B UNIT 15 TIME = 1222.6 MINUTES
SET 1 CLASS 6 MACH N JOB C UNIT 1 TIME = 34.5 MINUTES
....
SET 1 CLASS 6 MACH N JOB C UNIT 18 TIME = 458.8 MINUTES
SET 1 CLASS 6 MACH N JOB D UNIT 17 TIME = 486.0 MINUTES
SET 1 CLASS 6 MACH N JOB D UNIT 18 TIME = 515.2 MINUTES
SET 1 CLASS 6 MACH N JOB D UNIT 19 TIME = 534.1 MINUTES
SET 1 CLASS 7 MACH P JOB B UNIT 1 TIME = 54.1 MINUTES
....
SET 1 CLASS 7 MACH P JOB B UNIT 15 TIME = 601.4 MINUTES

Problem Set No.2 for Functional Facility:

Full output has 1174 records or unique combinations, so only sample is listed below.

```
SET 2 CLASS 1 MACH P JOB A  UNIT  1 TIME =   40.6 MINUTES
.......................................................
SET 2 CLASS 1 MACH P JOB A  UNIT 10 TIME =  259.6 MINUTES
SET 2 CLASS 1 MACH P JOB B  UNIT  1 TIME =   35.7 MINUTES
.......................................................
SET 2 CLASS 1 MACH P JOB B  UNIT 14 TIME =  309.1 MINUTES
SET 2 CLASS 1 MACH P JOB B  UNIT 15 TIME =  330.5 MINUTES
SET 2 CLASS 1 MACH P JOB C  UNIT  1 TIME =   40.1 MINUTES
.......................................................
SET 2 CLASS 1 MACH P JOB C  UNIT 18 TIME =  456.4 MINUTES
SET 2 CLASS 1 MACH P JOB E  UNIT  1 TIME =   25.5 MINUTES
SET 2 CLASS 1 MACH P JOB E  UNIT  2 TIME =   35.7 MINUTES
.......................................................
SET 2 CLASS 1 MACH P JOB E  UNIT 27 TIME =  298.9 MINUTES
SET 2 CLASS 1 MACH P JOB E  UNIT 28 TIME =  304.0 MINUTES
SET 2 CLASS 1 MACH P JOB F  UNIT  1 TIME =   43.2 MINUTES
SET 2 CLASS 1 MACH P JOB F  UNIT  2 TIME =   71.1 MINUTES
.......................................................
SET 2 CLASS 1 MACH P JOB F  UNIT 13 TIME =  373.8 MINUTES
SET 2 CLASS 1 MACH P JOB H  UNIT  1 TIME =   26.8 MINUTES
SET 2 CLASS 1 MACH P JOB H  UNIT  2 TIME =   38.3 MINUTES
.......................................................
SET 2 CLASS 1 MACH P JOB H  UNIT 24 TIME =  297.4 MINUTES
SET 2 CLASS 1 MACH J JOB A  UNIT  1 TIME =   30.7 MINUTES
SET 2 CLASS 1 MACH J JOB A  UNIT  2 TIME =   53.8 MINUTES
.......................................................
SET 2 CLASS 1 MACH J JOB A  UNIT  9 TIME =  220.1 MINUTES
SET 2 CLASS 1 MACH J JOB A  UNIT 10 TIME =  232.2 MINUTES
SET 2 CLASS 1 MACH J JOB B  UNIT  1 TIME =   25.6 MINUTES
SET 2 CLASS 1 MACH J JOB B  UNIT  2 TIME =   43.6 MINUTES
SET 2 CLASS 1 MACH J JOB B  UNIT  3 TIME =   63.2 MINUTES
SET 2 CLASS 1 MACH J JOB B  UNIT 13 TIME =  250.8 MINUTES
.......................................................
SET 2 CLASS 1 MACH J JOB B  UNIT 15 TIME =  288.4 MINUTES
SET 2 CLASS 1 MACH J JOB C  UNIT  1 TIME =   30.0 MINUTES
SET 2 CLASS 1 MACH J JOB C  UNIT  2 TIME =   52.4 MINUTES
.......................................................
SET 2 CLASS 1 MACH J JOB C  UNIT 18 TIME =  407.3 MINUTES
SET 2 CLASS 1 MACH J JOB E  UNIT  1 TIME =   16.6 MINUTES
SET 2 CLASS 1 MACH J JOB E  UNIT  2 TIME =   25.6 MINUTES
.......................................................
SET 2 CLASS 1 MACH J JOB E  UNIT 27 TIME =  259.8 MINUTES
SET 2 CLASS 1 MACH J JOB E  UNIT 28 TIME =  264.3 MINUTES
SET 2 CLASS 1 MACH J JOB F  UNIT  1 TIME =   32.8 MINUTES
.......................................................
SET 2 CLASS 1 MACH J JOB F  UNIT 13 TIME =  333.0 MINUTES
SET 2 CLASS 1 MACH J JOB H  UNIT  1 TIME =   18.1 MINUTES
SET 2 CLASS 1 MACH J JOB H  UNIT  2 TIME =   28.6 MINUTES
.......................................................
SET 2 CLASS 1 MACH J JOB H  UNIT 24 TIME =  265.8 MINUTES
SET 2 CLASS 1 MACH Z JOB A  UNIT  1 TIME =   38.7 MINUTES
SET 2 CLASS 1 MACH Z JOB A  UNIT  2 TIME =   67.2 MINUTES
.......................................................
```

SET 2 CLASS 1 MACH Z JOB A UNIT 10 TIME = 278.4 MINUTES
SET 2 CLASS 1 MACH Z JOB B UNIT 1 TIME = 32.8 MINUTES
SET 2 CLASS 1 MACH Z JOB B UNIT 2 TIME = 55.4 MINUTES
....
SET 2 CLASS 1 MACH Z JOB B UNIT 14 TIME = 324.8 MINUTES
SET 2 CLASS 1 MACH Z JOB B UNIT 15 TIME = 347.5 MINUTES
SET 2 CLASS 1 MACH Z JOB C UNIT 1 TIME = 36.8 MINUTES
....
SET 2 CLASS 1 MACH Z JOB C UNIT 17 TIME = 455.6 MINUTES
SET 2 CLASS 1 MACH Z JOB C UNIT 18 TIME = 468.4 MINUTES
SET 2 CLASS 1 MACH Z JOB E UNIT 1 TIME = 22.0 MINUTES
SET 2 CLASS 1 MACH Z JOB E UNIT 2 TIME = 32.8 MINUTES
....
SET 2 CLASS 1 MACH Z JOB E UNIT 28 TIME = 319.4 MINUTES
SET 2 CLASS 1 MACH Z JOB F UNIT 1 TIME = 40.0 MINUTES
SET 2 CLASS 1 MACH Z JOB F UNIT 2 TIME = 69.8 MINUTES
....
SET 2 CLASS 2 MACH W JOB D UNIT 1 TIME = 33.7 MINUTES
....
SET 2 CLASS 2 MACH W JOB D UNIT 19 TIME = 491.5 MINUTES
SET 2 CLASS 2 MACH W JOB H UNIT 1 TIME = 21.2 MINUTES
SET 2 CLASS 2 MACH W JOB H UNIT 2 TIME = 33.7 MINUTES
....
SET 2 CLASS 2 MACH W JOB H UNIT 23 TIME = 305.3 MINUTES
SET 2 CLASS 2 MACH W JOB H UNIT 24 TIME = 317.8 MINUTES
SET 2 CLASS 3 MACH K JOB A UNIT 1 TIME = 49.6 MINUTES
....
SET 2 CLASS 3 MACH K JOB A UNIT 10 TIME = 372.0 MINUTES
SET 2 CLASS 3 MACH K JOB D UNIT 1 TIME = 53.2 MINUTES
....
SET 2 CLASS 3 MACH K JOB D UNIT 19 TIME = 789.6 MINUTES
SET 2 CLASS 3 MACH K JOB E UNIT 1 TIME = 32.6 MINUTES
....
SET 2 CLASS 3 MACH K JOB E UNIT 28 TIME = 582.4 MINUTES
SET 2 CLASS 3 MACH K JOB F UNIT 1 TIME = 42.8 MINUTES
....
SET 2 CLASS 3 MACH K JOB F UNIT 13 TIME = 406.0 MINUTES
SET 2 CLASS 3 MACH N JOB A UNIT 1 TIME = 57.0 MINUTES
....
SET 2 CLASS 3 MACH N JOB A UNIT 10 TIME = 411.3 MINUTES
SET 2 CLASS 3 MACH N JOB D UNIT 1 TIME = 61.3 MINUTES
....
SET 2 CLASS 3 MACH N JOB D UNIT 19 TIME = 876.2 MINUTES
SET 2 CLASS 3 MACH N JOB E UNIT 1 TIME = 38.5 MINUTES
....
SET 2 CLASS 3 MACH N JOB E UNIT 27 TIME = 632.0 MINUTES
SET 2 CLASS 3 MACH N JOB E UNIT 28 TIME = 643.1 MINUTES
SET 2 CLASS 3 MACH N JOB F UNIT 13 TIME = 448.3 MINUTES
SET 2 CLASS 3 MACH W JOB A UNIT 1 TIME = 47.2 MINUTES
....
SET 2 CLASS 3 MACH W JOB A UNIT 10 TIME = 391.2 MINUTES
SET 2 CLASS 3 MACH W JOB D UNIT 1 TIME = 51.6 MINUTES
SET 2 CLASS 3 MACH W JOB D UNIT 2 TIME = 97.2 MINUTES
....
SET 2 CLASS 3 MACH W JOB D UNIT 19 TIME = 845.7 MINUTES
SET 2 CLASS 3 MACH W JOB E UNIT 1 TIME = 29.2 MINUTES

SET 2 CLASS 3 MACH W JOB E UNIT 2 TIME = 50.8 MINUTES
....
SET 2 CLASS 3 MACH W JOB E UNIT 28 TIME = 615.4 MINUTES
SET 2 CLASS 3 MACH W JOB F UNIT 1 TIME = 40.0 MINUTES
SET 2 CLASS 3 MACH W JOB F UNIT 2 TIME = 74.0 MINUTES
....
SET 2 CLASS 3 MACH W JOB F UNIT 4 TIME = 140.3 MINUTES
SET 2 CLASS 4 MACH J JOB A UNIT 1 TIME = 32.8 MINUTES
SET 2 CLASS 4 MACH J JOB A UNIT 2 TIME = 55.9 MINUTES
....
SET 2 CLASS 4 MACH J JOB A UNIT 10 TIME = 234.2 MINUTES
SET 2 CLASS 4 MACH J JOB C UNIT 1 TIME = 35.3 MINUTES
SET 2 CLASS 4 MACH J JOB C UNIT 18 TIME = 465.3 MINUTES
SET 2 CLASS 4 MACH J JOB H UNIT 1 TIME = 20.2 MINUTES
SET 2 CLASS 4 MACH J JOB H UNIT 2 TIME = 30.7 MINUTES
....
SET 2 CLASS 4 MACH J JOB H UNIT 24 TIME = 267.8 MINUTES
SET 2 CLASS 4 MACH W JOB A UNIT 1 TIME = 44.8 MINUTES
....
SET 2 CLASS 4 MACH W JOB A UNIT 10 TIME = 286.5 MINUTES
SET 2 CLASS 4 MACH W JOB C UNIT 1 TIME = 46.9 MINUTES
....
SET 2 CLASS 4 MACH W JOB C UNIT 18 TIME = 547.6 MINUTES
SET 2 CLASS 4 MACH W JOB H UNIT 1 TIME = 29.8 MINUTES
SET 2 CLASS 4 MACH W JOB H UNIT 2 TIME = 42.3 MINUTES
SET 2 CLASS 4 MACH W JOB H UNIT 3 TIME = 54.8 MINUTES
....
SET 2 CLASS 4 MACH W JOB H UNIT 23 TIME = 314.0 MINUTES
SET 2 CLASS 4 MACH W JOB H UNIT 24 TIME = 326.5 MINUTES
SET 2 CLASS 5 MACH K JOB A UNIT 1 TIME = 77.6 MINUTES
....
SET 2 CLASS 5 MACH K JOB A UNIT 10 TIME = 688.2 MINUTES
SET 2 CLASS 5 MACH K JOB B UNIT 1 TIME = 79.3 MINUTES
SET 2 CLASS 5 MACH K JOB B UNIT 2 TIME = 152.5 MINUTES
....
SET 2 CLASS 5 MACH K JOB F UNIT 1 TIME = 61.0 MINUTES
SET 2 CLASS 5 MACH K JOB F UNIT 2 TIME = 115.9 MINUTES
SET 2 CLASS 5 MACH K JOB F UNIT 12 TIME = 671.0 MINUTES
SET 2 CLASS 5 MACH K JOB F UNIT 13 TIME = 707.6 MINUTES
SET 2 CLASS 5 MACH K JOB H UNIT 1 TIME = 38.6 MINUTES
SET 2 CLASS 5 MACH K JOB H UNIT 2 TIME = 71.1 MINUTES
SET 2 CLASS 6 MACH N JOB E UNIT 27 TIME = 365.7 MINUTES
SET 2 CLASS 6 MACH N JOB E UNIT 28 TIME = 372.0 MINUTES
SET 2 CLASS 6 MACH N JOB F UNIT 1 TIME = 37.1 MINUTES
....
SET 2 CLASS 6 MACH N JOB F UNIT 13 TIME = 372.8 MINUTES
SET 2 CLASS 6 MACH N JOB H UNIT 1 TIME = 24.7 MINUTES
SET 2 CLASS 6 MACH N JOB H UNIT 2 TIME = 40.2 MINUTES
....
SET 2 CLASS 6 MACH N JOB H UNIT 24 TIME = 393.4 MINUTES
SET 2 CLASS 6 MACH Z JOB C UNIT 1 TIME = 37.3 MINUTES
SET 2 CLASS 6 MACH Z JOB C UNIT 2 TIME = 62.3 MINUTES
....
SET 2 CLASS 6 MACH Z JOB C UNIT 17 TIME = 430.4 MINUTES
SET 2 CLASS 6 MACH Z JOB C UNIT 18 TIME = 442.4 MINUTES
SET 2 CLASS 6 MACH Z JOB D UNIT 1 TIME = 38.3 MINUTES

```
......................................................
SET 2 CLASS 6 MACH Z JOB D  UNIT 19 TIME =   493.0 MINUTES
SET 2 CLASS 6 MACH Z JOB E  UNIT  1 TIME =   25.3 MINUTES
SET 2 CLASS 6 MACH Z JOB E  UNIT  2 TIME =   37.3 MINUTES
......................................................
SET 2 CLASS 6 MACH Z JOB E  UNIT 28 TIME =   354.5 MINUTES
SET 2 CLASS 6 MACH Z JOB F  UNIT  1 TIME =   40.3 MINUTES
SET 2 CLASS 6 MACH Z JOB F  UNIT  2 TIME =   68.3 MINUTES
......................................................
SET 2 CLASS 6 MACH Z JOB F  UNIT 13 TIME =   362.4 MINUTES
SET 2 CLASS 6 MACH Z JOB H  UNIT  1 TIME =   28.3 MINUTES
......................................................
SET 2 CLASS 6 MACH Z JOB H  UNIT 24 TIME =   381.4 MINUTES
SET 2 CLASS 7 MACH P JOB B  UNIT  1 TIME =   53.2 MINUTES
......................................................
SET 2 CLASS 7 MACH P JOB B  UNIT 15 TIME =   600.0 MINUTES
SET 2 CLASS 7 MACH P JOB F  UNIT  1 TIME =   43.6 MINUTES
SET 2 CLASS 7 MACH P JOB F  UNIT  2 TIME =   72.4 MINUTES
SET 2 CLASS 7 MACH P JOB F  UNIT 12 TIME =   365.5 MINUTES
SET 2 CLASS 7 MACH P JOB F  UNIT 13 TIME =   384.7 MINUTES
SET 2 CLASS 7 MACH Z JOB B  UNIT  1 TIME =   51.5 MINUTES
SET 2 CLASS 7 MACH Z JOB B  UNIT  2 TIME =   89.7 MINUTES
......................................................
SET 2 CLASS 7 MACH Z JOB B  UNIT 15 TIME =   584.5 MINUTES
SET 2 CLASS 7 MACH Z JOB F  UNIT  1 TIME =   42.2 MINUTES
SET 2 CLASS 7 MACH Z JOB F  UNIT  2 TIME =   71.1 MINUTES
......................................................
SET 2 CLASS 7 MACH Z JOB F  UNIT 12 TIME =   356.2 MINUTES
SET 2 CLASS 7 MACH Z JOB F  UNIT 13 TIME =   374.8 MINUTES
```

Problem Set No.3 for Functional Facility:

The output given below has 1634 records or unique combinations. A very small segment of it is listed below.

```
SET 3 CLASS 1 MACH P JOB A  UNIT  1 TIME =   40.9 MINUTES
SET 3 CLASS 1 MACH P JOB A  UNIT  2 TIME =   67.2 MINUTES
......................................................

......................................................

......................................................
SET 3 CLASS 1 MACH P JOB Q  UNIT  9 TIME =   121.2 MINUTES
SET 3 CLASS 1 MACH P JOB Q  UNIT 10 TIME =   132.7 MINUTES
......................................................
SET 3 CLASS 1 MACH P JOB R  UNIT  1 TIME =   24.8 MINUTES
......................................................

......................................................
SET 3 CLASS 1 MACH J JOB C  UNIT 18 TIME =   407.6 MINUTES
......................................................
SET 3 CLASS 1 MACH J JOB E  UNIT  1 TIME =   16.8 MINUTES
SET 3 CLASS 1 MACH Z JOB B  UNIT 12 TIME =   280.0 MINUTES
......................................................
SET 3 CLASS 1 MACH Z JOB B  UNIT 14 TIME =   325.3 MINUTES
......................................................

......................................................
```

SET 3 CLASS 1 MACH Z JOB C UNIT 2 TIME = 63.7 MINUTES
SET 3 CLASS 2 MACH P JOB B UNIT 8 TIME = 208.6 MINUTES

....

....

....

....

SET 3 CLASS 3 MACH K JOB E UNIT 14 TIME = 302.8 MINUTES
SET 3 CLASS 3 MACH K JOB E UNIT 15 TIME = 323.2 MINUTES

....

....

SET 3 CLASS 3 MACH N JOB Q UNIT 16 TIME = 289.0 MINUTES
SET 3 CLASS 3 MACH W JOB R UNIT 15 TIME = 276.5 MINUTES

....

SET 3 CLASS 3 MACH W JOB R UNIT 17 TIME = 298.5 MINUTES

....

SET 3 CLASS 5 MACH K JOB B UNIT 14 TIME = 1040.4 MINUTES

....

SET 3 CLASS 5 MACH K JOB F UNIT 1 TIME = 61.1 MINUTES

....

SET 3 CLASS 5 MACH N JOB H UNIT 14 TIME = 517.8 MINUTES

....

....

SET 3 CLASS 5 MACH N JOB H UNIT 17 TIME = 626.4 MINUTES

....

....

SET 3 CLASS 6 MACH N JOB H UNIT 24 TIME = 393.8 MINUTES

....

SET 3 CLASS 6 MACH N JOB R UNIT 1 TIME = 21.8 MINUTES
SET 3 CLASS 6 MACH N JOB R UNIT 2 TIME = 34.2 MINUTES

....

SET 3 CLASS 6 MACH Z JOB D UNIT 5 TIME = 141.6 MINUTES

....

....

SET 3 CLASS 6 MACH Z JOB D UNIT 8 TIME = 218.7 MINUTES

....

SET 3 CLASS 7 MACH P JOB B UNIT 11 TIME = 443.7 MINUTES
SET 3 CLASS 7 MACH P JOB B UNIT 12 TIME = 483.2 MINUTES

....

SET 3 CLASS 7 MACH Z JOB Q UNIT 9 TIME = 157.2 MINUTES

....

SET 3 CLASS 7 MACH Z JOB S UNIT 1 TIME = 33.2 MINUTES

....

SET 3 CLASS 7 MACH Z JOB S UNIT 3 TIME = 71.4 MINUTES

....

SET 3 CLASS 7 MACH Z JOB S UNIT 8 TIME = 166.5 MINUTES
SET 3 CLASS 7 MACH Z JOB S UNIT 9 TIME = 172.7 MINUTES

Problem Set No.4 for Functional Facility:
Full set has 2129 records or unique combinations.

SET 4 CLASS 1 MACH P JOB A UNIT 1 TIME = 41.2 MINUTES
SET 4 CLASS 1 MACH P JOB A UNIT 2 TIME = 67.6 MINUTES
SET 4 CLASS 1 MACH P JOB A UNIT 3 TIME = 92.9 MINUTES

....

SET 4 CLASS 4 MACH J JOB U UNIT 9 TIME = 262.1 MINUTES
SET 4 CLASS 4 MACH J JOB U UNIT 10 TIME = 291.0 MINUTES

SET 4 CLASS 4 MACH J JOB U UNIT 11 TIME = 318.3 MINUTES

....

SET 4 CLASS 4 MACH W JOB H UNIT 18 TIME = 251.0 MINUTES
SET 4 CLASS 4 MACH W JOB H UNIT 19 TIME = 263.5 MINUTES
SET 4 CLASS 4 MACH W JOB H UNIT 20 TIME = 276.0 MINUTES
SET 4 CLASS 4 MACH W JOB H UNIT 21 TIME = 288.5 MINUTES

....

SET 4 CLASS 5 MACH K JOB A UNIT 3 TIME = 222.4 MINUTES
SET 4 CLASS 5 MACH K JOB A UNIT 4 TIME = 293.9 MINUTES
SET 4 CLASS 5 MACH K JOB A UNIT 5 TIME = 367.0 MINUTES
SET 4 CLASS 5 MACH K JOB A UNIT 6 TIME = 438.5 MINUTES
SET 4 CLASS 5 MACH K JOB A UNIT 7 TIME = 511.6 MINUTES

....

SET 4 CLASS 5 MACH K JOB R UNIT 6 TIME = 174.4 MINUTES
SET 4 CLASS 5 MACH K JOB R UNIT 7 TIME = 203.9 MINUTES
SET 4 CLASS 5 MACH K JOB R UNIT 8 TIME = 231.9 MINUTES
SET 4 CLASS 5 MACH K JOB R UNIT 9 TIME = 259.9 MINUTES

....

SET 4 CLASS 5 MACH N JOB A UNIT 9 TIME = 726.2 MINUTES
SET 4 CLASS 5 MACH N JOB A UNIT 10 TIME = 763.8 MINUTES
SET 4 CLASS 5 MACH N JOB B UNIT 1 TIME = 94.0 MINUTES
SET 4 CLASS 5 MACH N JOB B UNIT 2 TIME = 175.4 MINUTES
SET 4 CLASS 5 MACH N JOB B UNIT 3 TIME = 254.6 MINUTES

....

SET 4 CLASS 5 MACH N JOB R UNIT 12 TIME = 369.5 MINUTES
SET 4 CLASS 5 MACH N JOB R UNIT 13 TIME = 398.7 MINUTES
SET 4 CLASS 5 MACH N JOB R UNIT 14 TIME = 427.9 MINUTES

....

SET 4 CLASS 5 MACH T JOB H UNIT 17 TIME = 549.3 MINUTES
SET 4 CLASS 5 MACH T JOB H UNIT 18 TIME = 580.8 MINUTES
SET 4 CLASS 5 MACH T JOB H UNIT 19 TIME = 614.4 MINUTES
SET 4 CLASS 6 MACH N JOB E UNIT 1 TIME = 22.1 MINUTES
SET 4 CLASS 6 MACH N JOB E UNIT 2 TIME = 34.7 MINUTES
SET 4 CLASS 6 MACH N JOB E UNIT 3 TIME = 47.3 MINUTES

....

