MACHINE REQUIREMENTS PLANNING FOR CELLULAR MANUFACTURING SYSTEM

by

Hüseyin Sarper

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APPROVED:

R.P.Davis, Chairman

J.M.A.Tanchoco

M.H.Agee

T.J.Greene

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Blacksburg, Virginia

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure | Page

Chapter I

INTRODUCTION

Cellular Manufacturing (CM) is the physical division of a plant's manufacturing machinery into production cells in order to realize the benefits of Group Technology (GT). These benefits are basically the elimination of some indirect costs, reducing set up time and throughput time, and also increasing labor productivity. A cell is a grouping of manufacturing resources and is based on a commonality in manufacturing requirements of jobs assigned to each cell. The general objective of CM is to maximize manufacturing profits by trying to minimize costs through better production control, reduced work in process inventory levels, increased machine utilization, shorter job throughput time and job enrichment.

1.1 PRODUCTION ENVIRONMENTS

Production environment refers to the state of flow of jobs between machines or machine groups in a manufacturing facility when the machines are already laid out and fixed. A production environment can vary between two extreme cases. They are : pure job shop (PJS) and pure flow shop (PFS). In a PJS, the flow, entry and exit points of jobs are totally unrestricted. Each job may utilize a different order of machines while in a job shop (JS), this total freedom is slightly restricted. Modified flow shop (MFS), on the other hand, requires that job flow be as unidirectional as possiple, but allows for some amount of backtracking between the machines. Next, a flow shop (FS) is an environment in which the flow of jobs must be unidirectional, however, forward skipping of machines is allowed for some jobs. Finally, a PFS (or a transfer line) is the case in which all jobs must follow the exact same order in their use of machines, with absolutely no skipping allowed.

The independent single manufacturing cell obviously posseses many of the characteristics of these five shop environments. It is hard to state which of these five production environments best describes a CM environment, but the ideal case is a PFS because it would mean that the jobs are grouped so well that the machining needs of each group of jobs is identical. However, the real life case is somewhere between a JS and a FS, mainly because all jobs (parts) assigned to a cell do not use all the machines placed in that cell, although similiar jobs are grouped together in each cell.

1.2 PRODUCTION LAYOUTS

Here, production layout refers to the layout of machines in a facility given a fixed job mix and the routing. Historically, there have been three different types of production layouts. One of the older ones is a flowline or layout by product in which each product can simply flow from its first operation through its last operation. Next is the functional layout, or layout by process, that is characterized by groups of machine tools which perform the same functions.

CM is a recent design philosopy that favors the creation of special cells (not necessarily containing all machine types) which may fully manufacture a part (or parts) assigned to that cell. A CM layout is characterized by the grouping of machine tools which perform the operations in the production of a group of parts called a family.

1.3 DISCUSSION OF GROUP TECHNOLOGY, CELLS, AND JOB-MACHINE CHRACTERISTICS

Group Technology (GT) is defined as the organizing and grouping of common technological products [23] in order to minimize complex production related problems seen in job shops. GT consists of three major areas: classification and coding of parts (jobs), set-up and fixturing, and Cellular Manufacturing (CM) which is explained in more detail later.

Part classification and coding is concerned with assigning parts to classes and defining certain coded characteristics for each class in order to make use of the common design features and production processes. Set-up design, on the other hand, attempts to design a work area so that its set-up (fixtures, jigs) can be used by a family of parts and per part set-up cost can be minimized.

Most of the GT-related applications and developments have mainly originated in Europe, especially in England and the USSR. Among the subsets of GT, classifiction and coding has received the most attention and many codes have been developed.

Cell Characteristics

There is no known way of stating how many cells should be used in order to obtain the greatest benefits from CM. However, a consensus appears to be that 30 to 40 percent of the facility should remain as a general job shop and not be converted into special cells. Cell sizes may vary from 3 to 15 machines with 6 being the average number of machines in order not to lose some of the CM advantages such as lower material handling costs and effective control of production. The remainder cell (RC) is the portion of the production facility that is not converted into a cellular form. The RC 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, cannot be fully processed in their original cells. An example is shown in Figure 1.