SET 4 CLASS 6 MACH N JOB H UNIT 20 TIME = 330.1 MINUTES
SET 4 CLASS 6 MACH N JOB H UNIT 21 TIME = 345.6 MINUTES
SET 4 CLASS 6 MACH N JOB H UNIT 22 TIME = 361.1 MINUTES
SET 4 CLASS 6 MACH N JOB H UNIT 23 TIME = 376.6 MINUTES

....

SET 4 CLASS 6 MACH Z JOB D UNIT 7 TIME = 193.0 MINUTES
SET 4 CLASS 6 MACH Z JOB D UNIT 8 TIME = 219.1 MINUTES
SET 4 CLASS 6 MACH Z JOB D UNIT 9 TIME = 245.1 MINUTES

....

SET 4 CLASS 6 MACH Z JOB E UNIT 15 TIME = 200.1 MINUTES
SET 4 CLASS 6 MACH Z JOB E UNIT 16 TIME = 212.1 MINUTES
SET 4 CLASS 6 MACH Z JOB E UNIT 17 TIME = 224.1 MINUTES
SET 4 CLASS 6 MACH Z JOB E UNIT 18 TIME = 237.2 MINUTES
SET 4 CLASS 6 MACH Z JOB E UNIT 19 TIME = 249.2 MINUTES

....

SET 4 CLASS 6 MACH Z JOB R UNIT 7 TIME = 98.8 MINUTES
SET 4 CLASS 6 MACH Z JOB R UNIT 8 TIME = 111.9 MINUTES
SET 4 CLASS 6 MACH Z JOB R UNIT 9 TIME = 123.9 MINUTES
SET 4 CLASS 6 MACH Z JOB R UNIT 10 TIME = 135.9 MINUTES

....

SET 4 CLASS 7 MACH P JOB F UNIT 10 TIME = 307.6 MINUTES

SET 4 CLASS 7 MACH P JOB F UNIT 11 TIME = 336.4 MINUTES
SET 4 CLASS 7 MACH P JOB F UNIT 12 TIME = 366.3 MINUTES
SET 4 CLASS 7 MACH P JOB F UNIT 13 TIME = 385.5 MINUTES
SET 4 CLASS 7 MACH P JOB Q UNIT 1 TIME = 31.4 MINUTES
SET 4 CLASS 7 MACH P JOB Q UNIT 2 TIME = 47.4 MINUTES

....

SET 4 CLASS 7 MACH P JOB V UNIT 10 TIME = 567.8 MINUTES
SET 4 CLASS 7 MACH P JOB V UNIT 11 TIME = 623.3 MINUTES
SET 4 CLASS 7 MACH P JOB V UNIT 12 TIME = 678.8 MINUTES
SET 4 CLASS 7 MACH P JOB V UNIT 13 TIME = 734.2 MINUTES

....

SET 4 CLASS 7 MACH T JOB B UNIT 5 TIME = 174.7 MINUTES
SET 4 CLASS 7 MACH T JOB B UNIT 6 TIME = 209.2 MINUTES
SET 4 CLASS 7 MACH T JOB B UNIT 7 TIME = 241.6 MINUTES
SET 4 CLASS 7 MACH T JOB B UNIT 8 TIME = 276.2 MINUTES
SET 4 CLASS 7 MACH T JOB B UNIT 9 TIME = 308.6 MINUTES
SET 4 CLASS 7 MACH T JOB B UNIT 10 TIME = 343.1 MINUTES

....

SET 4 CLASS 7 MACH T JOB F UNIT 3 TIME = 83.5 MINUTES
SET 4 CLASS 7 MACH T JOB F UNIT 4 TIME = 107.8 MINUTES
SET 4 CLASS 7 MACH T JOB F UNIT 5 TIME = 132.1 MINUTES
SET 4 CLASS 7 MACH T JOB F UNIT 6 TIME = 158.5 MINUTES
SET 4 CLASS 7 MACH T JOB F UNIT 7 TIME = 182.8 MINUTES

....

SET 4 CLASS 7 MACH T JOB Q UNIT 5 TIME = 78.1 MINUTES
SET 4 CLASS 7 MACH T JOB Q UNIT 6 TIME = 91.6 MINUTES
SET 4 CLASS 7 MACH T JOB Q UNIT 7 TIME = 105.1 MINUTES
SET 4 CLASS 7 MACH T JOB Q UNIT 8 TIME = 118.6 MINUTES
SET 4 CLASS 7 MACH T JOB Q UNIT 9 TIME = 132.1 MINUTES
SET 4 CLASS 7 MACH T JOB Q UNIT 10 TIME = 147.7 MINUTES
SET 4 CLASS 7 MACH T JOB Q UNIT 11 TIME = 161.2 MINUTES

....

SET 4 CLASS 7 MACH T JOB S UNIT 3 TIME = 57.1 MINUTES
SET 4 CLASS 7 MACH T JOB S UNIT 4 TIME = 75.4 MINUTES
SET 4 CLASS 7 MACH T JOB S UNIT 5 TIME = 91.6 MINUTES
SET 4 CLASS 7 MACH T JOB S UNIT 6 TIME = 107.8 MINUTES
SET 4 CLASS 7 MACH T JOB S UNIT 7 TIME = 124.0 MINUTES
SET 4 CLASS 7 MACH T JOB S UNIT 8 TIME = 142.3 MINUTES
SET 4 CLASS 7 MACH T JOB S UNIT 9 TIME = 147.7 MINUTES

....

SET 4 CLASS 7 MACH T JOB V UNIT 8 TIME = 386.3 MINUTES
SET 4 CLASS 7 MACH T JOB V UNIT 9 TIME = 434.3 MINUTES
SET 4 CLASS 7 MACH T JOB V UNIT 10 TIME = 482.3 MINUTES
SET 4 CLASS 7 MACH T JOB V UNIT 11 TIME = 530.3 MINUTES
SET 4 CLASS 7 MACH T JOB V UNIT 12 TIME = 576.2 MINUTES
SET 4 CLASS 7 MACH T JOB V UNIT 13 TIME = 624.3 MINUTES
SET 4 CLASS 7 MACH T JOB V UNIT 14 TIME = 672.3 MINUTES
SET 4 CLASS 7 MACH T JOB V UNIT 15 TIME = 693.3 MINUTES

Cellular Facility:

This section gives a brief summary of the results of UNIT FORTRAN when run for cellular case. It should be noted that number of records in each corressponding set will be higher for cellular case (except for set No.1) since the same job mix is divided into 2 and 3 cells (sets No.2 and 3) and 3 and 4 sets (set No.4).

Problem Set No.1 for Cellular Facility:
Full output has 326 combinations.

```
SET 1 CELL  1 CLASS 1 MAC P JOB A  UNIT  1  UNIT TIME =    37.3
SET 1 CELL  1 CLASS 1 MAC P JOB A  UNIT  2  UNIT TIME =    63.4
SET 1 CELL  1 CLASS 1 MAC P JOB A  UNIT  3  UNIT TIME =    88.7
.............................................................
.............................................................
.............................................................
SET 1 CELL  2 CLASS 1 MAC P JOB C  UNIT  8  UNIT TIME =   207.4
SET 1 CELL  2 CLASS 1 MAC P JOB C  UNIT  9  UNIT TIME =   232.2
SET 1 CELL  2 CLASS 1 MAC P JOB C  UNIT 10  UNIT TIME =   257.5
SET 1 CELL  2 CLASS 1 MAC P JOB C  UNIT 11  UNIT TIME =   282.3
.............................................................
.............................................................
SET 1 CELL  2 CLASS 3 MAC K JOB D  UNIT  8  UNIT TIME =   336.3
SET 1 CELL  2 CLASS 3 MAC K JOB D  UNIT  9  UNIT TIME =   377.3
SET 1 CELL  2 CLASS 3 MAC K JOB D  UNIT 10  UNIT TIME =   419.0
SET 1 CELL  2 CLASS 3 MAC K JOB D  UNIT 11  UNIT TIME =   460.0
SET 1 CELL  2 CLASS 4 MAC J JOB C  UNIT 12  UNIT TIME =   314.2
SET 1 CELL  2 CLASS 4 MAC J JOB C  UNIT 13  UNIT TIME =   340.5
.............................................................
SET 1 CELL  2 CLASS 6 MAC N JOB C  UNIT  9  UNIT TIME =   230.7
SET 1 CELL  2 CLASS 6 MAC N JOB C  UNIT 10  UNIT TIME =   256.5
SET 1 CELL  2 CLASS 6 MAC N JOB C  UNIT 11  UNIT TIME =   281.3
.............................................................
SET 1 CELL  2 CLASS 6 MAC N JOB C  UNIT 13  UNIT TIME =   331.9
.............................................................
.............................................................
SET 1 CELL  2 CLASS 6 MAC N JOB D  UNIT 14  UNIT TIME =   389.5
SET 1 CELL  2 CLASS 6 MAC N JOB D  UNIT 15  UNIT TIME =   416.5
SET 1 CELL  2 CLASS 6 MAC N JOB D  UNIT 16  UNIT TIME =   444.5
SET 1 CELL  2 CLASS 6 MAC N JOB D  UNIT 17  UNIT TIME =   471.5
SET 1 CELL  2 CLASS 6 MAC N JOB D  UNIT 18  UNIT TIME =   499.5
SET 1 CELL  2 CLASS 6 MAC N JOB D  UNIT 19  UNIT TIME =   518.4
```

Problem Set No.2 for Cellular Facility:
Full output has 2348 combinations.

SET 2 CELL 1 CLASS 1 MAC P JOB A UNIT 1 UNIT TIME = 36.7
SET 2 CELL 1 CLASS 1 MAC P JOB A UNIT 2 UNIT TIME = 62.8
SET 2 CELL 1 CLASS 1 MAC P JOB A UNIT 3 UNIT TIME = 88.1
....
SET 2 CELL 1 CLASS 1 MAC J JOB H UNIT 17 UNIT TIME = 187.6
SET 2 CELL 1 CLASS 1 MAC J JOB H UNIT 18 UNIT TIME = 198.1
SET 2 CELL 1 CLASS 1 MAC J JOB H UNIT 19 UNIT TIME = 208.6
....

....
SET 2 CELL 1 CLASS 5 MAC K JOB H UNIT 5 UNIT TIME = 168.2
SET 2 CELL 1 CLASS 5 MAC K JOB H UNIT 6 UNIT TIME = 200.7
....
SET 2 CELL 2 CLASS 1 MAC Z JOB E UNIT 27 UNIT TIME = 301.3
SET 2 CELL 2 CLASS 1 MAC Z JOB E UNIT 28 UNIT TIME = 307.1
SET 2 CELL 2 CLASS 2 MAC P JOB C UNIT 1 UNIT TIME = 21.5
SET 2 CELL 2 CLASS 2 MAC P JOB C UNIT 2 UNIT TIME = 37.5
....
SET 2 CELL 2 CLASS 2 MAC W JOB D UNIT 5 UNIT TIME = 130.3
SET 2 CELL 2 CLASS 2 MAC W JOB D UNIT 6 UNIT TIME = 156.0
SET 2 CELL 2 CLASS 2 MAC W JOB D UNIT 7 UNIT TIME = 181.0
SET 2 CELL 2 CLASS 2 MAC W JOB D UNIT 8 UNIT TIME = 206.7
SET 2 CELL 2 CLASS 2 MAC W JOB D UNIT 9 UNIT TIME = 232.4
SET 2 CELL 2 CLASS 2 MAC W JOB D UNIT 10 UNIT TIME = 257.4
SET 2 CELL 2 CLASS 2 MAC W JOB D UNIT 11 UNIT TIME = 283.0
....
SET 2 CELL 2 CLASS 3 MAC K JOB E UNIT 20 UNIT TIME = 416.3
SET 2 CELL 2 CLASS 3 MAC K JOB E UNIT 21 UNIT TIME = 437.4
SET 2 CELL 2 CLASS 3 MAC K JOB E UNIT 22 UNIT TIME = 457.8
....
SET 2 CELL 2 CLASS 3 MAC W JOB D UNIT 5 UNIT TIME = 224.8
SET 2 CELL 2 CLASS 3 MAC W JOB D UNIT 6 UNIT TIME = 269.5
SET 2 CELL 2 CLASS 3 MAC W JOB D UNIT 7 UNIT TIME = 313.5
....
SET 2 CELL 2 CLASS 6 MAC N JOB C UNIT 4 UNIT TIME = 104.3
SET 2 CELL 2 CLASS 6 MAC N JOB C UNIT 5 UNIT TIME = 130.0
SET 2 CELL 2 CLASS 6 MAC N JOB C UNIT 6 UNIT TIME = 154.8
SET 2 CELL 2 CLASS 6 MAC N JOB C UNIT 7 UNIT TIME = 179.6
....
SET 2 CELL 3 CLASS 1 MAC P JOB F UNIT 10 UNIT TIME = 293.8
SET 2 CELL 3 CLASS 1 MAC P JOB F UNIT 11 UNIT TIME = 321.7
SET 2 CELL 3 CLASS 1 MAC P JOB F UNIT 12 UNIT TIME = 350.4
SET 2 CELL 3 CLASS 1 MAC P JOB F UNIT 13 UNIT TIME = 369.0
SET 2 CELL 3 CLASS 1 MAC J JOB A UNIT 1 UNIT TIME = 28.9
....
SET 2 CELL 3 CLASS 2 MAC W JOB B UNIT 1 UNIT TIME = 31.8
SET 2 CELL 3 CLASS 2 MAC W JOB B UNIT 2 UNIT TIME = 58.2
SET 2 CELL 3 CLASS 2 MAC W JOB B UNIT 3 UNIT TIME = 84.6
....
SET 2 CELL 3 CLASS 3 MAC W JOB F UNIT 1 UNIT TIME = 38.2
SET 2 CELL 3 CLASS 3 MAC W JOB F UNIT 2 UNIT TIME = 71.8
SET 2 CELL 3 CLASS 3 MAC W JOB F UNIT 3 UNIT TIME = 104.2
....
SET 2 CELL 3 CLASS 5 MAC N JOB B UNIT 13 UNIT TIME = 1051.4

SET 2 CELL 3 CLASS 5 MAC N JOB B UNIT 14 UNIT TIME = 1132.2
SET 2 CELL 3 CLASS 5 MAC N JOB B UNIT 15 UNIT TIME = 1213.0
SET 2 CELL 3 CLASS 5 MAC N JOB F UNIT 1 UNIT TIME = 70.3
SET 2 CELL 3 CLASS 5 MAC N JOB F UNIT 2 UNIT TIME = 129.7
SET 2 CELL 3 CLASS 5 MAC N JOB F UNIT 3 UNIT TIME = 190.7
....
SET 2 CELL 3 CLASS 7 MAC Z JOB F UNIT 12 UNIT TIME = 351.2
SET 2 CELL 3 CLASS 7 MAC Z JOB F UNIT 13 UNIT TIME = 369.8
SET 2 CELL 4 CLASS 1 MAC P JOB C UNIT 1 UNIT TIME = 42.5
SET 2 CELL 4 CLASS 1 MAC P JOB C UNIT 2 UNIT TIME = 67.3
SET 2 CELL 4 CLASS 1 MAC P JOB C UNIT 3 UNIT TIME = 93.3
SET 2 CELL 4 CLASS 1 MAC P JOB C UNIT 4 UNIT TIME = 118.1
SET 2 CELL 4 CLASS 1 MAC P JOB C UNIT 5 UNIT TIME = 144.1
....
SET 2 CELL 4 CLASS 1 MAC J JOB H UNIT 3 UNIT TIME = 40.3
SET 2 CELL 4 CLASS 1 MAC J JOB H UNIT 4 UNIT TIME = 50.8
SET 2 CELL 4 CLASS 1 MAC J JOB H UNIT 5 UNIT TIME = 63.1
SET 2 CELL 4 CLASS 1 MAC J JOB H UNIT 6 UNIT TIME = 73.6
SET 2 CELL 4 CLASS 1 MAC J JOB H UNIT 7 UNIT TIME = 84.1
SET 2 CELL 4 CLASS 1 MAC J JOB H UNIT 8 UNIT TIME = 94.6
SET 2 CELL 4 CLASS 1 MAC J JOB H UNIT 9 UNIT TIME = 105.1
SET 2 CELL 4 CLASS 1 MAC J JOB H UNIT 10 UNIT TIME = 117.4
SET 2 CELL 4 CLASS 1 MAC J JOB H UNIT 11 UNIT TIME = 127.9
....
SET 2 CELL 4 CLASS 2 MAC P JOB C UNIT 3 UNIT TIME = 63.3
SET 2 CELL 4 CLASS 2 MAC P JOB C UNIT 4 UNIT TIME = 79.3
SET 2 CELL 4 CLASS 2 MAC P JOB C UNIT 9 UNIT TIME = 161.7
....
SET 2 CELL 4 CLASS 5 MAC K JOB H UNIT 14 UNIT TIME = 465.6
SET 2 CELL 4 CLASS 5 MAC K JOB H UNIT 15 UNIT TIME = 499.9
....
SET 2 CELL 4 CLASS 6 MAC N JOB H UNIT 18 UNIT TIME = 299.1
SET 2 CELL 4 CLASS 6 MAC N JOB H UNIT 19 UNIT TIME = 314.6
SET 2 CELL 4 CLASS 6 MAC N JOB H UNIT 20 UNIT TIME = 332.4
SET 2 CELL 4 CLASS 6 MAC N JOB H UNIT 21 UNIT TIME = 347.9
SET 2 CELL 4 CLASS 6 MAC N JOB H UNIT 22 UNIT TIME = 363.4
SET 2 CELL 4 CLASS 6 MAC N JOB H UNIT 23 UNIT TIME = 378.9
SET 2 CELL 4 CLASS 6 MAC N JOB H UNIT 24 UNIT TIME = 396.8
SET 2 CELL 4 CLASS 6 MAC Z JOB C UNIT 1 UNIT TIME = 39.3
SET 2 CELL 4 CLASS 6 MAC Z JOB C UNIT 2 UNIT TIME = 64.5
SET 2 CELL 4 CLASS 6 MAC Z JOB C UNIT 3 UNIT TIME = 88.5
SET 2 CELL 4 CLASS 6 MAC Z JOB C UNIT 4 UNIT TIME = 113.7
....
SET 2 CELL 5 CLASS 1 MAC J JOB E UNIT 3 UNIT TIME = 30.9
SET 2 CELL 5 CLASS 1 MAC J JOB E UNIT 4 UNIT TIME = 39.9
SET 2 CELL 5 CLASS 1 MAC J JOB E UNIT 5 UNIT TIME = 49.7
SET 2 CELL 5 CLASS 1 MAC J JOB E UNIT 6 UNIT TIME = 58.7
SET 2 CELL 5 CLASS 1 MAC J JOB E UNIT 7 UNIT TIME = 67.7
SET 2 CELL 5 CLASS 1 MAC J JOB E UNIT 8 UNIT TIME = 76.7
....
SET 2 CELL 5 CLASS 2 MAC P JOB D UNIT 10 UNIT TIME = 238.8
SET 2 CELL 5 CLASS 2 MAC P JOB D UNIT 11 UNIT TIME = 261.8
SET 2 CELL 5 CLASS 2 MAC P JOB D UNIT 12 UNIT TIME = 285.4
SET 2 CELL 5 CLASS 2 MAC P JOB D UNIT 13 UNIT TIME = 308.4
SET 2 CELL 5 CLASS 2 MAC P JOB D UNIT 14 UNIT TIME = 331.9
SET 2 CELL 5 CLASS 2 MAC P JOB D UNIT 15 UNIT TIME = 354.9

```
SET 2 CELL 5 CLASS 2 MAC P JOB D UNIT 16 UNIT TIME = 378.4
SET 2 CELL 5 CLASS 2 MAC P JOB D UNIT 17 UNIT TIME = 401.4
SET 2 CELL 5 CLASS 2 MAC P JOB D UNIT 18 UNIT TIME = 424.9
............................................................
SET 2 CELL 5 CLASS 3 MAC N JOB D UNIT 2 UNIT TIME = 99.4
SET 2 CELL 5 CLASS 3 MAC N JOB D UNIT 3 UNIT TIME = 144.4
SET 2 CELL 5 CLASS 3 MAC N JOB D UNIT 4 UNIT TIME = 190.4
SET 2 CELL 5 CLASS 3 MAC N JOB D UNIT 5 UNIT TIME = 235.4
SET 2 CELL 5 CLASS 3 MAC N JOB D UNIT 6 UNIT TIME = 281.4
SET 2 CELL 5 CLASS 3 MAC N JOB D UNIT 7 UNIT TIME = 326.4
SET 2 CELL 5 CLASS 3 MAC N JOB D UNIT 8 UNIT TIME = 372.5
SET 2 CELL 5 CLASS 3 MAC N JOB D UNIT 9 UNIT TIME = 417.5
............................................................
SET 2 CELL 5 CLASS 3 MAC W JOB E UNIT 12 UNIT TIME = 266.2
SET 2 CELL 5 CLASS 3 MAC W JOB E UNIT 13 UNIT TIME = 287.8
SET 2 CELL 5 CLASS 3 MAC W JOB E UNIT 14 UNIT TIME = 309.4
SET 2 CELL 5 CLASS 3 MAC W JOB E UNIT 15 UNIT TIME = 331.8
SET 2 CELL 5 CLASS 3 MAC W JOB E UNIT 16 UNIT TIME = 353.4
SET 2 CELL 5 CLASS 3 MAC W JOB E UNIT 17 UNIT TIME = 375.0
SET 2 CELL 5 CLASS 3 MAC W JOB E UNIT 18 UNIT TIME = 397.4
............................................................
SET 2 CELL 5 CLASS 6 MAC N JOB E UNIT 18 UNIT TIME = 236.7
SET 2 CELL 5 CLASS 6 MAC N JOB E UNIT 19 UNIT TIME = 249.3
SET 2 CELL 5 CLASS 6 MAC N JOB E UNIT 20 UNIT TIME = 262.9
............................................................
```

Problem Set No.3 for Cellular Facility:

Full output has 3280 combinations.

```
SET 3 CELL 1 CLASS 1 MAC P JOB A UNIT 1 UNIT TIME = 38.8
SET 3 CELL 1 CLASS 1 MAC P JOB A UNIT 2 UNIT TIME = 65.0
SET 3 CELL 1 CLASS 1 MAC P JOB A UNIT 3 UNIT TIME = 90.3
............................................................
SET 3 CELL 2 CLASS 2 MAC W JOB C UNIT 16 UNIT TIME = 283.6
SET 3 CELL 2 CLASS 2 MAC W JOB C UNIT 17 UNIT TIME = 300.4
SET 3 CELL 2 CLASS 2 MAC W JOB C UNIT 18 UNIT TIME = 310.0
............................................................
SET 3 CELL 2 CLASS 4 MAC J JOB C UNIT 10 UNIT TIME = 266.9
SET 3 CELL 2 CLASS 4 MAC J JOB C UNIT 11 UNIT TIME = 292.5
SET 3 CELL 2 CLASS 4 MAC J JOB C UNIT 12 UNIT TIME = 318.1
SET 3 CELL 2 CLASS 4 MAC J JOB C UNIT 13 UNIT TIME = 344.9
............................................................
SET 3 CELL 2 CLASS 7 MAC P JOB S UNIT 1 UNIT TIME = 30.5
SET 3 CELL 2 CLASS 7 MAC P JOB S UNIT 2 UNIT TIME = 49.7
SET 3 CELL 2 CLASS 7 MAC P JOB S UNIT 3 UNIT TIME = 68.9
SET 3 CELL 2 CLASS 7 MAC P JOB S UNIT 4 UNIT TIME = 88.9
............................................................
SET 3 CELL 2 CLASS 7 MAC P JOB S UNIT 6 UNIT TIME = 127.3
SET 3 CELL 2 CLASS 7 MAC P JOB S UNIT 7 UNIT TIME = 147.3
SET 3 CELL 2 CLASS 7 MAC P JOB S UNIT 8 UNIT TIME = 166.5
SET 3 CELL 2 CLASS 7 MAC P JOB S UNIT 9 UNIT TIME = 172.9
SET 3 CELL 2 CLASS 7 MAC Z JOB Q UNIT 1 UNIT TIME = 26.4
............................................................
```

```
SET 3 CELL  3 CLASS 3 MAC W JOB Q  UNIT 12  UNIT TIME =    212.4
SET 3 CELL  3 CLASS 3 MAC W JOB Q  UNIT 13  UNIT TIME =    229.4
SET 3 CELL  3 CLASS 3 MAC W JOB Q  UNIT 14  UNIT TIME =    246.4
SET 3 CELL  3 CLASS 3 MAC W JOB Q  UNIT 15  UNIT TIME =    264.4
SET 3 CELL  3 CLASS 3 MAC W JOB Q  UNIT 16  UNIT TIME =    281.4
SET 3 CELL  3 CLASS 3 MAC W JOB Q  UNIT 17  UNIT TIME =    298.4
..............................................................
SET 3 CELL  3 CLASS 5 MAC K JOB B  UNIT 15  UNIT TIME =   1109.5
SET 3 CELL  3 CLASS 5 MAC K JOB F  UNIT  1  UNIT TIME =     59.1
SET 3 CELL  3 CLASS 5 MAC K JOB F  UNIT  2  UNIT TIME =    114.0
SET 3 CELL  3 CLASS 5 MAC K JOB F  UNIT  3  UNIT TIME =    169.9
SET 3 CELL  3 CLASS 5 MAC K JOB F  UNIT  4  UNIT TIME =    224.8
SET 3 CELL  3 CLASS 5 MAC K JOB F  UNIT  5  UNIT TIME =    279.7
..............................................................
SET 3 CELL  3 CLASS 5 MAC K JOB Q  UNIT 17  UNIT TIME =    559.8
SET 3 CELL  3 CLASS 5 MAC K JOB Q  UNIT 18  UNIT TIME =    592.3
..............................................................
SET 3 CELL  3 CLASS 7 MAC P JOB Q  UNIT 13  UNIT TIME =    220.2
SET 3 CELL  3 CLASS 7 MAC P JOB Q  UNIT 14  UNIT TIME =    236.2
SET 3 CELL  3 CLASS 7 MAC P JOB Q  UNIT 15  UNIT TIME =    252.2
..............................................................
SET 3 CELL  4 CLASS 1 MAC J JOB H  UNIT 14  UNIT TIME =    156.9
SET 3 CELL  4 CLASS 1 MAC J JOB H  UNIT 15  UNIT TIME =    168.8
SET 3 CELL  4 CLASS 1 MAC J JOB H  UNIT 16  UNIT TIME =    179.3
SET 3 CELL  4 CLASS 1 MAC J JOB H  UNIT 17  UNIT TIME =    189.8
SET 3 CELL  4 CLASS 1 MAC J JOB H  UNIT 18  UNIT TIME =    200.3
..............................................................
SET 3 CELL  4 CLASS 1 MAC Z JOB H  UNIT  1  UNIT TIME =     22.8
SET 3 CELL  4 CLASS 1 MAC Z JOB H  UNIT  2  UNIT TIME =     35.3
SET 3 CELL  4 CLASS 1 MAC Z JOB H  UNIT  3  UNIT TIME =     48.8
SET 3 CELL  4 CLASS 1 MAC Z JOB H  UNIT  4  UNIT TIME =     61.3
SET 3 CELL  4 CLASS 1 MAC Z JOB H  UNIT  5  UNIT TIME =     73.8
..............................................................
SET 3 CELL  4 CLASS 2 MAC P JOB C  UNIT 17  UNIT TIME =    288.9
SET 3 CELL  4 CLASS 2 MAC P JOB C  UNIT 18  UNIT TIME =    297.9
SET 3 CELL  4 CLASS 2 MAC P JOB H  UNIT  1  UNIT TIME =     22.8
SET 3 CELL  4 CLASS 2 MAC P JOB H  UNIT  2  UNIT TIME =     34.3
..............................................................
SET 3 CELL  4 CLASS 6 MAC N JOB C  UNIT  4  UNIT TIME =    109.5
SET 3 CELL  4 CLASS 6 MAC N JOB C  UNIT  5  UNIT TIME =    136.2
SET 3 CELL  4 CLASS 6 MAC N JOB C  UNIT  6  UNIT TIME =    161.0
SET 3 CELL  4 CLASS 6 MAC N JOB C  UNIT  7  UNIT TIME =    185.8
SET 3 CELL  4 CLASS 6 MAC N JOB C  UNIT  8  UNIT TIME =    212.5
..............................................................
SET 3 CELL  5 CLASS 3 MAC K JOB E  UNIT  9  UNIT TIME =    197.4
SET 3 CELL  5 CLASS 3 MAC K JOB E  UNIT 10  UNIT TIME =    217.8
SET 3 CELL  5 CLASS 3 MAC K JOB E  UNIT 11  UNIT TIME =    238.2
..............................................................
SET 3 CELL  5 CLASS 6 MAC N JOB R  UNIT 17  UNIT TIME =    215.3
SET 3 CELL  5 CLASS 6 MAC Z JOB D  UNIT  1  UNIT TIME =     37.0
SET 3 CELL  5 CLASS 6 MAC Z JOB D  UNIT  2  UNIT TIME =     62.9
SET 3 CELL  5 CLASS 6 MAC Z JOB D  UNIT  3  UNIT TIME =     88.8
..............................................................
```

Problem Set No.4 for Cellular Facility:

Full output has 4360 combinations.

```
SET 4 CELL  1 CLASS 1 MAC P JOB A  UNIT  1  UNIT TIME =    40.9
SET 4 CELL  1 CLASS 1 MAC P JOB A  UNIT  2  UNIT TIME =    67.2
SET 4 CELL  1 CLASS 1 MAC P JOB A  UNIT  3  UNIT TIME =    92.5
...........................................................
SET 4 CELL  1 CLASS 5 MAC N JOB H  UNIT 22  UNIT TIME =   806.0
SET 4 CELL  1 CLASS 5 MAC N JOB H  UNIT 23  UNIT TIME =   841.5
SET 4 CELL  1 CLASS 5 MAC N JOB H  UNIT 24  UNIT TIME =   879.0
...........................................................
SET 4 CELL  1 CLASS 5 MAC T JOB H  UNIT 22  UNIT TIME =   708.6
SET 4 CELL  1 CLASS 5 MAC T JOB H  UNIT 23  UNIT TIME =   742.2
SET 4 CELL  1 CLASS 5 MAC T JOB H  UNIT 24  UNIT TIME =   773.7
SET 4 CELL  1 CLASS 6 MAC N JOB D  UNIT  1  UNIT TIME =    36.4
...........................................................
SET 4 CELL  2 CLASS 4 MAC W JOB C  UNIT  4  UNIT TIME =   126.5
SET 4 CELL  2 CLASS 4 MAC W JOB C  UNIT  5  UNIT TIME =   156.8
SET 4 CELL  2 CLASS 4 MAC W JOB C  UNIT  6  UNIT TIME =   186.4
SET 4 CELL  2 CLASS 4 MAC W JOB C  UNIT  7  UNIT TIME =   216.7
SET 4 CELL  2 CLASS 4 MAC W JOB C  UNIT  8  UNIT TIME =   246.3
SET 4 CELL  2 CLASS 4 MAC W JOB C  UNIT  9  UNIT TIME =   276.5
...........................................................
SET 4 CELL  3 CLASS 1 MAC J JOB R  UNIT  3  UNIT TIME =    33.1
SET 4 CELL  3 CLASS 1 MAC J JOB R  UNIT  4  UNIT TIME =    41.6
SET 4 CELL  3 CLASS 1 MAC J JOB R  UNIT  5  UNIT TIME =    49.9
SET 4 CELL  3 CLASS 1 MAC J JOB R  UNIT  6  UNIT TIME =    58.4
...........................................................
SET 4 CELL  3 CLASS 3 MAC W JOB R  UNIT 10  UNIT TIME =   187.1
SET 4 CELL  3 CLASS 3 MAC W JOB R  UNIT 11  UNIT TIME =   204.7
SET 4 CELL  3 CLASS 3 MAC W JOB R  UNIT 12  UNIT TIME =   222.3
SET 4 CELL  3 CLASS 3 MAC W JOB R  UNIT 13  UNIT TIME =   239.9
...........................................................
SET 4 CELL  5 CLASS 2 MAC Y JOB S  UNIT  3  UNIT TIME =    50.8
SET 4 CELL  5 CLASS 2 MAC Y JOB S  UNIT  4  UNIT TIME =    67.0
SET 4 CELL  5 CLASS 2 MAC Y JOB S  UNIT  5  UNIT TIME =    84.3
...........................................................
SET 4 CELL  5 CLASS 3 MAC N JOB V  UNIT 13  UNIT TIME =  1011.2
SET 4 CELL  5 CLASS 3 MAC N JOB V  UNIT 14  UNIT TIME =  1087.7
SET 4 CELL  5 CLASS 3 MAC N JOB V  UNIT 15  UNIT TIME =  1120.1
SET 4 CELL  5 CLASS 3 MAC W JOB V  UNIT  1  UNIT TIME =    78.1
...........................................................
SET 4 CELL  6 CLASS 1 MAC P JOB E  UNIT 12  UNIT TIME =   139.0
SET 4 CELL  6 CLASS 1 MAC P JOB E  UNIT 13  UNIT TIME =   149.2
SET 4 CELL  6 CLASS 1 MAC P JOB E  UNIT 14  UNIT TIME =   160.3
SET 4 CELL  6 CLASS 1 MAC P JOB E  UNIT 15  UNIT TIME =   170.5
...........................................................
SET 4 CELL  6 CLASS 3 MAC K JOB D  UNIT  8  UNIT TIME =   343.2
SET 4 CELL  6 CLASS 3 MAC K JOB D  UNIT  9  UNIT TIME =   384.2
SET 4 CELL  6 CLASS 3 MAC K JOB D  UNIT 10  UNIT TIME =   426.6
SET 4 CELL  6 CLASS 3 MAC K JOB D  UNIT 11  UNIT TIME =   467.6
...........................................................
SET 4 CELL  7 CLASS 3 MAC K JOB Q  UNIT  1  UNIT TIME =    27.3
SET 4 CELL  7 CLASS 3 MAC K JOB Q  UNIT  2  UNIT TIME =    42.8
SET 4 CELL  7 CLASS 3 MAC K JOB Q  UNIT  3  UNIT TIME =    58.3
```

SET 4 CELL 7 CLASS 3 MAC K JOB Q UNIT 4 UNIT TIME = 73.8
SET 4 CELL 7 CLASS 3 MAC K JOB Q UNIT 5 UNIT TIME = 90.7
SET 4 CELL 7 CLASS 3 MAC K JOB Q UNIT 6 UNIT TIME = 106.2
SET 4 CELL 7 CLASS 3 MAC K JOB Q UNIT 7 UNIT TIME = 121.7
....
SET 4 CELL 7 CLASS 4 MAC W JOB U UNIT 8 UNIT TIME = 284.0
SET 4 CELL 7 CLASS 4 MAC W JOB U UNIT 9 UNIT TIME = 318.0
SET 4 CELL 7 CLASS 4 MAC W JOB U UNIT 10 UNIT TIME = 351.9
....
SET 4 CELL 7 CLASS 5 MAC T JOB Q UNIT 17 UNIT TIME = 548.2
SET 4 CELL 7 CLASS 5 MAC T JOB Q UNIT 18 UNIT TIME = 579.7
SET 4 CELL 7 CLASS 5 MAC T JOB Q UNIT 19 UNIT TIME = 613.2
SET 4 CELL 7 CLASS 6 MAC N JOB F UNIT 1 UNIT TIME = 36.7
....
SET 4 CELL 7 CLASS 7 MAC Z JOB F UNIT 10 UNIT TIME = 298.6
SET 4 CELL 7 CLASS 7 MAC Z JOB F UNIT 11 UNIT TIME = 326.5
SET 4 CELL 7 CLASS 7 MAC Z JOB F UNIT 12 UNIT TIME = 355.4
SET 4 CELL 7 CLASS 7 MAC Z JOB F UNIT 13 UNIT TIME = 374.0
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Partial Data of Operation Time Parameters Used in Simulation:

Parameters for functional and cellular cases of problem set No.4 are given below. Each line indicates mean and the standard deviation of operation time of simulation entity or specific unit load combination with respect to job, machine, and operation type. Those combinations which are in the other three problem sets, operation times are the the same.

Mean Operation Time and Standard Deviation Data for Problem Set No.4F:

SET 4 CLS 1 MC P JB A UNT 1 TIME = 25.3 MINS/ STD DEV. = 1.5 MINS
SET 4 CLS 1 MC P JB B UNT 1 TIME = 20.4 MINS/ STD DEV. = 1.2 MINS
SET 4 CLS 1 MC P JB C UNT 1 TIME = 24.8 MINS/ STD DEV. = 1.8 MINS
SET 4 CLS 1 MC P JB E UNT 1 TIME = 10.2 MINS/ STD DEV. = 0.8 MINS
SET 4 CLS 1 MC P JB F UNT 1 TIME = 27.9 MINS/ STD DEV. = 1.9 MINS
SET 4 CLS 1 MC P JB H UNT 1 TIME = 11.5 MINS/ STD DEV. = 1.0 MINS
SET 4 CLS 1 MC P JB Q UNT 1 TIME = 11.5 MINS/ STD DEV. = 1.0 MINS
SET 4 CLS 1 MC P JB R UNT 1 TIME = 9.2 MINS/ STD DEV. = 0.9 MINS
SET 4 CLS 1 MC J JB A UNT 1 TIME = 23.1 MINS/ STD DEV. = 1.4 MINS
SET 4 CLS 1 MC J JB B UNT 1 TIME = 18.0 MINS/ STD DEV. = 1.0 MINS
SET 4 CLS 1 MC J JB C UNT 1 TIME = 22.4 MINS/ STD DEV. = 1.6 MINS
SET 4 CLS 1 MC J JB E UNT 1 TIME = 9.0 MINS/ STD DEV. = 0.7 MINS
SET 4 CLS 1 MC J JB F UNT 1 TIME = 25.2 MINS/ STD DEV. = 1.7 MINS
SET 4 CLS 1 MC J JB H UNT 1 TIME = 10.5 MINS/ STD DEV. = 0.9 MINS
SET 4 CLS 1 MC J JB Q UNT 1 TIME = 10.5 MINS/ STD DEV. = 0.9 MINS
SET 4 CLS 1 MC J JB R UNT 1 TIME = 8.4 MINS/ STD DEV. = 0.8 MINS
SET 4 CLS 1 MC Z JB A UNT 1 TIME = 27.5 MINS/ STD DEV. = 1.7 MINS
SET 4 CLS 1 MC Z JB B UNT 1 TIME = 21.6 MINS/ STD DEV. = 1.2 MINS
SET 4 CLS 1 MC Z JB C UNT 1 TIME = 25.6 MINS/ STD DEV. = 1.8 MINS

SET 4 CLS 1 MC Z JB E UNT 1 TIME = 10.8 MINS/ STD DEV. = 0.9 MINS
SET 4 CLS 1 MC Z JB F UNT 1 TIME = 28.8 MINS/ STD DEV. = 1.9 MINS
SET 4 CLS 1 MC Z JB H UNT 1 TIME = 12.5 MINS/ STD DEV. = 1.1 MINS
SET 4 CLS 1 MC Z JB Q UNT 1 TIME = 12.5 MINS/ STD DEV. = 1.1 MINS
SET 4 CLS 1 MC Z JB R UNT 1 TIME = 10.0 MINS/ STD DEV. = 1.0 MINS
SET 4 CLS 2 MC P JB B UNT 1 TIME = 24.0 MINS/ STD DEV. = 1.4 MINS
SET 4 CLS 2 MC P JB C UNT 1 TIME = 16.0 MINS/ STD DEV. = 1.1 MINS
SET 4 CLS 2 MC P JB D UNT 1 TIME = 23.0 MINS/ STD DEV. = 1.5 MINS
SET 4 CLS 2 MC P JB H UNT 1 TIME = 11.5 MINS/ STD DEV. = 1.0 MINS
SET 4 CLS 2 MC P JB R UNT 1 TIME = 8.0 MINS/ STD DEV. = 0.8 MINS
SET 4 CLS 2 MC P JB S UNT 1 TIME = 12.0 MINS/ STD DEV. = 1.0 MINS
SET 4 CLS 2 MC P JB U UNT 1 TIME = 36.4 MINS/ STD DEV. = 2.0 MINS
SET 4 CLS 2 MC P JB V UNT 1 TIME = 39.1 MINS/ STD DEV. = 1.9 MINS
SET 4 CLS 2 MC W JB B UNT 1 TIME = 25.2 MINS/ STD DEV. = 1.5 MINS
SET 4 CLS 2 MC W JB C UNT 1 TIME = 16.8 MINS/ STD DEV. = 1.2 MINS
SET 4 CLS 2 MC W JB D UNT 1 TIME = 25.0 MINS/ STD DEV. = 1.6 MINS
SET 4 CLS 2 MC W JB H UNT 1 TIME = 12.5 MINS/ STD DEV. = 1.1 MINS
SET 4 CLS 2 MC W JB R UNT 1 TIME = 8.4 MINS/ STD DEV. = 0.8 MINS
SET 4 CLS 2 MC W JB S UNT 1 TIME = 12.6 MINS/ STD DEV. = 1.0 MINS
SET 4 CLS 2 MC W JB U UNT 1 TIME = 40.3 MINS/ STD DEV. = 2.2 MINS
SET 4 CLS 2 MC W JB V UNT 1 TIME = 42.5 MINS/ STD DEV. = 2.1 MINS
SET 4 CLS 2 MC Y JB B UNT 1 TIME = 32.4 MINS/ STD DEV. = 1.9 MINS
SET 4 CLS 2 MC Y JB C UNT 1 TIME = 21.6 MINS/ STD DEV. = 1.5 MINS
SET 4 CLS 2 MC Y JB D UNT 1 TIME = 29.0 MINS/ STD DEV. = 1.8 MINS
SET 4 CLS 2 MC Y JB H UNT 1 TIME = 14.5 MINS/ STD DEV. = 1.3 MINS
SET 4 CLS 2 MC Y JB R UNT 1 TIME = 10.8 MINS/ STD DEV. = 1.1 MINS
SET 4 CLS 2 MC Y JB S UNT 1 TIME = 16.2 MINS/ STD DEV. = 1.3 MINS
SET 4 CLS 2 MC Y JB U UNT 1 TIME = 41.6 MINS/ STD DEV. = 2.3 MINS
SET 4 CLS 2 MC Y JB V UNT 1 TIME = 49.3 MINS/ STD DEV. = 2.4 MINS
SET 4 CLS 3 MC K JB A UNT 1 TIME = 37.4 MINS/ STD DEV. = 2.3 MINS
SET 4 CLS 3 MC K JB D UNT 1 TIME = 41.0 MINS/ STD DEV. = 2.6 MINS
SET 4 CLS 3 MC K JB E UNT 1 TIME = 20.4 MINS/ STD DEV. = 1.7 MINS
SET 4 CLS 3 MC K JB F UNT 1 TIME = 30.6 MINS/ STD DEV. = 2.0 MINS
SET 4 CLS 3 MC K JB Q UNT 1 TIME = 15.5 MINS/ STD DEV. = 1.4 MINS
SET 4 CLS 3 MC K JB R UNT 1 TIME = 16.4 MINS/ STD DEV. = 1.6 MINS
SET 4 CLS 3 MC K JB V UNT 1 TIME = 69.7 MINS/ STD DEV. = 3.4 MINS
SET 4 CLS 3 MC N JB A UNT 1 TIME = 40.7 MINS/ STD DEV. = 2.5 MINS
SET 4 CLS 3 MC N JB D UNT 1 TIME = 45.0 MINS/ STD DEV. = 2.8 MINS
SET 4 CLS 3 MC N JB E UNT 1 TIME = 22.2 MINS/ STD DEV. = 1.8 MINS
SET 4 CLS 3 MC N JB F UNT 1 TIME = 33.3 MINS/ STD DEV. = 2.2 MINS
SET 4 CLS 3 MC N JB Q UNT 1 TIME = 16.5 MINS/ STD DEV. = 1.5 MINS
SET 4 CLS 3 MC N JB R UNT 1 TIME = 18.0 MINS/ STD DEV. = 1.8 MINS
SET 4 CLS 3 MC N JB V UNT 1 TIME = 76.5 MINS/ STD DEV. = 3.7 MINS
SET 4 CLS 3 MC W JB A UNT 1 TIME = 39.6 MINS/ STD DEV. = 2.4 MINS
SET 4 CLS 3 MC W JB D UNT 1 TIME = 44.0 MINS/ STD DEV. = 2.8 MINS
SET 4 CLS 3 MC W JB E UNT 1 TIME = 21.6 MINS/ STD DEV. = 1.8 MINS
SET 4 CLS 3 MC W JB F UNT 1 TIME = 32.4 MINS/ STD DEV. = 2.2 MINS
SET 4 CLS 3 MC W JB Q UNT 1 TIME = 17.0 MINS/ STD DEV. = 1.5 MINS
SET 4 CLS 3 MC W JB R UNT 1 TIME = 17.6 MINS/ STD DEV. = 1.8 MINS
SET 4 CLS 3 MC W JB V UNT 1 TIME = 74.8 MINS/ STD DEV. = 3.6 MINS
SET 4 CLS 4 MC J JB A UNT 1 TIME = 23.1 MINS/ STD DEV. = 1.4 MINS
SET 4 CLS 4 MC J JB C UNT 1 TIME = 25.6 MINS/ STD DEV. = 1.8 MINS
SET 4 CLS 4 MC J JB H UNT 1 TIME = 10.5 MINS/ STD DEV. = 0.9 MINS
SET 4 CLS 4 MC J JB S UNT 1 TIME = 19.2 MINS/ STD DEV. = 1.6 MINS
SET 4 CLS 4 MC J JB U UNT 1 TIME = 27.3 MINS/ STD DEV. = 1.5 MINS
SET 4 CLS 4 MC J JB V UNT 1 TIME = 54.4 MINS/ STD DEV. = 2.6 MINS