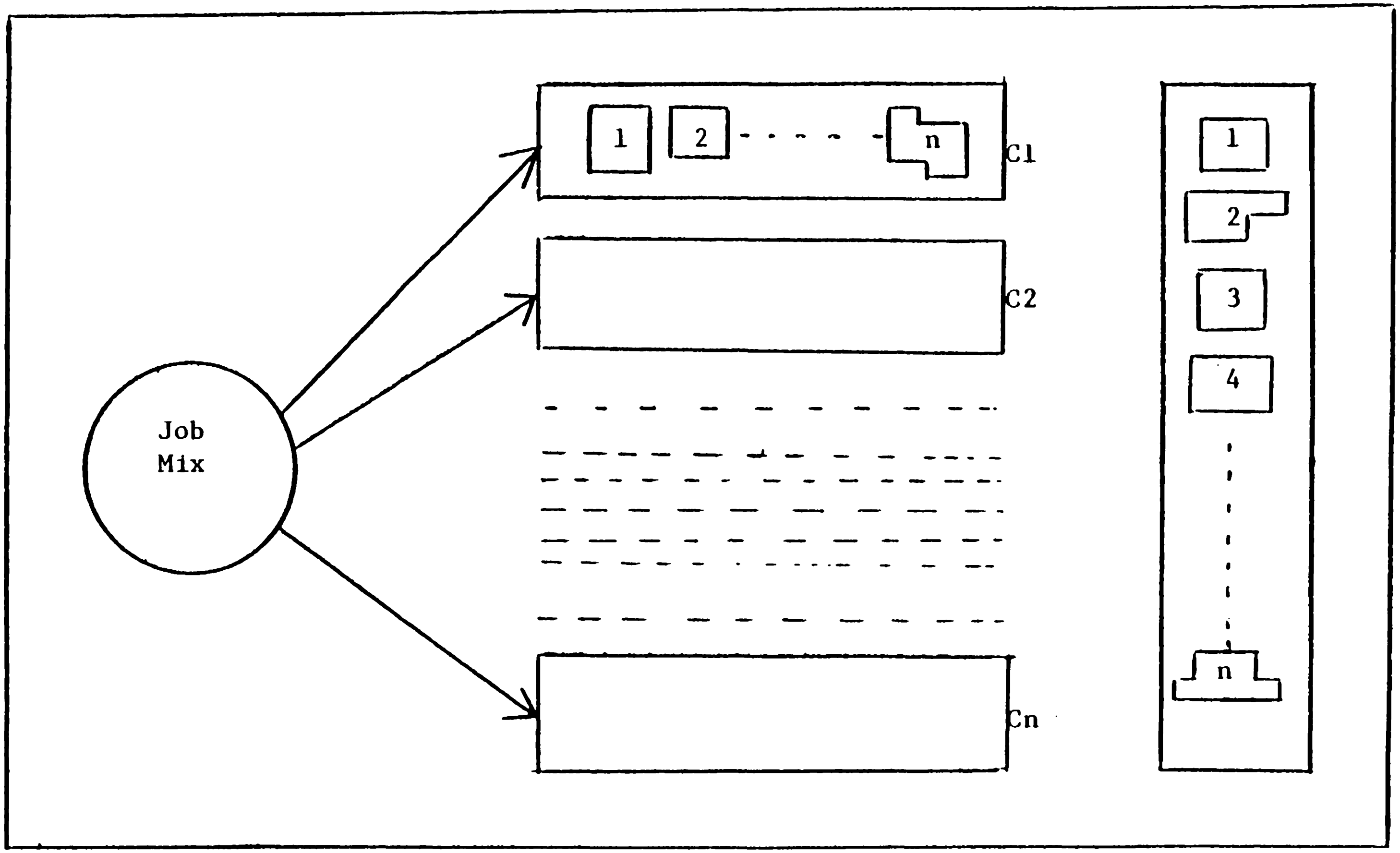

Figure 1. n Cell CM System

Job-Machine Characteristics

Job routing is the order of machines required (or operations if one machine can perform multiple operations) to complete a given job (part). In the case of the CM, jobs may fit any of the five production environments discussed earlier. As the CM system ages, the flow of jobs is expected to become closer to the job shop case. Published literature gives no indication as to the ratio of the number of operations per job to the size of the cell so that the benefits of CM can be maximized. However, there should always be enough machines in each cell so that a job, once assigned to that cell, can visit every machine it needs and be fully processed in the cell to which it is assigned.