SET 4 CLS 4 MC W JB A UNT 1 TIME = 27.5 MINS/ STD DEV. = 1.7 MINS
SET 4 CLS 4 MC W JB C UNT 1 TIME = 29.6 MINS/ STD DEV. = 2.1 MINS
SET 4 CLS 4 MC W JB H UNT 1 TIME = 12.5 MINS/ STD DEV. = 1.1 MINS
SET 4 CLS 4 MC W JB S UNT 1 TIME = 22.2 MINS/ STD DEV. = 1.8 MINS
SET 4 CLS 4 MC W JB U UNT 1 TIME = 32.5 MINS/ STD DEV. = 1.8 MINS
SET 4 CLS 4 MC W JB V UNT 1 TIME = 62.9 MINS/ STD DEV. = 3.1 MINS
SET 4 CLS 5 MC K JB A UNT 1 TIME = 71.5 MINS/ STD DEV. = 4.3 MINS
SET 4 CLS 5 MC K JB B UNT 1 TIME = 73.2 MINS/ STD DEV. = 4.2 MINS
SET 4 CLS 5 MC K JB F UNT 1 TIME = 54.9 MINS/ STD DEV. = 3.7 MINS
SET 4 CLS 5 MC K JB H UNT 1 TIME = 32.5 MINS/ STD DEV. = 2.9 MINS
SET 4 CLS 5 MC K JB Q UNT 1 TIME = 32.5 MINS/ STD DEV. = 2.9 MINS
SET 4 CLS 5 MC K JB R UNT 1 TIME = 28.0 MINS/ STD DEV. = 2.8 MINS
SET 4 CLS 5 MC N JB A UNT 1 TIME = 78.1 MINS/ STD DEV. = 4.7 MINS
SET 4 CLS 5 MC N JB B UNT 1 TIME = 79.2 MINS/ STD DEV. = 4.6 MINS
SET 4 CLS 5 MC N JB F UNT 1 TIME = 59.4 MINS/ STD DEV. = 4.0 MINS
SET 4 CLS 5 MC N JB H UNT 1 TIME = 35.5 MINS/ STD DEV. = 3.2 MINS
SET 4 CLS 5 MC N JB Q UNT 1 TIME = 35.5 MINS/ STD DEV. = 3.2 MINS
SET 4 CLS 5 MC N JB R UNT 1 TIME = 29.2 MINS/ STD DEV. = 2.9 MINS
SET 4 CLS 5 MC T JB A UNT 1 TIME = 69.3 MINS/ STD DEV. = 4.2 MINS
SET 4 CLS 5 MC T JB B UNT 1 TIME = 68.4 MINS/ STD DEV. = 3.9 MINS
SET 4 CLS 5 MC T JB F UNT 1 TIME = 51.3 MINS/ STD DEV. = 3.4 MINS
SET 4 CLS 5 MC T JB H UNT 1 TIME = 31.5 MINS/ STD DEV. = 2.8 MINS
SET 4 CLS 5 MC T JB Q UNT 1 TIME = 31.5 MINS/ STD DEV. = 2.8 MINS
SET 4 CLS 5 MC T JB R UNT 1 TIME = 27.2 MINS/ STD DEV. = 2.7 MINS
SET 4 CLS 6 MC N JB C UNT 1 TIME = 24.8 MINS/ STD DEV. = 1.8 MINS
SET 4 CLS 6 MC N JB D UNT 1 TIME = 27.0 MINS/ STD DEV. = 1.7 MINS
SET 4 CLS 6 MC N JB E UNT 1 TIME = 12.6 MINS/ STD DEV. = 1.0 MINS
SET 4 CLS 6 MC N JB F UNT 1 TIME = 27.9 MINS/ STD DEV. = 1.9 MINS
SET 4 CLS 6 MC N JB H UNT 1 TIME = 15.5 MINS/ STD DEV. = 1.4 MINS
SET 4 CLS 6 MC N JB R UNT 1 TIME = 12.4 MINS/ STD DEV. = 1.2 MINS
SET 4 CLS 6 MC N JB S UNT 1 TIME = 16.2 MINS/ STD DEV. = 1.3 MINS
SET 4 CLS 6 MC N JB U UNT 1 TIME = 40.3 MINS/ STD DEV. = 2.2 MINS
SET 4 CLS 6 MC Z JB C UNT 1 TIME = 24.0 MINS/ STD DEV. = 1.7 MINS
SET 4 CLS 6 MC Z JB D UNT 1 TIME = 25.0 MINS/ STD DEV. = 1.6 MINS
SET 4 CLS 6 MC Z JB E UNT 1 TIME = 12.0 MINS/ STD DEV. = 1.0 MINS
SET 4 CLS 6 MC Z JB F UNT 1 TIME = 27.0 MINS/ STD DEV. = 1.8 MINS
SET 4 CLS 6 MC Z JB H UNT 1 TIME = 15.0 MINS/ STD DEV. = 1.3 MINS
SET 4 CLS 6 MC Z JB R UNT 1 TIME = 12.0 MINS/ STD DEV. = 1.2 MINS
SET 4 CLS 6 MC Z JB S UNT 1 TIME = 15.0 MINS/ STD DEV. = 1.2 MINS
SET 4 CLS 6 MC Z JB U UNT 1 TIME = 39.0 MINS/ STD DEV. = 2.2 MINS
SET 4 CLS 7 MC P JB B UNT 1 TIME = 38.4 MINS/ STD DEV. = 2.2 MINS
SET 4 CLS 7 MC P JB F UNT 1 TIME = 28.8 MINS/ STD DEV. = 1.9 MINS
SET 4 CLS 7 MC P JB Q UNT 1 TIME = 16.0 MINS/ STD DEV. = 1.4 MINS
SET 4 CLS 7 MC P JB S UNT 1 TIME = 19.2 MINS/ STD DEV. = 1.6 MINS
SET 4 CLS 7 MC P JB V UNT 1 TIME = 54.4 MINS/ STD DEV. = 2.6 MINS
SET 4 CLS 7 MC Z JB B UNT 1 TIME = 37.2 MINS/ STD DEV. = 2.1 MINS
SET 4 CLS 7 MC Z JB F UNT 1 TIME = 27.9 MINS/ STD DEV. = 1.9 MINS
SET 4 CLS 7 MC Z JB Q UNT 1 TIME = 15.5 MINS/ STD DEV. = 1.4 MINS
SET 4 CLS 7 MC Z JB S UNT 1 TIME = 18.6 MINS/ STD DEV. = 1.5 MINS
SET 4 CLS 7 MC Z JB V UNT 1 TIME = 52.7 MINS/ STD DEV. = 2.6 MINS
SET 4 CLS 7 MC T JB B UNT 1 TIME = 32.4 MINS/ STD DEV. = 1.9 MINS
SET 4 CLS 7 MC T JB F UNT 1 TIME = 24.3 MINS/ STD DEV. = 1.6 MINS
SET 4 CLS 7 MC T JB Q UNT 1 TIME = 13.5 MINS/ STD DEV. = 1.2 MINS
SET 4 CLS 7 MC T JB S UNT 1 TIME = 16.2 MINS/ STD DEV. = 1.3 MINS
SET 4 CLS 7 MC T JB V UNT 1 TIME = 45.9 MINS/ STD DEV. = 2.2 MINS

Mean Operation Time and Standard Deviation Data for Problem Set No.4C:

SET 4 CL 1 CLS 1 MC P JB A UNT 1 MEAN = 25.3 MINS/ STD DEV. = 1.5 MINS
SET 4 CL 1 CLS 1 MC P JB B UNT 1 MEAN = 20.4 MINS/ STD DEV. = 1.2 MINS
SET 4 CL 1 CLS 1 MC P JB H UNT 1 MEAN = 11.5 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 1 CLS 1 MC J JB A UNT 1 MEAN = 23.1 MINS/ STD DEV. = 1.4 MINS
SET 4 CL 1 CLS 1 MC J JB B UNT 1 MEAN = 18.0 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 1 CLS 1 MC J JB H UNT 1 MEAN = 10.5 MINS/ STD DEV. = 0.9 MINS
SET 4 CL 1 CLS 1 MC Z JB A UNT 1 MEAN = 27.5 MINS/ STD DEV. = 1.7 MINS
SET 4 CL 1 CLS 1 MC Z JB B UNT 1 MEAN = 21.6 MINS/ STD DEV. = 1.2 MINS
SET 4 CL 1 CLS 1 MC Z JB H UNT 1 MEAN = 12.5 MINS/ STD DEV. = 1.1 MINS
SET 4 CL 1 CLS 2 MC P JB B UNT 1 MEAN = 24.0 MINS/ STD DEV. = 1.4 MINS
SET 4 CL 1 CLS 2 MC P JB D UNT 1 MEAN = 23.0 MINS/ STD DEV. = 1.5 MINS
SET 4 CL 1 CLS 2 MC P JB H UNT 1 MEAN = 11.5 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 1 CLS 2 MC W JB B UNT 1 MEAN = 25.2 MINS/ STD DEV. = 1.5 MINS
SET 4 CL 1 CLS 2 MC W JB D UNT 1 MEAN = 25.0 MINS/ STD DEV. = 1.6 MINS
SET 4 CL 1 CLS 2 MC W JB H UNT 1 MEAN = 12.5 MINS/ STD DEV. = 1.1 MINS
SET 4 CL 1 CLS 2 MC Y JB B UNT 1 MEAN = 32.4 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 1 CLS 2 MC Y JB D UNT 1 MEAN = 29.0 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 1 CLS 2 MC Y JB H UNT 1 MEAN = 14.5 MINS/ STD DEV. = 1.3 MINS
SET 4 CL 1 CLS 3 MC K JB A UNT 1 MEAN = 37.4 MINS/ STD DEV. = 2.3 MINS
SET 4 CL 1 CLS 3 MC K JB D UNT 1 MEAN = 41.0 MINS/ STD DEV. = 2.6 MINS
SET 4 CL 1 CLS 3 MC N JB A UNT 1 MEAN = 40.7 MINS/ STD DEV. = 2.5 MINS
SET 4 CL 1 CLS 3 MC N JB D UNT 1 MEAN = 45.0 MINS/ STD DEV. = 2.8 MINS
SET 4 CL 1 CLS 3 MC W JB A UNT 1 MEAN = 39.6 MINS/ STD DEV. = 2.4 MINS
SET 4 CL 1 CLS 3 MC W JB D UNT 1 MEAN = 44.0 MINS/ STD DEV. = 2.8 MINS
SET 4 CL 1 CLS 4 MC J JB A UNT 1 MEAN = 23.1 MINS/ STD DEV. = 1.4 MINS
SET 4 CL 1 CLS 4 MC J JB H UNT 1 MEAN = 10.5 MINS/ STD DEV. = 0.9 MINS
SET 4 CL 1 CLS 4 MC W JB A UNT 1 MEAN = 27.5 MINS/ STD DEV. = 1.7 MINS
SET 4 CL 1 CLS 4 MC W JB H UNT 1 MEAN = 12.5 MINS/ STD DEV. = 1.1 MINS
SET 4 CL 1 CLS 5 MC K JB A UNT 1 MEAN = 71.5 MINS/ STD DEV. = 4.3 MINS
SET 4 CL 1 CLS 5 MC K JB B UNT 1 MEAN = 73.2 MINS/ STD DEV. = 4.2 MINS
SET 4 CL 1 CLS 5 MC K JB H UNT 1 MEAN = 32.5 MINS/ STD DEV. = 2.9 MINS
SET 4 CL 1 CLS 5 MC N JB A UNT 1 MEAN = 78.1 MINS/ STD DEV. = 4.7 MINS
SET 4 CL 1 CLS 5 MC N JB B UNT 1 MEAN = 79.2 MINS/ STD DEV. = 4.6 MINS
SET 4 CL 1 CLS 5 MC N JB H UNT 1 MEAN = 35.5 MINS/ STD DEV. = 3.2 MINS
SET 4 CL 1 CLS 5 MC T JB A UNT 1 MEAN = 69.3 MINS/ STD DEV. = 4.2 MINS
SET 4 CL 1 CLS 5 MC T JB B UNT 1 MEAN = 68.4 MINS/ STD DEV. = 3.9 MINS
SET 4 CL 1 CLS 5 MC T JB H UNT 1 MEAN = 31.5 MINS/ STD DEV. = 2.8 MINS
SET 4 CL 1 CLS 6 MC N JB D UNT 1 MEAN = 27.0 MINS/ STD DEV. = 1.7 MINS
SET 4 CL 1 CLS 6 MC N JB H UNT 1 MEAN = 15.5 MINS/ STD DEV. = 1.4 MINS
SET 4 CL 1 CLS 6 MC Z JB D UNT 1 MEAN = 25.0 MINS/ STD DEV. = 1.6 MINS
SET 4 CL 1 CLS 6 MC Z JB H UNT 1 MEAN = 15.0 MINS/ STD DEV. = 1.3 MINS
SET 4 CL 1 CLS 7 MC P JB B UNT 1 MEAN = 38.4 MINS/ STD DEV. = 2.2 MINS
SET 4 CL 1 CLS 7 MC Z JB B UNT 1 MEAN = 37.2 MINS/ STD DEV. = 2.1 MINS
SET 4 CL 1 CLS 7 MC T JB B UNT 1 MEAN = 32.4 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 2 CLS 1 MC P JB C UNT 1 MEAN = 24.8 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 2 CLS 1 MC P JB E UNT 1 MEAN = 10.2 MINS/ STD DEV. = 0.8 MINS
SET 4 CL 2 CLS 1 MC J JB C UNT 1 MEAN = 22.4 MINS/ STD DEV. = 1.6 MINS
SET 4 CL 2 CLS 1 MC J JB E UNT 1 MEAN = 9.0 MINS/ STD DEV. = 0.7 MINS
SET 4 CL 2 CLS 1 MC Z JB C UNT 1 MEAN = 25.6 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 2 CLS 1 MC Z JB E UNT 1 MEAN = 10.8 MINS/ STD DEV. = 0.9 MINS
SET 4 CL 2 CLS 2 MC P JB C UNT 1 MEAN = 16.0 MINS/ STD DEV. = 1.1 MINS
SET 4 CL 2 CLS 2 MC P JB S UNT 1 MEAN = 12.0 MINS/ STD DEV. = 1.0 MINS

SET 4 CL 2 CLS 2 MC P JB V UNT 1 MEAN = 39.1 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 2 CLS 2 MC W JB C UNT 1 MEAN = 16.8 MINS/ STD DEV. = 1.2 MINS
SET 4 CL 2 CLS 2 MC W JB S UNT 1 MEAN = 12.6 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 2 CLS 2 MC W JB V UNT 1 MEAN = 42.5 MINS/ STD DEV. = 2.1 MINS
SET 4 CL 2 CLS 2 MC Y JB C UNT 1 MEAN = 21.6 MINS/ STD DEV. = 1.5 MINS
SET 4 CL 2 CLS 2 MC Y JB S UNT 1 MEAN = 16.2 MINS/ STD DEV. = 1.3 MINS
SET 4 CL 2 CLS 2 MC Y JB V UNT 1 MEAN = 49.3 MINS/ STD DEV. = 2.4 MINS
SET 4 CL 2 CLS 3 MC K JB E UNT 1 MEAN = 20.4 MINS/ STD DEV. = 1.7 MINS
SET 4 CL 2 CLS 3 MC K JB V UNT 1 MEAN = 69.7 MINS/ STD DEV. = 3.4 MINS
SET 4 CL 2 CLS 3 MC N JB E UNT 1 MEAN = 22.2 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 2 CLS 3 MC N JB V UNT 1 MEAN = 76.5 MINS/ STD DEV. = 3.7 MINS
SET 4 CL 2 CLS 3 MC W JB E UNT 1 MEAN = 21.6 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 2 CLS 3 MC W JB V UNT 1 MEAN = 74.8 MINS/ STD DEV. = 3.6 MINS
SET 4 CL 2 CLS 4 MC J JB C UNT 1 MEAN = 25.6 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 2 CLS 4 MC J JB S UNT 1 MEAN = 19.2 MINS/ STD DEV. = 1.6 MINS
SET 4 CL 2 CLS 4 MC J JB V UNT 1 MEAN = 54.4 MINS/ STD DEV. = 2.6 MINS
SET 4 CL 2 CLS 4 MC W JB C UNT 1 MEAN = 29.6 MINS/ STD DEV. = 2.1 MINS
SET 4 CL 2 CLS 4 MC W JB S UNT 1 MEAN = 22.2 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 2 CLS 4 MC W JB V UNT 1 MEAN = 62.9 MINS/ STD DEV. = 3.1 MINS
SET 4 CL 2 CLS 6 MC N JB C UNT 1 MEAN = 24.8 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 2 CLS 6 MC N JB E UNT 1 MEAN = 12.6 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 2 CLS 6 MC N JB S UNT 1 MEAN = 16.2 MINS/ STD DEV. = 1.3 MINS
SET 4 CL 2 CLS 6 MC Z JB C UNT 1 MEAN = 24.0 MINS/ STD DEV. = 1.7 MINS
SET 4 CL 2 CLS 6 MC Z JB E UNT 1 MEAN = 12.0 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 2 CLS 6 MC Z JB S UNT 1 MEAN = 15.0 MINS/ STD DEV. = 1.2 MINS
SET 4 CL 2 CLS 7 MC P JB S UNT 1 MEAN = 19.2 MINS/ STD DEV. = 1.6 MINS
SET 4 CL 2 CLS 7 MC P JB V UNT 1 MEAN = 54.4 MINS/ STD DEV. = 2.6 MINS
SET 4 CL 2 CLS 7 MC Z JB S UNT 1 MEAN = 18.6 MINS/ STD DEV. = 1.5 MINS
SET 4 CL 2 CLS 7 MC Z JB V UNT 1 MEAN = 52.7 MINS/ STD DEV. = 2.6 MINS
SET 4 CL 2 CLS 7 MC T JB S UNT 1 MEAN = 16.2 MINS/ STD DEV. = 1.3 MINS
SET 4 CL 2 CLS 7 MC T JB V UNT 1 MEAN = 45.9 MINS/ STD DEV. = 2.2 MINS
SET 4 CL 3 CLS 1 MC P JB F UNT 1 MEAN = 27.9 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 3 CLS 1 MC P JB Q UNT 1 MEAN = 11.5 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 3 CLS 1 MC P JB R UNT 1 MEAN = 9.2 MINS/ STD DEV. = 0.9 MINS
SET 4 CL 3 CLS 1 MC J JB F UNT 1 MEAN = 25.2 MINS/ STD DEV. = 1.7 MINS
SET 4 CL 3 CLS 1 MC J JB Q UNT 1 MEAN = 10.5 MINS/ STD DEV. = 0.9 MINS
SET 4 CL 3 CLS 1 MC J JB R UNT 1 MEAN = 8.4 MINS/ STD DEV. = 0.8 MINS
SET 4 CL 3 CLS 1 MC Z JB F UNT 1 MEAN = 28.8 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 3 CLS 1 MC Z JB Q UNT 1 MEAN = 12.5 MINS/ STD DEV. = 1.1 MINS
SET 4 CL 3 CLS 1 MC Z JB R UNT 1 MEAN = 10.0 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 3 CLS 2 MC P JB R UNT 1 MEAN = 8.0 MINS/ STD DEV. = 0.8 MINS
SET 4 CL 3 CLS 2 MC P JB U UNT 1 MEAN = 36.4 MINS/ STD DEV. = 2.0 MINS
SET 4 CL 3 CLS 2 MC W JB R UNT 1 MEAN = 8.4 MINS/ STD DEV. = 0.8 MINS
SET 4 CL 3 CLS 2 MC W JB U UNT 1 MEAN = 40.3 MINS/ STD DEV. = 2.2 MINS
SET 4 CL 3 CLS 2 MC Y JB R UNT 1 MEAN = 10.8 MINS/ STD DEV. = 1.1 MINS
SET 4 CL 3 CLS 2 MC Y JB U UNT 1 MEAN = 41.6 MINS/ STD DEV. = 2.3 MINS
SET 4 CL 3 CLS 3 MC K JB F UNT 1 MEAN = 30.6 MINS/ STD DEV. = 2.0 MINS
SET 4 CL 3 CLS 3 MC K JB Q UNT 1 MEAN = 15.5 MINS/ STD DEV. = 1.4 MINS
SET 4 CL 3 CLS 3 MC K JB R UNT 1 MEAN = 16.4 MINS/ STD DEV. = 1.6 MINS
SET 4 CL 3 CLS 3 MC N JB F UNT 1 MEAN = 33.3 MINS/ STD DEV. = 2.2 MINS
SET 4 CL 3 CLS 3 MC N JB Q UNT 1 MEAN = 16.5 MINS/ STD DEV. = 1.5 MINS
SET 4 CL 3 CLS 3 MC N JB R UNT 1 MEAN = 18.0 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 3 CLS 3 MC W JB F UNT 1 MEAN = 32.4 MINS/ STD DEV. = 2.2 MINS
SET 4 CL 3 CLS 3 MC W JB Q UNT 1 MEAN = 17.0 MINS/ STD DEV. = 1.5 MINS
SET 4 CL 3 CLS 3 MC W JB R UNT 1 MEAN = 17.6 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 3 CLS 4 MC J JB U UNT 1 MEAN = 27.3 MINS/ STD DEV. = 1.5 MINS

SET 4 CL 3 CLS 4 MC W JB U UNT 1 MEAN = 32.5 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 3 CLS 5 MC K JB F UNT 1 MEAN = 54.9 MINS/ STD DEV. = 3.7 MINS
SET 4 CL 3 CLS 5 MC K JB Q UNT 1 MEAN = 32.5 MINS/ STD DEV. = 2.9 MINS
SET 4 CL 3 CLS 5 MC K JB R UNT 1 MEAN = 28.0 MINS/ STD DEV. = 2.8 MINS
SET 4 CL 3 CLS 5 MC N JB F UNT 1 MEAN = 59.4 MINS/ STD DEV. = 4.0 MINS
SET 4 CL 3 CLS 5 MC N JB Q UNT 1 MEAN = 35.5 MINS/ STD DEV. = 3.2 MINS
SET 4 CL 3 CLS 5 MC N JB R UNT 1 MEAN = 29.2 MINS/ STD DEV. = 2.9 MINS
SET 4 CL 3 CLS 5 MC T JB F UNT 1 MEAN = 51.3 MINS/ STD DEV. = 3.4 MINS
SET 4 CL 3 CLS 5 MC T JB Q UNT 1 MEAN = 31.5 MINS/ STD DEV. = 2.8 MINS
SET 4 CL 3 CLS 5 MC T JB R UNT 1 MEAN = 27.2 MINS/ STD DEV. = 2.7 MINS
SET 4 CL 3 CLS 6 MC N JB F UNT 1 MEAN = 27.9 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 3 CLS 6 MC N JB R UNT 1 MEAN = 12.4 MINS/ STD DEV. = 1.2 MINS
SET 4 CL 3 CLS 6 MC N JB U UNT 1 MEAN = 40.3 MINS/ STD DEV. = 2.2 MINS
SET 4 CL 3 CLS 6 MC Z JB F UNT 1 MEAN = 27.0 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 3 CLS 6 MC Z JB R UNT 1 MEAN = 12.0 MINS/ STD DEV. = 1.2 MINS
SET 4 CL 3 CLS 6 MC Z JB U UNT 1 MEAN = 39.0 MINS/ STD DEV. = 2.2 MINS
SET 4 CL 3 CLS 7 MC P JB F UNT 1 MEAN = 28.8 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 3 CLS 7 MC P JB Q UNT 1 MEAN = 16.0 MINS/ STD DEV. = 1.4 MINS
SET 4 CL 3 CLS 7 MC Z JB F UNT 1 MEAN = 27.9 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 3 CLS 7 MC Z JB Q UNT 1 MEAN = 15.5 MINS/ STD DEV. = 1.4 MINS
SET 4 CL 3 CLS 7 MC T JB F UNT 1 MEAN = 24.3 MINS/ STD DEV. = 1.6 MINS
SET 4 CL 3 CLS 7 MC T JB Q UNT 1 MEAN = 13.5 MINS/ STD DEV. = 1.2 MINS
SET 4 CL 4 CLS 1 MC P JB A UNT 1 MEAN = 25.3 MINS/ STD DEV. = 1.5 MINS
SET 4 CL 4 CLS 1 MC P JB B UNT 1 MEAN = 20.4 MINS/ STD DEV. = 1.2 MINS
SET 4 CL 4 CLS 1 MC P JB H UNT 1 MEAN = 11.5 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 4 CLS 1 MC J JB A UNT 1 MEAN = 23.1 MINS/ STD DEV. = 1.4 MINS
SET 4 CL 4 CLS 1 MC J JB B UNT 1 MEAN = 18.0 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 4 CLS 1 MC J JB H UNT 1 MEAN = 10.5 MINS/ STD DEV. = 0.9 MINS
SET 4 CL 4 CLS 1 MC Z JB A UNT 1 MEAN = 27.5 MINS/ STD DEV. = 1.7 MINS
SET 4 CL 4 CLS 1 MC Z JB B UNT 1 MEAN = 21.6 MINS/ STD DEV. = 1.2 MINS
SET 4 CL 4 CLS 1 MC Z JB H UNT 1 MEAN = 12.5 MINS/ STD DEV. = 1.1 MINS
SET 4 CL 4 CLS 2 MC P JB B UNT 1 MEAN = 24.0 MINS/ STD DEV. = 1.4 MINS
SET 4 CL 4 CLS 2 MC P JB H UNT 1 MEAN = 11.5 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 4 CLS 2 MC W JB B UNT 1 MEAN = 25.2 MINS/ STD DEV. = 1.5 MINS
SET 4 CL 4 CLS 2 MC W JB H UNT 1 MEAN = 12.5 MINS/ STD DEV. = 1.1 MINS
SET 4 CL 4 CLS 2 MC Y JB B UNT 1 MEAN = 32.4 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 4 CLS 2 MC Y JB H UNT 1 MEAN = 14.5 MINS/ STD DEV. = 1.3 MINS
SET 4 CL 4 CLS 3 MC K JB A UNT 1 MEAN = 37.4 MINS/ STD DEV. = 2.3 MINS
SET 4 CL 4 CLS 3 MC N JB A UNT 1 MEAN = 40.7 MINS/ STD DEV. = 2.5 MINS
SET 4 CL 4 CLS 3 MC W JB A UNT 1 MEAN = 39.6 MINS/ STD DEV. = 2.4 MINS
SET 4 CL 4 CLS 4 MC J JB A UNT 1 MEAN = 23.1 MINS/ STD DEV. = 1.4 MINS
SET 4 CL 4 CLS 4 MC J JB H UNT 1 MEAN = 10.5 MINS/ STD DEV. = 0.9 MINS
SET 4 CL 4 CLS 4 MC W JB A UNT 1 MEAN = 27.5 MINS/ STD DEV. = 1.7 MINS
SET 4 CL 4 CLS 4 MC W JB H UNT 1 MEAN = 12.5 MINS/ STD DEV. = 1.1 MINS
SET 4 CL 4 CLS 5 MC K JB A UNT 1 MEAN = 71.5 MINS/ STD DEV. = 4.3 MINS
SET 4 CL 4 CLS 5 MC K JB B UNT 1 MEAN = 73.2 MINS/ STD DEV. = 4.2 MINS
SET 4 CL 4 CLS 5 MC K JB H UNT 1 MEAN = 32.5 MINS/ STD DEV. = 2.9 MINS
SET 4 CL 4 CLS 5 MC N JB A UNT 1 MEAN = 78.1 MINS/ STD DEV. = 4.7 MINS
SET 4 CL 4 CLS 5 MC N JB B UNT 1 MEAN = 79.2 MINS/ STD DEV. = 4.6 MINS
SET 4 CL 4 CLS 5 MC N JB H UNT 1 MEAN = 35.5 MINS/ STD DEV. = 3.2 MINS
SET 4 CL 4 CLS 5 MC T JB A UNT 1 MEAN = 69.3 MINS/ STD DEV. = 4.2 MINS
SET 4 CL 4 CLS 5 MC T JB B UNT 1 MEAN = 68.4 MINS/ STD DEV. = 3.9 MINS
SET 4 CL 4 CLS 5 MC T JB H UNT 1 MEAN = 31.5 MINS/ STD DEV. = 2.8 MINS
SET 4 CL 4 CLS 6 MC N JB H UNT 1 MEAN = 15.5 MINS/ STD DEV. = 1.4 MINS
SET 4 CL 4 CLS 6 MC Z JB H UNT 1 MEAN = 15.0 MINS/ STD DEV. = 1.3 MINS
SET 4 CL 4 CLS 7 MC P JB B UNT 1 MEAN = 38.4 MINS/ STD DEV. = 2.2 MINS

SET 4 CL 4 CLS 7 MC Z JB B UNT 1 MEAN = 37.2 MINS/ STD DEV. = 2.1 MINS
SET 4 CL 4 CLS 7 MC T JB B UNT 1 MEAN = 32.4 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 5 CLS 1 MC P JB C UNT 1 MEAN = 24.8 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 5 CLS 1 MC J JB C UNT 1 MEAN = 22.4 MINS/ STD DEV. = 1.6 MINS
SET 4 CL 5 CLS 1 MC Z JB C UNT 1 MEAN = 25.6 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 5 CLS 2 MC P JB C UNT 1 MEAN = 16.0 MINS/ STD DEV. = 1.1 MINS
SET 4 CL 5 CLS 2 MC P JB S UNT 1 MEAN = 12.0 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 5 CLS 2 MC P JB V UNT 1 MEAN = 39.1 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 5 CLS 2 MC W JB C UNT 1 MEAN = 16.8 MINS/ STD DEV. = 1.2 MINS
SET 4 CL 5 CLS 2 MC W JB S UNT 1 MEAN = 12.6 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 5 CLS 2 MC W JB V UNT 1 MEAN = 42.5 MINS/ STD DEV. = 2.1 MINS
SET 4 CL 5 CLS 2 MC Y JB C UNT 1 MEAN = 21.6 MINS/ STD DEV. = 1.5 MINS
SET 4 CL 5 CLS 2 MC Y JB S UNT 1 MEAN = 16.2 MINS/ STD DEV. = 1.3 MINS
SET 4 CL 5 CLS 2 MC Y JB V UNT 1 MEAN = 49.3 MINS/ STD DEV. = 2.4 MINS
SET 4 CL 5 CLS 3 MC K JB V UNT 1 MEAN = 69.7 MINS/ STD DEV. = 3.4 MINS
SET 4 CL 5 CLS 3 MC N JB V UNT 1 MEAN = 76.5 MINS/ STD DEV. = 3.7 MINS
SET 4 CL 5 CLS 3 MC W JB V UNT 1 MEAN = 74.8 MINS/ STD DEV. = 3.6 MINS
SET 4 CL 5 CLS 4 MC J JB C UNT 1 MEAN = 25.6 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 5 CLS 4 MC J JB S UNT 1 MEAN = 19.2 MINS/ STD DEV. = 1.6 MINS
SET 4 CL 5 CLS 4 MC J JB V UNT 1 MEAN = 54.4 MINS/ STD DEV. = 2.6 MINS
SET 4 CL 5 CLS 4 MC W JB C UNT 1 MEAN = 29.6 MINS/ STD DEV. = 2.1 MINS
SET 4 CL 5 CLS 4 MC W JB S UNT 1 MEAN = 22.2 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 5 CLS 4 MC W JB V UNT 1 MEAN = 62.9 MINS/ STD DEV. = 3.1 MINS
SET 4 CL 5 CLS 6 MC N JB C UNT 1 MEAN = 24.8 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 5 CLS 6 MC N JB S UNT 1 MEAN = 16.2 MINS/ STD DEV. = 1.3 MINS
SET 4 CL 5 CLS 6 MC Z JB C UNT 1 MEAN = 24.0 MINS/ STD DEV. = 1.7 MINS
SET 4 CL 5 CLS 6 MC Z JB S UNT 1 MEAN = 15.0 MINS/ STD DEV. = 1.2 MINS
SET 4 CL 5 CLS 7 MC P JB S UNT 1 MEAN = 19.2 MINS/ STD DEV. = 1.6 MINS
SET 4 CL 5 CLS 7 MC P JB V UNT 1 MEAN = 54.4 MINS/ STD DEV. = 2.6 MINS
SET 4 CL 5 CLS 7 MC Z JB S UNT 1 MEAN = 18.6 MINS/ STD DEV. = 1.5 MINS
SET 4 CL 5 CLS 7 MC Z JB V UNT 1 MEAN = 52.7 MINS/ STD DEV. = 2.6 MINS
SET 4 CL 5 CLS 7 MC T JB S UNT 1 MEAN = 16.2 MINS/ STD DEV. = 1.3 MINS
SET 4 CL 5 CLS 7 MC T JB V UNT 1 MEAN = 45.9 MINS/ STD DEV. = 2.2 MINS
SET 4 CL 6 CLS 1 MC P JB E UNT 1 MEAN = 10.2 MINS/ STD DEV. = 0.8 MINS
SET 4 CL 6 CLS 1 MC P JB R UNT 1 MEAN = 9.2 MINS/ STD DEV. = 0.9 MINS
SET 4 CL 6 CLS 1 MC J JB E UNT 1 MEAN = 9.0 MINS/ STD DEV. = 0.7 MINS
SET 4 CL 6 CLS 1 MC J JB R UNT 1 MEAN = 8.4 MINS/ STD DEV. = 0.8 MINS
SET 4 CL 6 CLS 1 MC Z JB E UNT 1 MEAN = 10.8 MINS/ STD DEV. = 0.9 MINS
SET 4 CL 6 CLS 1 MC Z JB R UNT 1 MEAN = 10.0 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 6 CLS 2 MC P JB D UNT 1 MEAN = 23.0 MINS/ STD DEV. = 1.5 MINS
SET 4 CL 6 CLS 2 MC P JB R UNT 1 MEAN = 8.0 MINS/ STD DEV. = 0.8 MINS
SET 4 CL 6 CLS 2 MC W JB D UNT 1 MEAN = 25.0 MINS/ STD DEV. = 1.6 MINS
SET 4 CL 6 CLS 2 MC W JB R UNT 1 MEAN = 8.4 MINS/ STD DEV. = 0.8 MINS
SET 4 CL 6 CLS 2 MC Y JB D UNT 1 MEAN = 29.0 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 6 CLS 2 MC Y JB R UNT 1 MEAN = 10.8 MINS/ STD DEV. = 1.1 MINS
SET 4 CL 6 CLS 3 MC K JB D UNT 1 MEAN = 41.0 MINS/ STD DEV. = 2.6 MINS
SET 4 CL 6 CLS 3 MC K JB E UNT 1 MEAN = 20.4 MINS/ STD DEV. = 1.7 MINS
SET 4 CL 6 CLS 3 MC K JB R UNT 1 MEAN = 16.4 MINS/ STD DEV. = 1.6 MINS
SET 4 CL 6 CLS 3 MC N JB D UNT 1 MEAN = 45.0 MINS/ STD DEV. = 2.8 MINS
SET 4 CL 6 CLS 3 MC N JB E UNT 1 MEAN = 22.2 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 6 CLS 3 MC N JB R UNT 1 MEAN = 18.0 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 6 CLS 3 MC W JB D UNT 1 MEAN = 44.0 MINS/ STD DEV. = 2.8 MINS
SET 4 CL 6 CLS 3 MC W JB E UNT 1 MEAN = 21.6 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 6 CLS 3 MC W JB R UNT 1 MEAN = 17.6 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 6 CLS 5 MC K JB R UNT 1 MEAN = 28.0 MINS/ STD DEV. = 2.8 MINS
SET 4 CL 6 CLS 5 MC N JB R UNT 1 MEAN = 29.2 MINS/ STD DEV. = 2.9 MINS

SET 4 CL 6 CLS 5 MC T JB R UNT 1 MEAN = 27.2 MINS/ STD DEV. = 2.7 MINS
SET 4 CL 6 CLS 6 MC N JB D UNT 1 MEAN = 27.0 MINS/ STD DEV. = 1.7 MINS
SET 4 CL 6 CLS 6 MC N JB E UNT 1 MEAN = 12.6 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 6 CLS 6 MC N JB R UNT 1 MEAN = 12.4 MINS/ STD DEV. = 1.2 MINS
SET 4 CL 6 CLS 6 MC Z JB D UNT 1 MEAN = 25.0 MINS/ STD DEV. = 1.6 MINS
SET 4 CL 6 CLS 6 MC Z JB E UNT 1 MEAN = 12.0 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 6 CLS 6 MC Z JB R UNT 1 MEAN = 12.0 MINS/ STD DEV. = 1.2 MINS
SET 4 CL 7 CLS 1 MC P JB F UNT 1 MEAN = 27.9 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 7 CLS 1 MC P JB Q UNT 1 MEAN = 11.5 MINS/ STD DEV. = 1.0 MINS
SET 4 CL 7 CLS 1 MC J JB F UNT 1 MEAN = 25.2 MINS/ STD DEV. = 1.7 MINS
SET 4 CL 7 CLS 1 MC J JB Q UNT 1 MEAN = 10.5 MINS/ STD DEV. = 0.9 MINS
SET 4 CL 7 CLS 1 MC Z JB F UNT 1 MEAN = 28.8 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 7 CLS 1 MC Z JB Q UNT 1 MEAN = 12.5 MINS/ STD DEV. = 1.1 MINS
SET 4 CL 7 CLS 2 MC P JB U UNT 1 MEAN = 36.4 MINS/ STD DEV. = 2.0 MINS
SET 4 CL 7 CLS 2 MC W JB U UNT 1 MEAN = 40.3 MINS/ STD DEV. = 2.2 MINS
SET 4 CL 7 CLS 2 MC Y JB U UNT 1 MEAN = 41.6 MINS/ STD DEV. = 2.3 MINS
SET 4 CL 7 CLS 3 MC K JB F UNT 1 MEAN = 30.6 MINS/ STD DEV. = 2.0 MINS
SET 4 CL 7 CLS 3 MC K JB Q UNT 1 MEAN = 15.5 MINS/ STD DEV. = 1.4 MINS
SET 4 CL 7 CLS 3 MC N JB F UNT 1 MEAN = 33.3 MINS/ STD DEV. = 2.2 MINS
SET 4 CL 7 CLS 3 MC N JB Q UNT 1 MEAN = 16.5 MINS/ STD DEV. = 1.5 MINS
SET 4 CL 7 CLS 3 MC W JB F UNT 1 MEAN = 32.4 MINS/ STD DEV. = 2.2 MINS
SET 4 CL 7 CLS 3 MC W JB Q UNT 1 MEAN = 17.0 MINS/ STD DEV. = 1.5 MINS
SET 4 CL 7 CLS 4 MC J JB U UNT 1 MEAN = 27.3 MINS/ STD DEV. = 1.5 MINS
SET 4 CL 7 CLS 4 MC W JB U UNT 1 MEAN = 32.5 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 7 CLS 5 MC K JB F UNT 1 MEAN = 54.9 MINS/ STD DEV. = 3.7 MINS
SET 4 CL 7 CLS 5 MC K JB Q UNT 1 MEAN = 32.5 MINS/ STD DEV. = 2.9 MINS
SET 4 CL 7 CLS 5 MC N JB F UNT 1 MEAN = 59.4 MINS/ STD DEV. = 4.0 MINS
SET 4 CL 7 CLS 5 MC N JB Q UNT 1 MEAN = 35.5 MINS/ STD DEV. = 3.2 MINS
SET 4 CL 7 CLS 5 MC T JB F UNT 1 MEAN = 51.3 MINS/ STD DEV. = 3.4 MINS
SET 4 CL 7 CLS 5 MC T JB Q UNT 1 MEAN = 31.5 MINS/ STD DEV. = 2.8 MINS
SET 4 CL 7 CLS 6 MC N JB F UNT 1 MEAN = 27.9 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 7 CLS 6 MC N JB U UNT 1 MEAN = 40.3 MINS/ STD DEV. = 2.2 MINS
SET 4 CL 7 CLS 6 MC Z JB F UNT 1 MEAN = 27.0 MINS/ STD DEV. = 1.8 MINS
SET 4 CL 7 CLS 6 MC Z JB U UNT 1 MEAN = 39.0 MINS/ STD DEV. = 2.2 MINS
SET 4 CL 7 CLS 7 MC P JB F UNT 1 MEAN = 28.8 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 7 CLS 7 MC P JB Q UNT 1 MEAN = 16.0 MINS/ STD DEV. = 1.4 MINS
SET 4 CL 7 CLS 7 MC Z JB F UNT 1 MEAN = 27.9 MINS/ STD DEV. = 1.9 MINS
SET 4 CL 7 CLS 7 MC Z JB Q UNT 1 MEAN = 15.5 MINS/ STD DEV. = 1.4 MINS
SET 4 CL 7 CLS 7 MC T JB F UNT 1 MEAN = 24.3 MINS/ STD DEV. = 1.6 MINS
SET 4 CL 7 CLS 7 MC T JB Q UNT 1 MEAN = 13.5 MINS/ STD DEV. = 1.2 MINS

Appendix L. Sample SIMAN Codes Used in Simulation

Model Frame for Functional Facility in Problem Set No.4:

SIMAN MODEL PROCESSOR RELEASE 3.0
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```
BEGIN;
;
;*****************************************************************
;
;         PROBLEM SET NO. 4 (FUNCTIONAL FACILITY)
;*****************************************************************
;
; ATTRIBUTES :
;        A(1)  =  OPERATION TIME OF THE JOB (UNIT LOAD OR SETUP JOB)
;        A(2)  =  ENTRY TIME EACH JOB/ENTITY TO THE FACILITY
;        A(3)  =  JOB TYPE , 1 = A, 2 = B IN SEQUENCE IN FUNC. CASE
;                 AND 1 = A, 2 = C (EXAMPLE) IN CELLULAR CASE
;        A(4)  =  NUMBER OF OPERATIONS RECEIVED AT A GIVEN TIME
;        A(5)  =  INDEX OF THE SELECTED TRANSPORTER FOR THE JOB
;        A(6)  =  1 FOR SETUP JOBS AND 0 FOR OTHERS
;VARIABLES :
;    X(1) = NUMBER OF UNIT LOADS OF JOB TYPE A RELEASED EVERY PERIOD
;    X(2) = NUMBER OF UNIT LOADS OF JOB TYPE B RELEASED EVERY PERIOD
;    X(3) = NUMBER OF UNIT LOADS OF JOB TYPE C RELEASED EVERY PERIOD
;    X(4) = NUMBER OF UNIT LOADS OF JOB TYPE D RELEASED EVERY PERIOD
;    X(5) = NUMBER OF UNIT LOADS OF JOB TYPE E RELEASED EVERY PERIOD
;    X(6) = NUMBER OF UNIT LOADS OF JOB TYPE F RELEASED EVERY PERIOD
;    X(7) = NUMBER OF UNIT LOADS OF JOB TYPE H RELEASED EVERY PERIOD
;    X(8) = NUMBER OF UNIT LOADS OF JOB TYPE Q RELEASED EVERY PERIOD
;    X(9) = NUMBER OF UNIT LOADS OF JOB TYPE R RELEASED EVERY PERIOD
;   X(10) = NUMBER OF UNIT LOADS OF JOB TYPE S RELEASED EVERY PERIOD
```

```
;    X(11) = NUMBER OF UNIT LOADS OF JOB TYPE U RELEASED EVERY PERIOD
;    X(12) = NUMBER OF UNIT LOADS OF JOB TYPE V RELEASED EVERY PERIOD
;
;    X(15) = NUMBER OF DPT1 STUP JOBS PERFORMED EVERY PERIOD
;    X(16) = NUMBER OF DPT2 STUP JOBS PERFORMED EVERY PERIOD
;    X(17) = NUMBER OF DPT3 STUP JOBS PERFORMED EVERY PERIOD
;    X(18) = NUMBER OF DPT4 STUP JOBS PERFORMED EVERY PERIOD
;    X(19) = NUMBER OF DPT5 STUP JOBS PERFORMED EVERY PERIOD
;    X(20) = NUMBER OF DPT6 STUP JOBS PERFORMED EVERY PERIOD
;    X(21) = NUMBER OF DPT7 STUP JOBS PERFORMED EVERY PERIOD
 x(15) through x(21) are the same in cellular case
;
SYNONYMS:JOBTYPE=A(3);
;
; SETUP JOBS ARE CREATED AT THE BEGINNING OF EACH PERIOD, ASSIGNED
; HIGH PRIORITY FOR SEIZING MACHINES AT THE ONLY ONE ZONE/STATION
; THEY VISIT IN ADDITION TO EXIT STATION
;
      CREATE,X(15):480:MARK(2);
      TALLY:32,X(15);
      ASSIGN:A(3) = 13;
      ASSIGN:A(6) = 1 :NEXT(START);
      CREATE,X(16):480:MARK(2);
      TALLY:33,X(16);
      ASSIGN:A(3) = 14;
      ASSIGN:A(6) = 1 :NEXT(START);
      CREATE,X(17):480:MARK(2);
      TALLY:34,X(17);
      ASSIGN:A(3) = 15;
      ASSIGN:A(6) = 1 :NEXT(START);
      CREATE,X(18):480:MARK(2);
      TALLY:35,X(18);
      ASSIGN:A(3) = 16;
      ASSIGN:A(6) = 1 :NEXT(START);
      CREATE,X(19):480:MARK(2);
      TALLY:36,X(19);
      ASSIGN:A(3) = 17;
      ASSIGN:A(6) = 1 :NEXT(START);
      CREATE,X(20):480:MARK(2);
      TALLY:37,X(20);
      ASSIGN:A(3) = 18;
      ASSIGN:A(6) = 1 :NEXT(START);
      CREATE,X(21):480:MARK(2);
      TALLY:38,X(21);
      ASSIGN:A(3) = 19;
      ASSIGN:A(6) = 1 :NEXT(START);
;
; REGULAR JOBS ARE CREATED. A(6) IS NOT ASSIGNED AS 1 FOR REGULAR
; JOBS/UNIT LOADS.
;
; DETERMINATION OF RANDOM NUMBER OF UNIT LOADS OF EACH JOB TYPE
; BY FIRST DRAWING DAILY DEMANDS FROM THEIR DISTRIBUTIONS AND THEN
; DIVIDING DAILY DEMANDS BY NUMBER OF JOBS THAT FIT TO THE PALLET.
; DIVISION STEP IS SKIPPED IN PROBLEM SETS NO.1 AND NO.2.
;
      CREATE,X(1):480:MARK(2);
```