A job type is defined as having a unique job routing. The number of different job types is limited by the job routing, number of operations per job and a given total number of machine types. Job mix is defined as the composition by job type among the jobs in the system. Typically, a single job mix that does not vary over time is used for research purposes. Also, job mix is a facility specific function which varies greatly from facility to facility.

The processing time for a job is the sum of the job's operation times. Operation time is the time required to complete one particular operation of a part (such as drilling, milling). If the CM system is not assumed to be deterministic, usually an exponential distribution is used to model operation times because each job is taken to be independent of all other jobs. Due date is a facility specific parameter and is set by each individual facility based on its own criteria.

Machine density is the commonality of machine types between cells and it encompasses all of the cell characteristics mentioned above. Job density, on the other hand, is the proportion of cells that jobs could be assigned to. Job density is composed of the job characteristics, number of cells and each cell's composition.

1.4 CM DESIGN

A CM system design is composed of four major facets that should be examined in the following order (See Figure 2). First, jobs should be grouped according to their machining requirements. The better and more efficient grouping performed in the first segment, the lower the total cost should be. The number of cells and cell structures should be determined. Secondly, capacity planning of each cell is to be performed by using the demand for each job assigned to that cell, and by considering the cost and the performance of each machine that can be selected to perform required operations. This is the segment of the CM design where the total operating cost can be minimized by carefully selecting machines according to requirements.

The next task is to determine a layout after all machine-cell assignments are made. Here, there may be several objectives that conflict with each other such as minimization of backtracking versus minimization of the overall material handling. Capacity planning should preceed layout design so that the designer can know the type and the number of each type of machine to be laid out in each cell.

Finally, once jobs are assigned to cells, cell scheduling represents the last major segment that has to be carried out. Even if the CM design objective is to minimize the total cost of production, minimizing the mean flowtime of all jobs will at least help reach that goal by helping meet due dates and minimizing mean waiting time. If the due dates are met and the mean waiting times are kept as short as possible, then it should be easier to reduce the total cost by keeping work in process inventory and customer dissatisfaction as low as possible.

Actually, it is unclear between scheduling and layout design as to which one should precede the other one because once one of the two is selected as the third major CM design component, it will have direct effect on the other. These four, as stated above, are typical regardless of the CM system considered. A literature review suggests that the second segment above has received no attention among the subsets of CM design.