```
300        TALLY:20,X(1);          NUMBER OF UNIT LOADS OF JOB A
310        ASSIGN:X(1) = AINT((RN(1,1)/11)) ;
320        ASSIGN:A(3) = 1 :NEXT(START) ;    A(3) HAS JOB TYPE OF 1 OR A
330        CREATE,X(2):480:MARK(2);
340        TALLY:21,X(2);
350        ASSIGN:X(2) = AINT((RN(2,1)/12)) ;
360        ASSIGN:A(3) = 2 :NEXT(START) ;
370        CREATE,X(3):480:MARK(2);
380        TALLY:22,X(3);
390        ASSIGN:X(3) = AINT((RN(3,1)/8)) ;
400        ASSIGN:A(3) = 3 :NEXT(START) ;
410        CREATE,X(4):480:MARK(2);
420        TALLY:23,X(4);
430        ASSIGN:X(4) = AINT((RN(4,1)/10)) ;
440        ASSIGN:A(3) = 4 :NEXT(START);
450        CREATE,X(5):480:MARK(2);
460        TALLY:24,X(5);
470        ASSIGN:X(5) = AINT((RN(5,1)/6)) ;
480        ASSIGN:A(3) = 5 :NEXT(START);
490        CREATE,X(6):480:MARK(2);
500        TALLY:25,X(6);
510        ASSIGN:X(6) = AINT((RN(6,1)/9)) ;
520        ASSIGN:A(3) = 6 :NEXT(START);
530        CREATE,X(7):480:MARK(2);
540        TALLY:26,X(7);
550        ASSIGN:X(7) = AINT((RN(7,1)/5)) ;
560        ASSIGN:A(3) = 7 :NEXT(START);
570        CREATE,X(8):480:MARK(2);
580        TALLY:27,X(8);
590        ASSIGN:X(8) = AINT((RN(8,1)/5)) ;
600        ASSIGN:A(3) = 8 : NEXT(START);
610        CREATE,X(9):480:MARK(2);
620        TALLY:28,X(9);
630        ASSIGN:X(9) = AINT((RN(9,1)/4)) ;
640        ASSIGN:A(3) = 9 : NEXT(START);
650        CREATE,X(10):480:MARK(2);
660        TALLY:29,X(10);
670        ASSIGN:X(10) = AINT((RN(10,1)/6)) ;
680        ASSIGN:A(3) = 10 : NEXT(START);
690        CREATE,X(11):480:MARK(2);
700        TALLY:30,X(11);
710        ASSIGN:X(11) = AINT((RN(11,1)/13)) ;
720        ASSIGN:A(3) = 11 : NEXT(START);
730        CREATE,X(12):480:MARK(2);
740        TALLY:31,X(12);
750        ASSIGN:X(12) = AINT((RN(12,1)/17)) ;
760        ASSIGN:A(3) = 12;
770 START    ASSIGN:NS='JOBTYPE';
   ;  EACH UNIT LOAD IS SENT TO ITS FIRST DEPT. TO BE VISITED AND
   ;  THIS FIRST VISIT IS ASSUMED INSTANT.
   ;
780        ROUTE:0.0,SEQ;
   ;
790        STATION,1-7;   EACH STATION CORRESPONDS TO A DEPARTMENT
   ;
   ; A(4) IS CHECKED TO DETERMINE IF THE CURRENT UNIT LOAD IS NEW ENTRY
```

```
   ; WITH NO CART.  A(4) > 0 INDICATES THAT UNIT LOAD IS ON A CART AND
   ; DESTINED TO THE QUEUE OF THE NEXT DEPARTMENT.
   ;
800           BRANCH,1:
              IF,A(4).EQ.0,NEW:
              ELSE,OLD;
810 OLD      FREE:CART(A(5));
820 NEW      QUEUE,M;
830        SEIZE:MACHINE(M);
   ; ONCE TRANSPORTED TO NEXT DEPT. IN SEQUENCE, PROC. TIME IS RETRIEVED
   ; FROM EXPMT FRAME (SEQUENCING FEATURE USED HERE ALLOWS BOTH DISTR.,
   ; PARAMETERS, AND SEQUENCE ORDER INFORMATION TO BE STORED TOGETHER)
840 OPR      DELAY:A(1);
   ;  ONCE THE UNIT LOAD GETS ITS OPERATION PERFORMED AND RELASES THE
   ;  MACHINE, A(4) IS INCREMENTED TO COUNT NUMBER OF DISTINCT OPERATIONS
   ;  EACH UNIT LOAD RECEIVES
850        RELEASE : MACHINE(M);
860        ASSIGN:A(4) = A(4) + 1;
   ; UPON COMPLETION OF AN OPERATION, UNIT LOAD WAITS IN QUEUE FOR
   ; TRANSPORTER THAT WILL TRANSPORT IT TO THE QUEUE IN NEXT DEPT.
   ; TO BE VISITED.
870 QTR      QUEUE,(M+7);
   ;    NEAREST AVAILABLE ACTIVE CART IS REQUESTED.  THE INDEX OF THE
   ;    CART IS STORED AS ATTRIBUTE NO.5.
880        REQUEST:CART(SDS,5);
890 TR       TRANSPORT:CART(A(5)),SEQ;
   ; EXIT STATION
900        STATION,8;
910        FREE:CART(A(5));
920        TALLY : A(3),INT(2) : DISPOSE;
   END;
```

Experiment Frame of Functional Facilities: This section contains the experiment frames of functional facilities in all problem sets. Lines marked with semi-colons belong to other problem sets.

```
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   BEGIN;
 10 PROJECT,FUNCTIONAL FACILITY,H SARPER,6/16/88 ;
   ;
   ;DISCRETE,150,6,15,8;       ! SET 1F
   ;DISCRETE,800,6,20,8;       ! SET 2F
   ;DISCRETE,1800,6,39,8;      ! SET 3F
 20 DISCRETE,7000,6,50,8;      ! SET 4F
   ;
   ;TALLIES : 1,FLOW TIME JOB A:2,FLOW TIME JOB B:   ! SET 1F
   ;       3,FLOW TIME JOB C:4,FLOW TIME JOB D:
   ;       5,DPT1 STUP JOB:6,DPT2 STUP JOB:
   ;       7,DPT3 STUP JOB:8,DPT4 STUP JOB:
```

```
;       9,DPT5 STUP JOB:10,DPT6 STUP JOB:
;       11,DPT7 STUP JOB:
;       12,JOB A DMD IN UN LDS:13,JOB B DMD IN UN LDS:
;       14,JOB C DMD IN UN LDS:15,JOB D DMD IN UN LDS:
;       16,DPT1 SETUP:17,DPT2 SETUP:18,DPT3 SETUP:
;       19,DPT4 SETUP:20,DPT5 SETUP:21,DPT6 SETUP:
;       22,DPT7 SETUP;
;
;TALLIES : 1,FLOW TIME JOB A:2,FLOW TIME JOB B:   ! SET 2F
;       3,FLOW TIME JOB C:4,FLOW TIME JOB D:
;       5,FLOW TIME JOB E:6,FLOW TIME JOB F:
;       7,DPT1 STUP JOB:8,DPT2 STUP JOB:
;       9,DPT3 STUP JOB:10,DPT4 STUP JOB:
;       11,DPT5 STUP JOB:12,DPT6 STUP JOB:
;       13,DPT7 STUP JOB:
;       14,JOB A DMD IN UN LDS:15,JOB B DMD IN UN LDS:
;       16,JOB C DMD IN UN LDS:17,JOB D DMD IN UN LDS:
;       18,JOB E DMD IN UN LDS:19,JOB F DMD IN UN LDS:
;       20,DPT1 SETUP:21,DPT2 SETUP:22,DPT3 SETUP:
;       23,DPT4 SETUP:24,DPT5 SETUP:25,DPT6 SETUP:
;       26,DPT7 SETUP;
;
;TALLIES : 1,FLOW TIME JOB A:2,FLOW TIME JOB B:   ! SET 3F
;       3,FLOW TIME JOB C:4,FLOW TIME JOB D:
;       5,FLOW TIME JOB E:6,FLOW TIME JOB F:
;       7,FLOW TIME JOB H:8,FLOW TIME JOB Q:
;       9,FLOW TIME JOB R:10,FLOW TIME JOB S:
;       11,DPT1 STUP JOB:12,DPT2 STUP JOB:
;       13,DPT3 STUP JOB:14,DPT4 STUP JOB:
;       15,DPT5 STUP JOB:16,DPT6 STUP JOB:
;       17,DPT7 STUP JOB:
;       18,JOB A DMD IN UN LDS:19,JOB B DMD IN UN LDS:
;       20,JOB C DMD IN UN LDS:21,JOB D DMD IN UN LDS:
;       22,JOB E DMD IN UN LDS:23,JOB F DMD IN UN LDS:
;       24,JOB H DMD IN UN LDS:25,JOB Q DMD IN UN LDS:
;       26,JOB R DMD IN UN LDS:27,JOB S DMD IN UN LDS:
;       28,DPT1 SETUP:29,DPT2 SETUP:30,DPT3 SETUP:
;       31,DPT4 SETUP:32,DPT5 SETUP:33,DPT6 SETUP:
;       34,DPT7 SETUP;
;
30 TALLIES : 1,FLOW TIME JOB A,32:2,FLOW TIME JOB B,33:   ! SET 4F
        3,FLOW TIME JOB C,34:4,FLOW TIME JOB D,35:
        5,FLOW TIME JOB E,36:6,FLOW TIME JOB F,37:
        7,FLOW TIME JOB H,38:8,FLOW TIME JOB Q,39:
        9,FLOW TIME JOB R,40:10,FLOW TIME JOB S,41:
        11,FLOW TIME JOB U,42:12,FLOW TIME JOB V,43:
        13,DPT1 STUP JOB:14,DPT2 STUP JOB:
        15,DPT3 STUP JOB:16,DPT4 STUP JOB:
        17,DPT5 STUP JOB:18,DPT6 STUP JOB:
        19,DPT7 STUP JOB:
        20,JOB A DMD IN UN LDS:21,JOB B DMD IN UN LDS:
        22,JOB C DMD IN UN LDS:23,JOB D DMD IN UN LDS:
        24,JOB E DMD IN UN LDS:25,JOB F DMD IN UN LDS:
        26,JOB H DMD IN UN LDS:27,JOB Q DMD IN UN LDS:
        28,JOB R DMD IN UN LDS:29,JOB S DMD IN UN LDS:
        30,JOB U DMD IN UN LDS:31,JOB V DMD IN UN LDS:
```

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        32,DPT1 SETUP:33,DPT2 SETUP:34,DPT3 SETUP:
        35,DPT4 SETUP:36,DPT5 SETUP:37,DPT6 SETUP:
        38,DPT7 SETUP;
;
;
;  FOLLOWING SECTION IS COMMON IN ALL PROBLEM SETS
;
40 DSTAT:1,NQ(1),DEPT 1 QUEUE :2,NQ(2),DEPT 2 QUEUE:
      3,NQ(3),DEPT 3 QUEUE :4,NQ(4),DEPT 4 QUEUE:
      5,NQ(5),DEPT 5 QUEUE :6,NQ(6),DEPT 6 QUEUE:
      7,NQ(7),DEPT 7 QUEUE :
      8,NQ(8),CT Q ATR DP1:9,NQ(9),CT Q ATR DP2:
      10,NQ(10),CT Q ATR DP3:11,NQ(11),CT Q ATR DP4:
      12,NQ(12),CT Q ATR DP5:13,NQ(13),CT Q ATR DP6:
      14,NQ(14),CT Q ATR DP7:
      15,NR(1),DEPT 1 UTIL. :16,NR(2),DEPT 2 UTIL. :
      17,NR(3),DEPT 3 UTIL. :18,NR(4),DEPT 4 UTIL. :
      19,NR(5),DEPT 5 UTIL. :20,NR(6),DEPT 6 UTIL. :
      21,NR(7),DEPT 7 UTIL. :
      22,NT(1),CART UTIL.;
;
;RESOURCES:1-7,MACHINE,2,2,2,2,3,2,1;      ! SET 1F
;RESOURCES:1-7,MACHINE,3,2,3,1,5,2,2;      ! SET 2F
;RESOURCES:1-7,MACHINE,5,4,6,3,10,6,4;     ! SET 3F
50 RESOURCES:1-7,MACHINE,5,7,9,6,10,7,5;   ! SET 4F
;
; SPECIAL SETUP JOBS HAVE PRIORITY IN SEIZING THE MACHINES SO THAT
; SETUP ACTIVITY CAN TAKE PLACE BEFORE PROCESSING ANY REAL JOBS.
; A(6) IS 0 FOR REAL JOBS AND 1 FOR SETUP JOBS.
;
60 RANKINGS:1-7,HVF(6);
;
;  FACILITY HAS CARTS ALL ACTIVE AND PARKED AT STATION NO.1
;
;TRANSPORTERS:1,CART,2,1,3.0,1-A,1-A;            ! 2 TRANSPORTERS IN SET 1F
;TRANSPORTERS:1,CART,3,1,3.0,1-A,1-A,1-A;        ! 3 TRANSPORTRES IN SET 2F
;TRANSPORTERS:1,CART,3,1,9.0,1-A,1-A,1-A;        ! 3 TRANSPORTRES IN SET 3F
70 TRANSPORTERS:1,CART,4,1,9.0,1-A,1-A,1-A,1-A;  ! 4 TRANSPORTRES IN SET 4F
;
;  NOTE : #8 BELOW REFERS TO EXIT STATION WHICH IS NOT THE SAME AS
;        DEPT NO.8 USED IN CHAPTER 5
;
; DEPT. VISITS OF JOBS, E.G. JOB A TRAVELS IN #1,#2, AND #8 ORDER.
;       DPT1 SETUP JOB TRAVELS IN #1 AND #8 ORDER.
;
;SEQUENCES:1,1,RN(13,1)/3,RN(14,1)/4,RN(15,1)/5,RN(16,1)/8: ! JOB A (1F)
;         2,1,RN(17,1)/5,RN(18,1)/7,RN(19,1)/2,RN(20,1)/8: ! JOB B
;         3,4,RN(21,1)/1,RN(22,1)/2,RN(23,1)/6,RN(24,1)/8: ! JOB C
;         4,3,RN(25,1)/6,RN(26,1)/2,RN(27,1)/8:            ! JOB D
;         5,1,RN(28,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.1
;         6,2,RN(29,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.2
;         7,3,RN(30,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.3
;         8,4,RN(31,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.4
;         9,5,RN(32,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.5
;        10,6,RN(33,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.6
;        11,7,RN(34,1)/8;  ! SETUP JOB FOR DEPARTMENT NO.7
```

```
;
;SEQUENCES:1,1,RN(13,1)/3,RN(14,1)/4,RN(15,1)/5,RN(16,1)/8: ! JOB A (2F)
;         2,1,RN(17,1)/5,RN(18,1)/7,RN(19,1)/2,RN(20,1)/8: ! JOB B
;         3,4,RN(21,1)/1,RN(22,1)/2,RN(23,1)/6,RN(24,1)/8: ! JOB C
;         4,3,RN(25,1)/6,RN(26,1)/2,RN(27,1)/8:            ! JOB D
;         5,1,RN(28,1)/3,RN(29,1)/6,RN(30,1)/8:            ! JOB E
;         6,3,RN(31,1)/6,RN(32,1)/5,RN(33,1)/1,RN(34,1)/
;           7,RN(35,1)/8:                                  ! JOB F
;         7,1,RN(36,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.1
;         8,2,RN(37,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.2
;         9,3,RN(38,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.3
;        10,4,RN(39,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.4
;        11,5,RN(40,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.5
;        12,6,RN(41,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.6
;        13,7,RN(42,1)/8;  ! SETUP JOB FOR DEPARTMENT NO.7
;
;SEQUENCES:1,1,RN(13,1)/3,RN(14,1)/4,RN(15,1)/5,RN(16,1)/8: ! JOB A (3F)
;         2,1,RN(17,1)/5,RN(18,1)/7,RN(19,1)/2,RN(20,1)/8: ! JOB B
;         3,4,RN(21,1)/1,RN(22,1)/2,RN(23,1)/6,RN(24,1)/8: ! JOB C
;         4,3,RN(25,1)/6,RN(26,1)/2,RN(27,1)/8:            ! JOB D
;         5,1,RN(28,1)/3,RN(29,1)/6,RN(30,1)/8:            ! JOB E
;         6,3,RN(31,1)/6,RN(32,1)/5,RN(33,1)/1,RN(34,1)/
;           7,RN(35,1)/8:                                  ! JOB F
;         7,2,RN(36,1)/1,RN(37,1)/4,RN(38,1)/5,RN(39,1)/
;           6,RN(40,1)/8:                                  ! JOB H
;         8,1,RN(41,1)/3,RN(42,1)/7,RN(43,1)/5,RN(44,1)/8: ! JOB Q
;         9,1,RN(45,1)/2,RN(46,1)/5,RN(47,1)/6,RN(48,1)/
;           3,RN(49,1)/8:                                  ! JOB R
;        10,4,RN(50,1)/6,RN(51,1)/2,RN(52,1)/7,RN(53,1)/8: ! JOB S
;        11,1,RN(54,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.1
;        12,2,RN(55,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.2
;        13,3,RN(56,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.3
;        14,4,RN(57,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.4
;        15,5,RN(58,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.5
;        16,6,RN(59,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.6
;        17,7,RN(60,1)/8;  ! SETUP JOB FOR DEPARTMENT NO.7
;
80 SEQUENCES:1,1,RN(13,1)/3,RN(14,1)/4,RN(15,1)/5,RN(16,1)/8: ! JOB A (4F)
          2,1,RN(17,1)/5,RN(18,1)/7,RN(19,1)/2,RN(20,1)/8: ! JOB B
          3,4,RN(21,1)/1,RN(22,1)/2,RN(23,1)/6,RN(24,1)/8: ! JOB C
          4,3,RN(25,1)/6,RN(26,1)/2,RN(27,1)/8:            ! JOB D
          5,1,RN(28,1)/3,RN(29,1)/6,RN(30,1)/8:            ! JOB E
          6,3,RN(31,1)/6,RN(32,1)/5,RN(33,1)/1,RN(34,1)/
            7,RN(35,1)/8:                                  ! JOB F
          7,2,RN(36,1)/1,RN(37,1)/4,RN(38,1)/5,RN(39,1)/
            6,RN(40,1)/8:                                  ! JOB H
          8,1,RN(41,1)/3,RN(42,1)/7,RN(43,1)/5,RN(44,1)/8: ! JOB Q
          9,1,RN(45,1)/2,RN(46,1)/5,RN(47,1)/6,RN(48,1)/
            3,RN(49,1)/8:                                  ! JOB R
         10,4,RN(50,1)/6,RN(51,1)/2,RN(52,1)/7,RN(53,1)/8: ! JOB S
         11,6,RN(54,1)/4,RN(55,1)/2,RN(56,1)/8:            ! JOB U
         12,3,RN(57,1)/4,RN(58,1)/7,RN(59,1)/2,RN(60,1)/8: ! JOB V
         13,1,RN(61,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.1
         14,2,RN(62,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.2
         15,3,RN(63,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.3
         16,4,RN(64,1)/8:  ! SETUP JOB FOR DEPARTMENT NO.4
```

```
        17,5,RN(65,1)/8:   ! SETUP JOB FOR DEPARTMENT NO.5
        18,6,RN(66,1)/8:   ! SETUP JOB FOR DEPARTMENT NO.6
        19,7,RN(67,1)/8;   ! SETUP JOB FOR DEPARTMENT NO.7
   ;
   ;INITIALIZE,X(1)=8,X(2)=10,X(3)=16,X(4)=13,X(15)=2,X(16)=2,X(17)=2,
   ;          X(18)=2,X(19)=3,X(20)=2,X(21)=1; ! FOR SET 1F
   ;INITIALIZE,X(1)=6,X(2)=15,X(3)=10,X(4)=11,X(5)=10,X(6)=8,X(7)=0,
   ;          X(15)=3,X(16)=2,X(17)=3,X(18)=1,X(19)=5,X(20)=2,X(21)=2;
   ;                (FOR SET 2F ABOVE)
   ;INITIALIZE,X(1)=9,X(2)=15,X(3)=17,X(4)=18,X(5)=27,X(6)=12,X(7)=24,
   ;          X(8)=19,X(9)=16,X(10)=8,
   ;          X(15)=5,X(16)=4,X(17)=6,X(18)=3,X(19)=10,X(20)=6,X(21)=4;
   ;                (FOR SET 3F ABOVE)
 90 INITIALIZE,X(1)=9,X(2)=15,X(3)=17,X(4)=18,X(5)=27,X(6)=12,X(7)=24,
            X(8)=19,X(9)=16,X(10)=8,X(11)=16,X(12)=14,
            X(15)=5,X(16)=7,X(17)=9,X(18)=6,X(19)=10,X(20)=7,X(21)=5;
   ;                (FOR SET 4F ABOVE)
   ;
   ;
   ;      DISTANCE OF 0 LENGTH INDICATES AN UNUSED FLOW DIRECTION
   ;
   ;
   ;DISTANCES:1,1-8,6,20,4,17,4,4,1/0,0,0,11,0,1/28,0,4,0,1/4,0,0,1/
   ;          0,3,1/0,1/1;              ! SET 1F
   ;DISTANCES:1,1-8,28,12,2,7,0,27,1/0,0,12,5,5,1/8,0,5,0,1/5,0,0,1/
   ;          5,13,1/0,1/1;             ! SET 2F
   ;DISTANCES:1,1-8,7,28,18,35,0,27,1/0,0,19,22,7,1/11,0,7,32,1/28,7,0,1/
   ;          7,16,1/0,1/1;             ! SET 3F
100 DISTANCES:1,1-8,13,23,8,33,0,30,1/0,8,8,26,17,1/32,0,12,50,1/
            14,26,8,1/10,9,1/0,1/1;    ! SET 4F
   ;
   ; ALL EXCEPT FIRST 12 PARAMETERS SHOW TOTAL OPERATION TIME AND STD OF
   ; UNIT LOADS OR REAL JOBS AT THE DEPARTMENTS THEY VISIT
   ;
   ;PARAMETERS:1,104,4.2 : 2,180,4.9 : 3,140,4.1 : 4,187,3.5 : ! DEMAND DATA
   ;        5,165,5.8 :6,114,5.1  : 7,120,4.5 : 8,95,2.5  : ! FOR ALL 12
   ;        9,65,1.4  :10,50,2.2  :11,218,7.4 :12,245,8.4 : ! JOB TYPES
   ;        13,24.2,1.5 : 14,37.4,2.3 : 15,23.1,1.4 : ! OPERATIONS
   ;        16,71.5,4.3 : 17,19.2,1.2 : 18,73.2,4.2 : ! TIMES FOR
   ;        19,38.4,2.2 : 20,24,1.4   : 21,25.6,1.8 : ! JOBS
   ;        22,23.6,1.8 : 23,16.0,1.1 : 24,24.8,1.8 : ! A,B,C,D OF
   ;        25,41.0,2.6 : 26,27.0,1.7 : 27,23.0,1.5 : ! SET NO.1F
   ;        28,25.2,2.5 : 29,35.1,3.5 : 30,25.9,2.6 : ! **7 SETUP
   ;        31,16.8,1.7 : 32,11.3,1.1 : 33,22.7,2.3 : ! JOBS OF THE
   ;        34,22.1,2.2 ;                             !  SAME SET
   ;
   ;
   ;
   ;PARAMETERS:1,104,4.2 : 2,180,4.9 : 3,140,4.1 : 4,187,3.5 : ! DEMAND DATA
   ;        5,165,5.8 :6,114,5.1  : 7,120,4.5 : 8,95,2.5  : ! FOR ALL 12
   ;        9,65,1.4  :10,50,2.2  :11,218,7.4 :12,245,8.4 : ! JOB TYPES
   ;        13,25.3,1.7 : 14,38.9,2.4 : 15,23.1,1.4 : ! OPERATIONS
   ;        16,74.1,4.7 : 17,20,1.2   : 18,75.6,1.6 : ! TIMES FOR
   ;        19,37.8,2.2 : 20,24.6,1.5 : 21,25.6,1.8 : ! JOBS
   ;        22,24.3,1.8 : 23,16.4,1.2 : 24,24.4,1.8 : ! A,B,C,D,E,F OF
   ;        25,43,2.8   : 26,26,1.7   : 27,24,1.6   : ! SET NO.2F
   ;        28,10,0.9   : 29,21.8,1.8 : 30,12.3,1.2 :
   ;        31,31.8,2.2 : 32,27.5,1.9 : 33,56.7,4   :
   ;        34,27.3,1.9 : 35,28.4,1.9 :
```

```
  ;        36,27.7,2.8 : 37,27,2.7   : 38,26.5,2.7 : ! SET UP JOBS
  ;        39,27,2.7   : 40,18.2,1.8 : 41,41.8,4.2 : ! FOR SET 2F
  ;        42,28.3,2.8 ;
  ;
  ;
  ;PARAMETERS:1,104,4.2 : 2,180,4.9 : 3,140,4.1 : 4,187,3.5 : ! DEMAND DATA
  ;        5,165,5.8 :6,114,5.1  : 7,120,4.5 : 8,95,2.5  : ! FOR ALL 12
  ;        9,65,1.4  :10,50,2.2  :11,218,7.4 :12,245,8.4 : ! JOB TYPES
  ;        13,23.1,1.4 : 14,37.4,2.3 : 15,23.1,1.4 : ! OPERATIONS
  ;        16,71.5,4.3 : 17,18.0,1.0 : 18,73.2,4.2 : ! TIMES FOR
  ;        19,37.2,2.1 : 20,24.0,1.4 : 21,25.6,1.8 : ! JOBS
  ;        22,22.4,1.6 : 23,16.0,1.1 : 24,24.0,1.7 : ! A,B,C,D,E,F
  ;        25,41.0,2.6 : 26,25.0,1.6 : 27,23.0,1.5 : ! H,Q,R,S OF
  ;        28,9.0,0.7  : 29,20.4,1.7 : 30,12.0,1.0 : ! SET NO.3F
  ;        31,30.6,2.0 : 32,27.0,1.8 : 33,54.9,3.7 :
  ;        34,25.2,1.7 : 35,27.9,1.9 :
  ;        36,11.5,1.0 : 37,10.5,0.9 : 38,10.5,0.9 :
  ;        39,32.5,2.9 : 40,15.0,1.3 : 41,10.5,0.9 :
  ;        42,15.5,1.4 : 43,15.5,1.4 :
  ;        44,32.5,2.9 : 45,8.4,0.8  : 46,8.0,0.8  :
  ;        47,28.0,2.8 : 48,12.0,1.2 : 49,16.4,1.6 :
  ;        50,19.2,1.6 : 51,15.0,1.2 : 52,12.0,1.0:53,18.6,1.5:
  ;        54,24.6,2.5 : 55,28.1,2.8 : 56,28.7,2.9 : ! SET UP JOBS
  ;        57,21,2.1   : 58,12.8,1.3 : 59,31.7,3.2 : ! FOR SET 3F
  ;        60,25.2,2.5 ;
  ;
  ;
  ;
110 PARAMETERS:1,104,4.2 : 2,180,4.9 : 3,140,4.1 : 4,187,3.5 : ! DEMAND DATA
           5,165,5.8 :6,114,5.1  : 7,120,4.5 : 8,95,2.5  : ! FOR ALL 12
           9,65,1.4  :10,50,2.2  :11,218,7.4 :12,245,8.4 : ! JOB TYPES
           13,23.1,1.4 : 14,37.4,2.3 : 15,23.1,1.4 : ! OPERATIONS
           16,69.3,4.2 : 17,18.0,1.0 : 18,68.4,3.9 : ! TIMES FOR
           19,32.4,1.9 : 20,24.0,1.4 : 21,25.6,1.8 : ! JOBS
           22,22.4,1.6 : 23,16.0,1.1 : 24,24.0,1.7 : ! A,B,C,D,E,F
           25,41.0,2.6 : 26,25.0,1.6 : 27,23.0,1.5 : ! H,Q,R,S,U,V
           28,9.0,2.7  : 29,20.4,1.7 : 30,12.0,1.0 : ! OF SET NO.4F
           31,30.6,2.0 : 32,27.0,1.8 : 33,51.3,3.4 :
           34,25.2,1.7 : 35,24.3,1.6 :
           36,11.5,1.0 : 37,10.5,0.9 : 38,10.5,0.9 :
           39,31.5,2.8 : 40,15.0,1.3 : 41,10.5,0.9 :
           42,15.5,1.4 : 43,13.5,1.2 :
           44,31.5,2.8 : 45,9.2,0.9  : 46,8.0,0.8  :
           47,27.2,2.7 : 48,12.0,1.2 : 49,16.4,1.6 :
           50,19.2,1.6 : 51,15.0,1.2 : 52,12.0,1.0:53,16.2,1.3:
           54,39.0,2.2 : 55,27.3,1.5 : 56,36.4,2.0 :
           57,69.7,3.4 : 58,54.4,2.6 : 59,45.9,2.2:60,39.1,1.9:
           61,25.4,2.5 : 62,28.6,2.9 : 63,24.7,2.5 : ! SET UP JOBS
           64,21.9,2.2 : 65,14.2,1.4 : 66,30.0,3.0 : ! FOR SET 4F
           67,23.8,2.4 ;
  ;
120 REPLICATE,1,0.,288000.,NO,NO,10000.;
  ;TRACE,0,960,,NT(1),NQ(1),NQ(2),NQ(3);
  END;
```

Sample Functional Facility Output Using Problem Set No.3

SIMAN RUN PROCESSOR RELEASE 3.0
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SIMAN SUMMARY REPORT

RUN NUMBER 1 OF 1

PROJECT: FUNCTIONAL FACILITY
ANALYST: H SARPER
DATE : 6/30/1988

RUN ENDED AT TIME : 0.2880E+06

TALLY VARIABLES

NUMBER	IDENTIFIER	AVERAGE	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	NUMBER OF OBS.
1	FLOW TIME JOB A	445.26025	39.99785	316.50000	533.43750	5203
2	FLOW TIME JOB B	328.14941	55.37039	198.68750	435.81250	8410
3	FLOW TIME JOB C	434.00049	39.57451	334.06250	554.96484	9836
4	FLOW TIME JOB D	174.50542	37.99371	110.43750	324.56250	10512
5	FLOW TIME JOB E	349.10229	37.39813	275.81250	435.18750	15626
6	FLOW TIME JOB F	486.22144	56.93741	388.93750	599.50000	7051
7	FLOW TIME JOB H	467.73950	67.56493	297.06250	573.25000	13623
8	FLOW TIME JOB Q	538.90674	35.10956	446.37500	683.68750	10713
9	FLOW TIME JOB R	440.82690	20.71454	401.18750	714.37500	9147
10	FLOW TIME JOB S	325.22339	25.86089	251.93750	422.37500	4550
11	DPT1 STUP JOB	24.64609	2.51093	15.62500	33.25000	2895
12	DPT2 STUP JOB	28.22198	2.70413	19.43750	37.22656	2316
13	DPT3 STUP JOB	28.92650	2.92718	19.00000	46.87500	3474
14	DPT4 STUP JOB	21.09329	2.13381	14.12500	28.93750	1737
15	DPT5 STUP JOB	26.59978	7.09776	10.12500	46.87500	5790
16	DPT6 STUP JOB	40.71857	6.72822	22.00000	60.43750	3474
17	DPT7 STUP JOB	37.08557	8.94089	19.06250	61.56250	2316
18	JOB A DMD IN UN	8.96716	0.43547	7.00000	10.00000	5208
	job A demand in unit loads					
19	JOB B DMD IN UN	14.50172	0.52790	13.00000	16.00000	8423
20	JOB C DMD IN UN	17.00162	0.58687	15.00000	19.00000	9841
21	JOB D DMD IN UN	18.18280	0.43736	17.00000	19.00000	10530
22	JOB E DMD IN UN	26.99890	1.01465	23.00000	30.00000	15650
23	JOB F DMD IN UN	12.16310	0.63329	10.00000	14.00000	7057
24	JOB H DMD IN UN	23.50311	0.94782	20.00000	27.00000	13639
25	JOB Q DMD IN UN	18.51080	0.58582	16.00000	20.00000	10730
26	JOB R DMD IN UN	15.78015	0.45483	14.00000	17.00000	9147
27	JOB S DMD IN UN	7.84573	0.44461	7.00000	9.00000	4557
28	DPT1 SETUP	5.00000	0.00000	5.00000	5.00000	2900
	number of set-up jobs in department No.1					

29	DPT2 SETUP	4.00000	0.00000	4.00000	4.00000	2320
30	DPT3 SETUP	6.00000	0.00000	6.00000	6.00000	3480
31	DPT4 SETUP	3.00000	0.00000	3.00000	3.00000	1740
32	DPT5 SETUP	10.00000	0.00000	10.00000	10.00000	5800
33	DPT6 SETUP	6.00000	0.00000	6.00000	6.00000	3480
34	DPT7 SETUP	4.00000	0.00000	4.00000	4.00000	2320

DISCRETE CHANGE VARIABLES

NUMBER	IDENTIFIER	AVERAGE	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	TIME PERIOD
1	DEPT 1 QUEUE	42.55722	35.09416	0.00000	101.00000	278000.00
2	DEPT 2 QUEUE	7.83239	7.52961	0.00000	26.00000	278000.00
3	DEPT 3 QUEUE	27.50392	14.02140	0.00000	56.00000	278000.00
4	DEPT 4 QUEUE	8.44441	7.75191	0.00000	27.00000	278000.00
5	DEPT 5 QUEUE	6.24603	5.72405	0.00000	26.00000	278000.00
6	DEPT 6 QUEUE	2.59163	3.35213	0.00000	19.00000	278000.00
7	DEPT 7 QUEUE	3.78542	4.73675	0.00000	21.00000	278000.00
8	CT Q ATR DP1	0.62933	1.03790	0.00000	9.00000	278000.00
9	CT Q ATR DP2	0.27012	0.61262	0.00000	7.00000	278000.00
	Cart queue formed after using department No.1					
10	CT Q ATR DP3	0.35702	0.79116	0.00000	8.00000	278000.00
11	CT Q ATR DP4	0.25699	0.56635	0.00000	5.00000	278000.00
12	CT Q ATR DP5	0.97823	2.02746	0.00000	16.00000	278000.00
13	CT Q ATR DP6	0.71631	1.22207	0.00000	11.00000	278000.00
14	CT Q ATR DP7	0.55145	1.15141	0.00000	10.00000	278000.00
15	DEPT 1 UTIL.	4.33628	1.59967	0.00000	5.00000	278000.00
16	DEPT 2 UTIL.	3.41248	1.23293	0.00000	4.00000	278000.00
17	DEPT 3 UTIL.	5.62546	1.40277	0.00000	6.00000	278000.00
18	DEPT 4 UTIL.	2.29227	1.21930	0.00000	3.00000	278000.00
19	DEPT 5 UTIL.	8.90797	2.05941	0.00000	10.00000	278000.00
20	DEPT 6 UTIL.	4.87770	1.81703	0.00000	6.00000	278000.00
21	DEPT 7 UTIL.	2.94181	1.59683	0.00000	4.00000	278000.00
22	CART UTIL.	2.37508	0.92446	0.00000	3.00000	278000.00

1

Model Frame for Cellular Facility in Problem Set No.3C2-1:

This is one of the nineteen SIMAN simulation codes utilized in Chapter six.

```
BEGIN;
;
; *******************************************************************
;
;          PROBLEM SET NO. 3 (CELLULAR FACILITY, 2 CELLS, CELL # 1)
; *******************************************************************
;
;
SYNONYMS:JOBTYPE=A(3);
;
; SETUP JOBS ARE CREATED AT THE BEGINNING OF EACH PERIOD, ASSIGNED
; HIGH PRIORITY FOR SEIZING MACHINES AT THE ONLY ONE ZONE/STATION
; THEY VISIT IN ADDITION TO EXIT STATION
;
      CREATE,X(15):480:MARK(2);
      TALLY:26,X(15);
      ASSIGN:A(3) = 10;
      ASSIGN:A(6) = 1 :NEXT(START);
      .........................
      (other set-up jobs are created
      with A(3)= 11,12,13,14,15,and 16)
      ..............................
      CREATE,X(17):480:MARK(2);
      ASSIGN:A(6) = 1 :NEXT(START);
;
; REGULAR JOBS ARE CREATED. A(6) IS NOT ASSIGNED AS 1 FOR REGULAR
; JOBS/UNIT LOADS.
;
; DETERMINATION OF RANDOM NUMBER OF UNIT LOADS OF EACH JOB TYPE
;..............................................................
;
      CREATE,X(1):480:MARK(2);
      TALLY:17,X(1);          NUMBER OF UNIT LOADS OF JOB A
      ASSIGN:X(1) = AINT((RN(1,1)/11)) ;
      ASSIGN:A(3) = 1 :NEXT(START) ;   A(3) HAS JOB TYPE OF 1 OR A
      CREATE,X(2):480:MARK(2);         ; JOB B
      TALLY:18,X(2);
      ASSIGN:X(2) = AINT((RN(2,1)/12)) ;
        ASSIGN:X(2) = X(2)-X(3) ;
      ASSIGN:A(3) = 2 :NEXT(START) ;
      CREATE,X(3):480:MARK(2);         ; JOB B1  (DETERMINISTIC AMOUNT)
      TALLY:19,X(3);
      ASSIGN:A(3) = 3 :NEXT(START) ;
      CREATE,X(4):480:MARK(2);         ;  JOB F
      TALLY:20,X(4);
      ASSIGN:X(4) = AINT((RN(6,1)/9)) ;
      ASSIGN:A(3) = 4 :NEXT(START) ;
      CREATE,X(5):480:MARK(2);         ; JOB H
      TALLY:21,X(5);
      ASSIGN:X(5) = AINT((RN(7,1)/5)) ;
        ASSIGN:X(5) = X(5)-X(6)-X(7);
      ASSIGN:A(3) = 5 :NEXT(START) ;
      CREATE,X(6):480:MARK(2);         ; JOB H1 (DETERMINISTIC AMOUNT)
```

```
       TALLY:22,X(6);
       ASSIGN:A(3) = 6 :NEXT(START) ;
       CREATE,X(7):480:MARK(2);       ; JOB H2 (DETERMINISTIC AMOUNT)
       TALLY:23,X(7);
       ASSIGN:A(3) = 7 :NEXT(START) ;
       CREATE,X(8):480:MARK(2);       ; JOB R
       TALLY:24,X(8);
       ASSIGN:X(8) = AINT((RN(9,1)/4)) ;
         ASSIGN:X(8) = X(8)-X(9);
       ASSIGN:A(3) = 8 :NEXT(START) ;
       CREATE,X(9):480:MARK(2);       ; JOB R1 (DETERMINISTIC AMOUNT)
       TALLY:25,X(9);
       ASSIGN:A(3) = 9 :NEXT(START) ;
START   ASSIGN:NS='JOBTYPE';
;  EACH UNIT LOAD IS SENT TO ITS FIRST MINI-DEPT. TO BE VISITED AND
;  THIS FIRST VISIT IS ASSUMED INSTANT.
;
       ROUTE:0.0,SEQ;
;
       STATION,1-7;   EACH STATION CORRESPONDS TO A MINI-DEPARTMENT
;
;     this section is same as the FUNCTIONAL facility SIMAN Model
; ..............................................................
; DESTINED TO THE QUEUE OF THE NEXT MINI-DEPARTMENT.
;
          BRANCH,1:
; ONCE TRANSPORTED TO NEXT M-DEPT. IN SEQUENCE, PROC. TIME IS RETRIEVED
;...............................................................
; TRANSPORTER THAT WILL TRANSPORT IT TO THE QUEUE IN NEXT MINI-DEPT.
       REQUEST:CART;      ! there is only one cart, no cart selection
 END;
```

Resource, Distance, Parameters, and Sequences elements of SIMAN Experiment Frames:

Following list contains nineteen RESOURCES/DISTANCES elements used in nineteen cells of four problem sets.

```
;
RESOURCES:1-7,MACHINE,1,1,2,1,3,0,1;   ! 1C21   # 1  SET 1
RESOURCES:1-7,MACHINE,1,1,1,1,0,2,0;   ! 1C22   # 2
RESOURCES:1-7,MACHINE,2,1,1,1,3,1,1;   ! 2C21   # 3  SET 2
RESOURCES:1-7,MACHINE,2,1,3,1,0,2,0;   ! 2C22   # 4
RESOURCES:1-7,MACHINE,1,1,0,1,3,1,1;   ! 2C31   # 5
RESOURCES:1-7,MACHINE,2,1,0,2,1,1,0;   ! 2C32   # 6
RESOURCES:1-7,MACHINE,1,1,1,0,0,1,0;   ! 2C33   # 7
RESOURCES:1-7,MACHINE,3,2,3,1,8,2,2;   ! 3C21   # 8  SET 3
RESOURCES:1-7,MACHINE,2,2,4,2,1,4,1;   ! 3C22   # 9
RESOURCES:1-7,MACHINE,2,1,3,1,7,1,3;   ! 3C31   #10
RESOURCES:1-7,MACHINE,2,2,0,2,2,2,1;   ! 3C32   #11
RESOURCES:1-7,MACHINE,0,2,4,0,1,3,0;   ! 3C33   #12
RESOURCES:1-7,MACHINE,2,3,3,1,6,2,1;   ! 4C31   #13 SET 4
RESOURCES:1-7,MACHINE,2,3,4,3,0,2,2;   ! 4C32   #14
RESOURCES:1-7,MACHINE,2,2,3,1,4,3,2;   ! 4C33   #15
```

```
RESOURCES:1-7,MACHINE,2,2,1,1,6,1,1;     ! 4C41    #16
RESOURCES:1-7,MACHINE,1,2,3,3,0,2,2;     ! 4C42    #17
RESOURCES:1-7,MACHINE,1,2,4,0,1,3,0;     ! 4C43    #18
RESOURCES:1-7,MACHINE,2,2,2,1,3,3,1;     ! 4C44    #19
;
;       DISTANCE OF 0 LENGTH INDICATES AN UNUSED FLOW DIRECTION
;
DISTANCES:1,1-8,0,14,0,3,0,0,1/6,0,0,0,5,1/0,5,0,0,1/0,0,0,1/
        0,3,1/0,1/1;       ! 1C21  SET 1
DISTANCES:1,1-8,5,0,6,0,0,0,1/0,0,0,3,0,1/0,0,2,0,1/0,0,0,1/
        0,0,1/0,1/1;       ! 1C22  SET 1
DISTANCES:1,1-8,15,2,5,4,0,0,1/0,0,0,0,5,1/0,0,4,13,1/4,0,0,1/
        4,4,1/0,1/1;       ! 2C21  SET 2
DISTANCES:1,1-8,17,2,3,0,0,0,1/0,0,0,7,0,1/0,0,3,0,1/0,0,0,1/
        0,0,1/0,1/1;       ! 2C22  SET 2
DISTANCES:1,1-8,0,0,0,3,20,0,1/0,0,0,2,4,1/0,0,0,0,1/3,5,0,1/
        0,6,1/0,1/1;       ! 2C31  SET 2
DISTANCES:1,1-8,3,0,0,0,0,0,1/0,0,0,8,0,1/0,0,2,0,1/0,0,0,1/
        0,0,1/0,1/1;       ! 2C32  SET 2
DISTANCES:1,1-8,3,0,3,3,0,0,1/0,0,0,5,0,1/0,0,0,0,1/9,0,0,1/
        0,0,1/0,1/1;       ! 2C33  SET 2

DISTANCES:1,1-8,5,16,6,18,0,6,1/0,0,5,0,4,1/8,0,5,30,1/18,4,0,1/
        6,15,1/0,1/1;      ! 3C21  SET 3
DISTANCES:1,1-8,6,3,6,0,0,0,1/0,0,0,20,9,1/0,0,3,14,1/0,3,0,1/
        0,3,1/0,1/1;       ! 3C22  SET 3
DISTANCES:1,1-8,0,7,0,3,0,0,1/0,0,0,0,42,1/23,0,7,12,1/6,0,32,1/
        3,3,1/0,1/1;       ! 3C31  SET 3
DISTANCES:1,1-8,4,0,6,0,0,0,1/0,0,0,4,16,1/0,0,0,0,1/4,18,13,1/
        5,0,1/0,1/1;       ! 3C32  SET 3
DISTANCES:1,1-8,0,0,0,0,0,0,1/13,0,6,4,0,1/0,0,4,0,1/0,0,0,1/
        3,0,1/0,1/1;       ! 3C33  SET 3

DISTANCES:1,1-8,36,14,5,5,0,0,1/0,0,5,9,2,1/8,0,6,0,1/5,0,0,1/
        12,12,1/0,1/1;     ! 4C31  SET 4
DISTANCES:1,1-8,5,5,7,0,5,0,1/0,0,0,7,8,1/7,0,11,0,1/0,0,5,1/
        0,0,1/0,1/1;       ! 4C32  SET 4
DISTANCES:1,1-8,8,20,0,9,26,2,1/0,2,4,0,0,1/0,0,6,8,1/0,7,0,1/
        7,4,1/0,1/1;       ! 4C33  SET 4
DISTANCES:1,1-8,7,8,6,4,0,0,1/0,0,6,0,3,1/3,0,0,0,1/4,0,0,1/
        15,7,1/0,1/1;      ! 4C41  SET 4
DISTANCES:1,1-8,2,0,5,0,0,0,1/0,0,0,4,12,1/4,0,8,0,1/0,7,4,1/
        0,0,1/0,1/1;       ! 4C42  SET 4
DISTANCES:1,1-8,4,4,0,0,0,0,1/0,0,7,4,0,1/0,0,4,0,1/0,0,0,1/
        3,0,1/0,1/1;       ! 4C43  SET 4
DISTANCES:1,1-8,0,4,0,16,0,5,1/0,2,0,0,0,1/0,0,6,4,1/0,4,0,1/
        4,2,1/0,1/1;       ! 4C44  SET 4
```