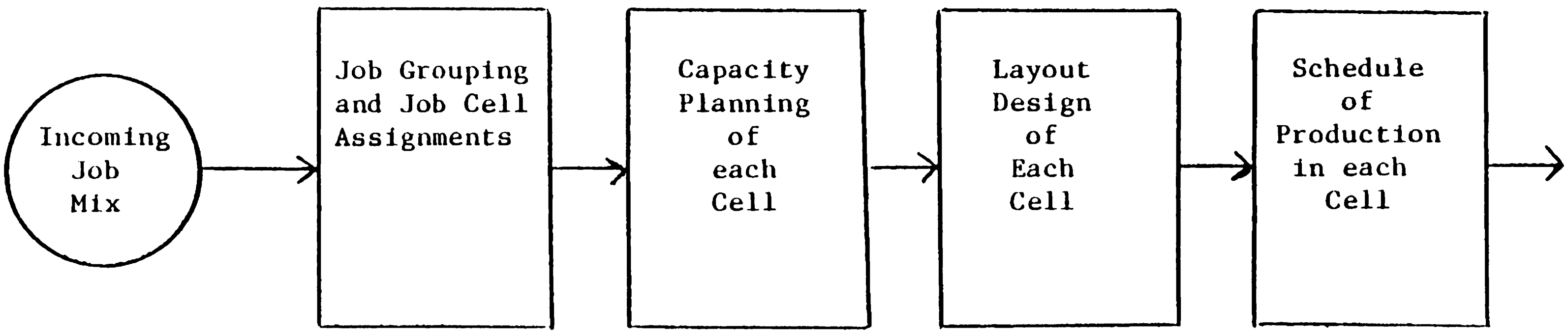

Figure 2. CM Design Components

Objective

Since investment in machine tools is the largest single item of capital expenditure in most manufacturing companies, this research is concerned with developing a basis for determining which machines should be placed in a cell so that the available capital is spent in an optimal manner. More specifically, a normative mathematical basis is developed for resolving the primary issues of: the types of machines assigned to each cell, and the number of each of these machines utilized. The literature review which follows clearly indicates that CM can provide a worthwhile basis for a production system design. It typically reduces flow time and work in process inventory in addition to providing other advantages. Although the literature indicates some disadvantages of CM, it should at least be investigated as a viable way of production system design.

Chapter II

LITERATURE REVIEW

To date, there is little published information that deals directly with the problem issues stated in the preceding chapter. In addition, literature that even mentions cellular manufacturing is rarely found. However, there is a considerable amount of literature that can be applied to segments of the problem. These are articles and texts written in the fields of: cost modelling, capacity and machine requirements planning, plant layout and design, and job and flow shop scheduling. It must, however, be noted that all of these are usually based on some kind of mathematical model such as linear, integer, nonlinear, and quadratic programming. Limited literature in Group Technology (GT) must be considered directly applicable to this problem area since CM is considered to be a component of GT concepts.

2.1 COST MODELLING MACHINE REQUIREMENTS AND CAPACITY PLANNING

Capacity planning, machine loading, and load balancing of cells are all related topics which should be used when dealing with overall machine requirements planning of a CM system. A job can be assigned to a cell only if the machining capacity of the cell can handle that job's machining requirements.

Ignizio [29], in 1981, presents an interactive multi-objective methodology which deals with real world capital budgeting problems and attempts to maximize the discounted return over a planning horizon by a goal programming technique. Bernard [6] sets up a general mathematical program that considers the initial investment, cash in and outflows, the interest rate, the dividends and all other real world cost items faced by a firm. This model is later solved using nonlinear programming methods in order to determine an investment course so that the final present worth can be maximized.

An article by Miller and Davis [35], in 1978, explains how to determine the number of machines in a production environment and treats it as a resource allocation problem that considers budget limits, the floor space, and the available overtime. A mixed integer program which minimizes all discounted cash flows is also presented. Two other papers by Davis and Miller [14,36] also investigate the machine requirements problem. The first one provides an overview of the general problem, describes and classifies alternative ways of formulating and solving the problem. In the latter one, a model is presented for resolving the problem of determining the optimum number of machines, and their discrete operating rates, required to meet discretely distributed demands with a minimum possible total expected cost.

Reference [36] is an example in which the objective is not cost modelling, but the minimization of the total machining time. Such articles are also directly related to this topic because lower total machining time will at least help, in the long run, reduce the total cost of all production. The authors of reference [13] develop a model which can be used to determine an optimum tool change schedule for a machining operation and provide a heuristic solution method using dynamic programming.

Sadowski and Jacobson [42], in 1977, propose two new heuristic algorithms called INEXT and OWAAT for scheduling of production in an unbalanced production line. Both methods try to distribute the available number of workers to each station so that the cost of holding in-process inventory is minimized. They later compare their methods with other mathematical models which take much more effort to solve and yield a solution that is not significantly better than that obtained from OWAAT or INEXT.

Hayes, Davis, and Wysk [26] develop a model to find the optimal number of machines, and their operating rates, for each machine in a serial-flow production system. The model developed is later solved by using dynamic programming and a standard MIP package; it is observed that the same minimum cost of production is reached by using dynamic programming which costs much less to compute than the MIP package.