Actual list of parameters is too long for listing and a segment of it is shown below.

```
PARAMETERS:1,104,4.2 : 2,180,4.9 : 3,140,4.1 : 4,187,3.5 : ! DEMAND DATA
        5,165,5.8 :6,114,5.1  : 7,120,4.5 : 8,95,2.5  : ! FOR ALL 12
        9,65,1.4  :10,50,2.2  :11,218,7.4 :12,245,8.4 : ! JOB TYPES
        13,25.3,1.5 : 14,37.4,2.3 : 15,23.1,1.4 : ! OPERATIONS
        16,71.5,4.3 : 17,23.1,1.4 : 18,37.4,2.3 : ! TIMES FOR
```

```
        19,23.1,1.4 : 20,71.5,4.3 : 21,20.4,1.2 : ! JOBS
        22,73.2,4.2 : 23,38.4,2.2 : 24,24.0,1.4 : ! A,A1,B,B1 OF
        25,20.4,1.2 : 26,73.2,4.2 : 27,62.4,2.6 : ! SET NO.1C21
        28,32.0,3.2 : 29,28.4,2.8 : 30,11.4,1.1 : ! **7 SETUP
        31,17.2,1.7 : 32,8.8,0.9 : 33,0,0 :       ! JOBS OF THE
        34,17.2,1.7 ;                             !  SAME SET
*****
SKIPPING TO CELL NO.1 IN PROBLEM SET NO.3 WITH 2 CELLS
BEGIN;
PARAMETERS:1,104,4.2 : 2,180,4.9 : 3,140,4.1 : 4,187,3.5 : ! DEMAND DATA
        5,165,5.8 : 6,114,5.1  : 7,120,4.5 : 8,95,2.5  : ! FOR ALL 12
        9,65,1.4  :10,50,2.2  :11,218,7.4 :12,245,8.4 : ! JOB TYPES
        13,23.1,1.4 : 14,37.4,2.3 : 15,23.1,1.4 : ! OPERATIONS
        16,71.5,4.3 : 17,18.0,1.0 : 18,73.2,4.2 : ! TIMES FOR
        19,37.2,2.1 : 20,24.0,1.4 : 21,18.0,1.0 : ! JOBS
        22,73.2,4.2 : 23,62.4,2.6 : 24,30.6,2.0 : !
        25,27.0,1.8 : 26,54.9,3.7 : 27,25.2,1.7 : !
        28,27.9,1.9 : 29,11.5,1.0 : 30,10.5,0.9 : !
        31,10.5,0.9 : 32,32.5,2.9 : 33,15.0,1.3 :
        34,11.5,1.0 : 35,10.5,0.9 : 36,10.5,0.9 :
        37,32.5,2.9 : 38,15.0,1.3 : 39,11.5,1.0 : !
        40,21.0,1.3 : 41,32.5,2.9 : 42,15.0,1.3 : !
        43,8.4,0.8  : 44,8.0,0.8 : 45,28.0,2.8  :
        46,12.0,1.2 : 47,16.4,1.6: 48,15.0,1.3  :
        49,8.0,0.8  : 50,28.0,2.8 : 51,12.0,1.2 : 52,16.4,1.6 :
        53,25.1,2.5 : 54,37.8,3.8: 55,18.9,1.9  :
        56,27.8,2.8 : 57,10.5,1.0: 58,31.5,3.2  :
        59,25.7,2.6 ;
;
SKIPPING TO CELL NO.4 IN PROBLEM SET NO.4 WITH 4 CELLS
;
PARAMETERS:1,104,4.2 : 2,180,4.9 : 3,140,4.1 : 4,187,3.5 : ! DEMAND DATA
        5,165,5.8 : 6,114,5.1  : 7,120,4.5 : 8,95,2.5  : ! FOR ALL 12
        9,65,1.4  :10,50,2.2  :11,218,7.4 :12,245,8.4 : ! JOB TYPES
        13,30.6,2.0 : 14,27.0,1.8 : 15,51.3,3.4 : ! OPERATIONS
        16,25.2,1.7 : 17,24.3,1.6 : 18,10.5,0.9 : ! TIMES FOR
        19,15.5,1.4 : 20,15.5,1.4 : 21,31.5,2.8 : ! JOBS
        22,39.0,2.2 : 23,27.3,1.5 : 24,36.4,2.0 : !
        25,12.5,1.3 :
        26,16.7,1.7 : 27,16.9,1.7 : 28,21.1,2.1: ! **7 SETUP
        29,14.3,1.4 : 30,30.7,3.1 : 31,17.6,1.8; ! JOBS
```

Segment of sequences elements is shown below :

```
;
SEQUENCES:1,1,RN(13,1)/3,RN(14,1)/4,RN(15,1)/5,RN(16,1)/8: ! JOB A (1C21)
        2,4,RN(17,1)/3,RN(18,1)/4,RN(19,1)/3,RN(20,1)/8: ! JOB A1
        3,1,RN(21,1)/5,RN(22,1)/7,RN(23,1)/2,RN(24,1)/8: ! JOB B (1C21)
        4,1,RN(25,1)/3,RN(26,1)/2,RN(27,1)/8:            ! JOB B1
        5,1,RN(28,1)/8:  ! SETUP JOB FOR MINI-DEPARTMENT NO.1
        6,2,RN(29,1)/8:  ! SETUP JOB FOR MINI-DEPARTMENT NO.2
        ....................................................
       11,7,RN(34,1)/8;  ! SETUP JOB FOR MINI-DEPARTMENT NO.7
;
```

```
SEQUENCES ELEMENT OF 17 OTHER CELLS ARE NOT SHOWN
;
SEQUENCES:1,3,RN(13,1)/6,RN(14,1)/5,RN(15,1)/1,RN(16,1)/7,RN(17,1)/8: ! F
       2,1,RN(18,1)/3,RN(19,1)/6,RN(20,1)/5,RN(21,1)/8  : !JOB Q (4C44)
       3,6,RN(22,1)/4,RN(23,1)/2,RN(24,1)/8:            !JOB U
        4,1,RN(25,1)/8:  ! SETUP JOB FOR MINI-DEPARTMENT NO.1
        ..................................................
D6       10,7,RN(31,1)/8;  ! SETUP JOB FOR MINI-DEPARTMENT NO.7
;
```

Sample Cellular Facility Output Using Problem Set No.3 (3C2-1)

SIMAN RUN PROCESSOR RELEASE 3.0
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SIMAN SUMMARY REPORT

RUN NUMBER 1 OF 1

PROJECT: CELLULAR FACILITY
ANALYST: H SARPER
DATE : 7/ 4/1988

RUN ENDED AT TIME : 0.2880E+06

TALLY VARIABLES

NUMBER	IDENTIFIER	AVERAGE	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	NUMBER OF OBS.
1	FLOW TIME JOB A	466.75977	99.89641	273.75000	846.50000	5171
2	FLOW TIME JOB B	396.41138	93.95242	232.06250	719.18750	6662
3	FLOW TIME JOB B1	408.06738	34.20821	331.25000	503.55859	1738
4	FLOW TIME JOB F	23795.66	12573.90	1887.06	45778.94	5937
5	FLOW TIME JOB H	23903.29	12589.78	2127.95	45901.94	8523
6	FLOW TIME JOB H1	24131.88	12583.27	2362.46	46035.25	1952
7	FLOW TIME JOB H2	23794.41	12583.43	2167.80	45600.44	976
8	FLOW TIME JOB R	23824.32	12589.36	1947.54	45782.12	6733
9	FLOW TIME JOB R1	630.56055	103.04648	417.31250	826.91016	1158
10	DPT1 STUP JOB	29.65714	7.79770	17.06250	58.25000	1737
11	DPT2 STUP JOB	47.66000	8.81359	27.25000	74.76953	1158
12	DPT3 STUP JOB	23.57198	6.85169	13.75000	52.81250	1737
13	DPT4 STUP JOB	34.88519	6.09085	20.68750	64.34375	579
14	DPT5 STUP JOB	22.38960	8.14394	7.56250	59.18750	4632
15	DPT6 STUP JOB	44.02235	9.41692	22.12500	70.50000	1158
16	DPT7 STUP JOB	40.66466	9.99235	17.18750	70.80859	1158
17	JOB A DMD IN UN	8.95615	0.42641	8.00000	10.00000	5177
18	JOB B DMD IN UN	11.50428	0.52982	10.00000	13.00000	6665
19	JOB B1 DMD IN UN	3.00000	0.00000	3.00000	3.00000	1740

20	JOB F DMD IN UN	12.17182	0.63185	10.00000	14.00000	7048
21	JOB H DMD IN UN	17.49002	0.95192	14.00000	21.00000	10124
22	JOB H1 DMD IN UN	4.00000	0.00000	4.00000	4.00000	2320
23	JOB H2 DMD IN UN	2.00000	0.00000	2.00000	2.00000	1160
24	JOB R DMD IN UN	13.78475	0.45181	12.00000	15.00000	7986
25	JOB R1 DMD IN UN	2.00000	0.00000	2.00000	2.00000	1160
26	DPT1 SETUP	3.00000	0.00000	3.00000	3.00000	1740
27	DPT2 SETUP	2.00000	0.00000	2.00000	2.00000	1160
28	DPT3 SETUP	3.00000	0.00000	3.00000	3.00000	1740
29	DPT4 SETUP	1.00000	0.00000	1.00000	1.00000	580
30	DPT5 SETUP	8.00000	0.00000	8.00000	8.00000	4640
31	DPT6 SETUP	2.00000	0.00000	2.00000	2.00000	1160
32	DPT7 SETUP	2.00000	0.00000	2.00000	2.00000	1160

DISCRETE CHANGE VARIABLES

NUMBER	IDENTIFIER	AVERAGE	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	TIME PERIOD
1	MDPT 1 QUEUE	21.83430	16.88785	0.00000	50.00000	278000.00
2	MDPT 2 QUEUE	7.08692	7.98054	0.00000	30.00000	278000.00
3	MDPT 3 QUEUE	7.89762	5.71274	0.00000	24.00000	278000.00
4	MDPT 4 QUEUE	9.64330	6.95154	0.00000	26.00000	278000.00
5	MDPT 5 QUEUE	5.78211	5.97092	0.00000	26.00000	278000.00
6	MDPT 6 QUEUE	2394.10	1303.07	166.00	4646.00	278000.00
7	MDPT 7 QUEUE	3.80278	3.12260	0.00000	13.00000	278000.00
8	CT Q ATR DP1	0.35975	0.76096	0.00000	7.00000	278000.00
9	CT Q ATR DP2	0.15522	0.40557	0.00000	4.00000	278000.00
10	CT Q ATR DP3	0.12158	0.37063	0.00000	3.00000	278000.00
11	CT Q ATR DP4	0.10592	0.32685	0.00000	4.00000	278000.00
12	CT Q ATR DP5	0.34699	0.68281	0.00000	7.00000	278000.00
13	CT Q ATR DP6	0.15022	0.39363	0.00000	3.00000	278000.00
14	CT Q ATR DP7	0.12567	0.37689	0.00000	4.00000	278000.00
15	MDPT 1 UTIL.	2.52427	0.94653	0.00000	3.00000	278000.00
16	MDPT 2 UTIL.	1.94442	0.28333	0.00000	2.00000	278000.00
17	MDPT 3 UTIL.	2.73663	0.68551	0.00000	3.00000	278000.00
18	MDPT 4 UTIL.	0.95465	0.20807	0.00000	1.00000	278000.00
19	MDPT 5 UTIL.	6.95570	1.94459	0.00000	8.00000	278000.00
20	MDPT 6 UTIL.	1.99980	0.00000	2.00000	2.00000	278000.00
21	MDPT 7 UTIL.	1.64227	0.73548	0.00000	2.00000	278000.00
22	CART UTIL.	0.77214	0.41945	0.00000	1.00000	278000.00

Appendix M. Description of MICRO-CRAFT Layout Package

This package is designed to make four layout related programs accessible through a menu which lists the programs as

1. FROM/TO Chart Generator,
2. MICRO-CRAFT,
3. Optimum Facility Location, and
4. Layout Evaluation.

The first two programs are chained together by first running program No.1 above to store FROM/TO charts needed in running MICRO-CRAFT program which can also create its own chart if one is not already available on diskette.

MICRO-CRAFT, an adaptation of CRAFT, uses two subprograms, CRAFT and CGRAPH, and two data/graphical files, CFLAG and CDATA. Final output requires little or no adjustment of the department borders because it assumes that departments are arranged in bays. There can be a maximum of fourty departments. A good initial layout must be input in order to reduce amount of time, usually from five to twenty-five minutes, taken on a micro-computer. Other required inputs are the area of each department, number of bays, overall plant dimensions (rectangular), trip cost of each job type in $/per unit distance, and user's choice on the euclidean or the rectilinear distance adaption in cost calculations.

MICRO-CRAFT allows user to fix some departments and stop the computations after each iteration before the best possible layout is found. Once a layout (final one or an intermediate) is found, the user may specify options such as the modification of the input data and reruning the program, or printing a hard copy of the layout. MICRO-CRAFT is an excellent alternative to traditional main-frame CRAFT which is coded in FORTRAN and very difficult to use due to the complicated and confusing input/output procedures. FROM/TO chart generator program prompts the user for information on total production quantity, batch/unit load size, and the sequence of departments to be visited by each job type. The output is stored on diskette for future use.

Appendix N. Derivation of Probability Density Functions for Product and Inverse of Normal Variables

In Chapter four, it was pointed out that overall chance constrained programming approach avoided cases such as product (non-zero) of two independent normal distributions, operation time, t, and demand, D, and the inverse of normally distributed operation time variable (subscripts and superscripts that accompany these two variables are dropped). For the sake of completeness, this section presents the derivation of probability density functions for the following cases where the distributions of D and t are independent of each other and the following inequalities hold :

$$\sigma_t \neq \sigma_D,$$

$$\mu_t \neq u_D$$

1. **Case 1)** D t (Product of two normals)

2. **Case 2)** $\frac{1}{t}$ (Inverse of a normal for $t > 0$)

Case 1)- $Z = D t$. The goal is the determination of f(Z) which is the probability density function, p.d.f., of the resulting distribution. The general formula between p.d.f and cumulative density function (c.d.f.) is :

$$F(Z) = \iint_{R_Z} f(t,D)\, \partial t\, \partial D \quad \text{where } R_Z \text{ is the area such that } P\{(t, D) \in R_Z\}$$

and $f_Z(Z) = \frac{\partial}{\partial Z} F_Z(Z)$.

Because t and D are independent, $F(Z) = \iint_{R_Z} f_t(t)\, f_D(D)\, \partial t\, \partial D$ and

$$f_t(t) = \frac{1}{\sigma_t \sqrt{2\pi}}\, e^{-(t-\mu_t)^2 / 2\sigma_t^2} \qquad f_D(D) = \frac{1}{\sigma_D \sqrt{2\pi}}\, e^{-(D-\mu_D)^2 / 2\sigma_D^2}$$

Since both the demand and the operation time must be non-negative, their product, Z, can not be negative, but $Z < 0$ possibility will be included any way in the overall p.d.f. expression derivation process below. Figure 47 on page 358 shows the areas for which each Z sign possibility regions are defined.

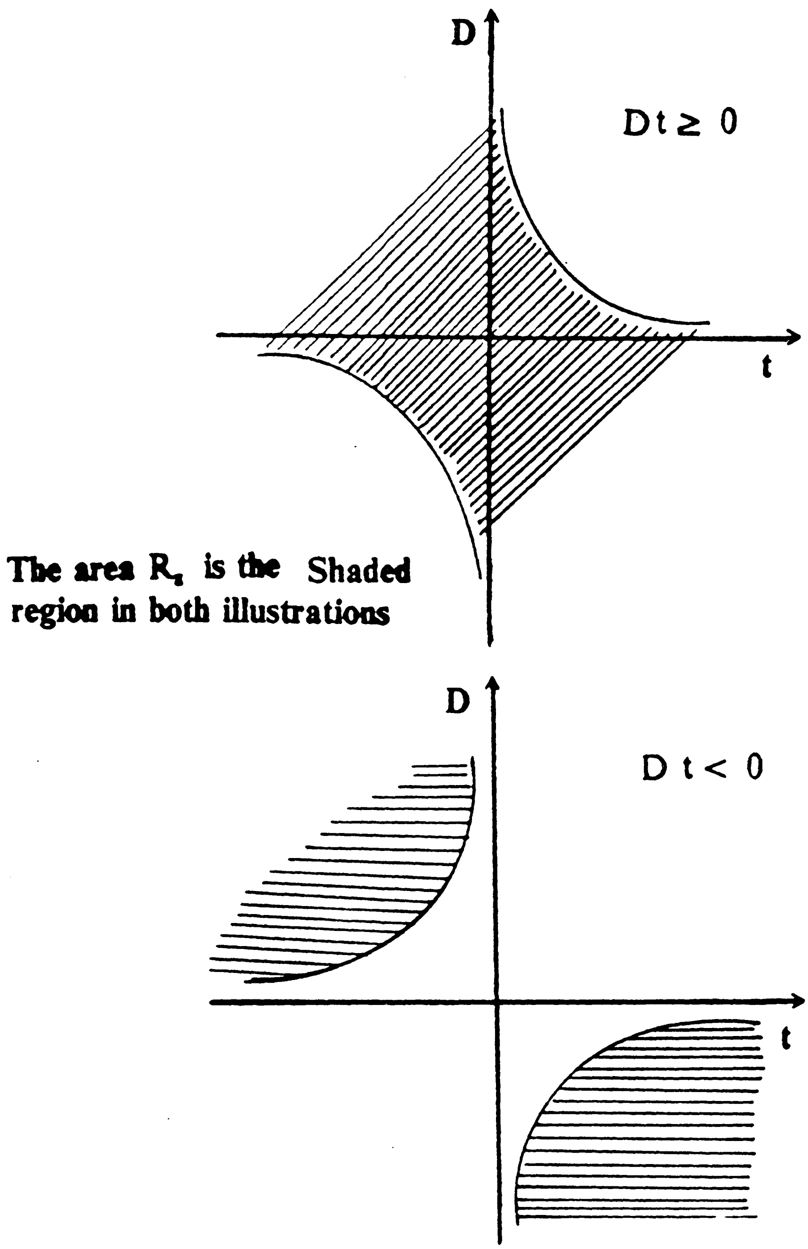

Figure 47. Regions of Definition for the Product of Two Independent Normal Variables

i) Positive Product $Z = D\,t > 0$:

$$F_Z(Z) = \int_{-\infty}^{0}\int_{Z/t}^{\infty} f_t(t)\ f_D(D)\ \partial t\,\partial D \ + \int_{0}^{\infty}\int_{-\infty}^{Z/t} f_t(t)\, f_D(D)\ \partial t\,\partial D$$

$$F_Z(Z) = -\int_{-\infty}^{0} \{ \int_{\infty}^{Z/t} f_D(D)\ \partial D \}\ f_t(t)\ \partial t \ + \int_{0}^{\infty} \{ \int_{-\infty}^{Z/t} f_D(D)\ \partial D \}\ f_t(t)\ \partial t$$

$$f_Z(Z) = \frac{\partial F_Z(Z)}{\partial Z} = -\int_{-\infty}^{0} \{ \frac{\partial}{\partial Z} \int_{\infty}^{Z/t} f_D(D)\ \partial D \}\ f_t(t)\ \partial t \ + \int_{0}^{\infty} \{ \frac{\partial}{\partial Z} \int_{-\infty}^{Z/t} f_D(D)\ \partial D \}\ f_t(t)\ \partial t$$

Applying, Leibnitz's rule for differentiation of integrals,

$$f_Z(Z) = -\int_{-\infty}^{0} \frac{1}{t}\ f_t(t)\ f_D(\frac{Z}{t})\ \partial t \ + \int_{0}^{\infty} \frac{1}{t}\ f_t(t)\ f_D(\frac{Z}{t})\ \partial t$$ where

$$f_D(Z/t) = \frac{1}{\sigma_D \sqrt{2\pi}}\ e^{-(Z/t - \mu_D)^2 / 2\sigma_D^2}$$ hence, the resulting Z can be found

by combining the component expressions derived above :

$$\begin{aligned} f_Z(Z) = & -\int_{-\infty}^{0} \frac{1}{t}\ \frac{1}{2\pi\,\sigma_t\,\sigma_D}\ e^{-(t-\mu_t)^2 / 2\sigma_t^2}\ e^{-(Z/t-\mu_D)^2 / 2\sigma_D^2}\ \partial t \\ & + \int_{0}^{\infty} \frac{1}{t}\ \frac{1}{2\pi\,\sigma_t\,\sigma_D}\ e^{-(t-\mu_t)^2 / 2\sigma_t^2}\ e^{-(Z/t-\mu_D)^2 / 2\sigma_D^2}\ \partial t \end{aligned}$$

Then,

$$\begin{aligned} f_Z(Z) = & -\frac{1}{2\,\pi\sigma_t\,\sigma_D} \int_{-\infty}^{0} \frac{1}{t}\ e^{-(t-\mu_t)^2 / 2\sigma_t^2}\ e^{-(Z/t-\mu_D)^2 / 2\sigma_D^2}\ \partial t \\ & + \frac{1}{2\,\pi\sigma_t\,\sigma_D} \int_{0}^{\infty} \frac{1}{t}\ e^{-(t-\mu_t)^2 / 2\sigma_t^2}\ e^{-(Z/t-\mu_D)^2 / 2\sigma_D^2}\ \partial t \end{aligned}$$

is obtained.

ii) Negative Product $Z = D\,t < 0$:

$$F_Z(Z) = \int_{-\infty}^{Z/t}\int_{Z/t}^{\infty} f_t(t)\ f_D(D)\ \partial t\, \partial D \ + \int_{Z/t}^{\infty}\int_{-\infty}^{Z/t} f_t(t)\, f_D(D)\ \partial t\, \partial D$$

$$f_Z(Z) = \frac{\partial F_Z(Z)}{\partial Z} = -\int_{-\infty}^{Z/t}\{ \frac{\partial}{\partial Z}\int_{\infty}^{Z/t} f_D(D)\ \partial D\ \}\ f_t(t)\ \partial t \ + \int_{Z/t}^{\infty}\{ \frac{\partial}{\partial Z}\int_{-\infty}^{Z/t} f_D(D)\ \partial D\ \}\ f_t(t)\ \partial t$$

Again, applying Leibnitz's rule for differentiation of integrals,

$$f_Z(Z) = -\int_{-\infty}^{Z/t} \frac{1}{t}\ f_t(t)\, f_D(\frac{Z}{t})\ \partial t + \int_{Z/t}^{\infty} \frac{1}{t}\ f_t(t)\, f_D(\frac{Z}{t})\ \partial t$$

As in case (i) above, rearrangement of the terms after proper substitutions result in the following expression for p.d.f. :

$$\begin{aligned} f_Z(Z) = & -\frac{1}{2\,\pi\sigma_t\,\sigma_D}\int_{-\infty}^{Z/t} \frac{1}{t}\ e^{-(t-\mu_t)^2\,/\,2\sigma_t^2}\ e^{-(Z/t-\mu_D)^2\,/\,2\sigma_D^2}\ \partial t \\ & + \frac{1}{2\,\pi\sigma_t\,\sigma_D}\int_{Z/t}^{\infty} \frac{1}{t}\ e^{-(t-\mu_t)^2\,/\,2\sigma_t^2}\ e^{-(Z/t-\mu_D)^2\,/\,2\sigma_D^2}\ \partial t \end{aligned}$$

Case 2)- $Z = \frac{1}{t}$. Here, it is desired to find an expression for the density distribution of the term $Z = g(t)$ in terms of the density distribution of t where $g(t) = 1/t$ and t is a normal random variable with the mean of μ_t and standard deviation of σ_t .

$z = g(t)$, $g(t) = 1/t$ hence $z = 1/t$ which may be solved for the root of $t_1 = \frac{1}{z}$. $f_z(z)$ is given by $f_z(z) = \frac{f_t(t_1)}{| g'(t_1) |}$

The deriative of g(t) evaluated at $t = t'$ (term g') is equal to $-z^2$ once $t = 1/z$ is substituted. The absolute value then is equal to z^2.

$$\frac{\partial g(t)}{\partial t}\Big|_{t=t_1} = \frac{\partial g(t)}{\partial t}\Big|_{t=1/z} = -\frac{1}{t^2}\Big|_{t=1/z} = -z^2$$

therefore,

$$\left| \frac{\partial g(t)}{\partial t}\Big|_{t=t_1} \right| = |g'(t_1)| = z^2 \quad \text{and}$$

$$f_t(t) = \frac{1}{\sigma_t\sqrt{2\pi}} \; e^{-(t-\mu_t)^2/2\sigma_t^2}$$

It follows that

$$f_z(z) = \frac{1}{z^2} \; \frac{1}{\sigma_t\sqrt{2\pi}} \; e^{-(1/z-\mu_t)^2/2\sigma_t^2}$$

The resulting p.d.f. is in the form of :

$$f_z(z) = \frac{1}{\sigma_t z^2 \sqrt{2\pi}} \; e^{-(1/z-\mu_t)^2 / 2\sigma_t^2}$$

Vita

The vita has been removed from the scanned document