Khator and Moodie [31] present a machine loading method which uses a coding system to take care of each part's complexity and each machine's capability by assuming that each machine is a universal machining center. They develop a rule called SCORE which performs well when investigated under performance criteria such as: increased shop capacity, shop utilization, and other job-flow measures.

Aley and Zimmer [1] describe what they see as being involved with effective capacity planning, both long and short range. They state the importance of production volume and job mix in capacity planning by explaining how a shift in job mix can cause (and change) bottlenecks in one or the other part of the plant. Graziano [22] explains a system used to perform long-term capacity planning for an organization that has an integrated production planning and control system. He explains the advantages of a computer based system and a manual system of capacity planning along with different ways of capacity planning such as backloading, forwardloading and capacity smoothing.

Articles by Vollman [47], Belt [5], Ravignani [40], and Eilon [16] are good sources of information on capacity planning and its effects on plant loading in some general terms.

2.2 PLANT LAYOUT DESIGN

This broad topic is usually presented as facility layout and location, however, facility location is not directly applicable here. In a CM system, one of the objectives is to determine how to lay machines out in each cell rather than to determine where the entire plant or the individual cell should be located. The following sources on plant layout design are by no means an exhaustive list, instead the intention is to present some of the publications directly applicable to CM system design.

Carrie and Mannion [11] derive an optimum layout sequence for machines contained in each cell and propose a computer method of preparing alternative line layout designs. They mainly attempt to eliminate backtracking (material handling) requirements so that jobs can travel from one machine to the next by a conveyor type device.

A text by Francis and White [18] is a very comprehensive source that presents the analyst with new techniques, approaches and philosophies in this area. It has ten chapters covering all topics ranging from computerized layout planning and single-multi facility location problems to mathematical program based location problems. A collection of notes by Enscore [17] summarizes most of the layout related problems, algorithms, and other heuristic methods along with computerized and analytical examples.

Texts by Apple [2] and Reed [41] are two other major sources of information. Also, articles by Vollman and Buffa [46], Bindschedles and Moore [7], and by Francis [19] are the most closely related ones to the kinds of problems considered in this research.

2.3 SCHEDULING AND SEQUENCING

Here, the goal is to cite certain sources that actually combine CM and scheduling issues in the body of the publication and mention some others that would be useful in the CM design. There are literally hundreds of articles published in the area of sequencing and scheduling of job shops and flow shops. Greene [23] has a rather complete list of such articles that would be useful in the field of cellular production. Since this review is not intended to be comprehensive in this area, most of these articles are not cited here.

Texts by Conway, Maxell and Miller [12] and Baker [3] contain numerous algorithms and heuristic methods which can be applicable in CM. They both begin with a single machine example and extend this to general cases by clearly separating job and flow shop type environments. Arrival of jobs are also clearly seperated and treated as deterministic or probabilistic. These two references [12,13] give a fairly comprehensive treatment of the scheduling rules one would need when dealing with CM.

Vaithianathan and McRoberts [45] examine a cell environment from a scheduling perspective and in relation to a job and flow shop. They later present a modified approach to scheduling within a GT cell that implicitly takes advantage of common setups and part family coding structures.

Some scheduling problems can be described as zero-one programs which require complete enumeration, branch and bound, and other complex IP methods to find an optimal solution. Balas [4] provides an additive algorithm that makes zero-one programming easier and feasible to solve. Some other IP techniques are also directly applicable in this area, but they will not be cited here since they are readily available in some of the sources references in this review.

Some other authors have also gathered an extensive list of all scheduling and sequencing rules, algorithms, and other heuristic methods applicable to research in this field. Some of these other lists are by Panwalker and Iskander [38], Day and Hottenstein [15] and Stecke [44].

2.4 GROUP TECHNOLOGY AND CELLULAR MANUFACTURING

T.J.Greene [23] has examined how to load a CM system in order to develop heuristic techniques which reduce variables such as job tardiness and job flow time. He also represents the loading problem as a MIP, which he does not solve. Furthermore, he does not directly deal with system profit, cost, and cell formation issues; instead, he considers a dynamic system which requires different structures over time. Jackson's [30] text is probably the best source of information on CM because it is the only text available which is fully devoted to CM and not GT as the main topic.Jackson has several chapters on cell formation and ten different case studies from England. However, it contains no single formulation of any kind to support all the benefits of CM that are stated.

Ragaopalan and Batra [39] present a method of forming machine cells while directly implementing GT. It makes use of similiarity coefficient and a graph-theoretic approach to form production cells. Two texts by Burbidge [8,9] provide most of the information one needs in the field of GT, but both texts treat CM in a cursory fashion. In both texts, Burbidge states the advantages and disadvantages of GT, design of groups, performance measures and implementation of GT. Production Planning by Burbidge [10] is a more general text which covers topics directly related to CM and other manufacturing systems. These topics include factory planning, process planning, and operation planning.

Grayson [21] reviews Soviet papers on their approach to evaluating the economic effectiveness of GT. He presents cost, machining and profit equations that go beyond the usual percentage increase in production or profit presented by Burbidge. Further, he presents equations that consider extra investment requirements due to new fixture needs, and ways to justify such costs arising from the implementation of GT.

Hitomi and Ham [25] present an analysis to optimally select parts to be manufactured, when time and resources are limited, by applying GT. However, they do not directly mention CM. Husain and Leonard [28] provide a technique for cell formation which is only applicable to plants already using a functional layout for their production. Their method uses machining statistics for parts to determine cell composition, rather than any direct use of GT. Lewis [32] describes very good reasons why GT and CM should be used and also why most plants have still not adopted these new philosophies.

Two recently published articles concentrate on cell formation and the benefits of CM in specific production environments. Reference [37] presents potential advantages of GT and CM concepts in the closing department of a shoe manufacturing factory. It examines the effects of creating a two-product groups, two production cell system by using a simulation model of the factory under performance measures such as: throughput time, waiting time, and utilization of resources. Witle [48] states that routings are the basic data from which interrelations between operations in a production environment can be found. His problem is to group components into families, and machines into cells, in such a way that each component can be fully processed in the cell to which it is assigned. This paper basically attempts to improve previous clustering and similarity coefficient methods of machine grouping by proposing several new definitions of similarity coefficients and demonstrating their application for the design of cell structures.

Milalic [34] defines a manufacturing cell in the factory environment as a physical object performing a defined production program and concentrates upon the design process in order to obtain the defined objectives of the manufacturing cell. To do so, a laboratory environment which varies between real and simulated conditions is set up to observe the effects of CM on various performance measures.

Sarper [43] presents two approaches to determining the number of cells, and the number of machines in each cell, in order to maximize profit in a CM system. First, a mathematical model is presented, later an alternative method, which makes sequential searches to find a near-optimal configuration, is given.

A technical paper by Ham [24], the text by Hitomi [27] and the MAPEC [33] newsletter are all good sources of information in the field of GT and in other related areas. Each of these publications emphasize different aspects of the overall problems encountered especially in grouping and scheduling of parts.

Summary

The literature review has revealed that there has been no work done that directly relates to the problem considered in this research. However, some components of the problem, such as GT, scheduling, plant layout, and general capacity planning have received considerable attention.

Chapter III

PROBLEM STATEMENT AND RESEARCH OBJECTIVE

The major objective of this research is to develop a model that can be used to make machine requirements planning decisions in a CM system. The goal is the design of a CM system which incurs the minimum possible cost of production (Both initial and future costs).

This research is closely related to the previous work done on CM and GT, but here the emphasis is not placed on topics such as scheduling and the sequencing of jobs, classification and coding of parts, or determining the optimum layout for a CM system. Instead, the objective is cost minimization in capacity planning; which would undoubtedly help increase profit of production that is directly linked to the ultimate goal of maximizing the wealth of the share holders of the company.

The core problem of this research lies in determining a cellular composition given a fixed job-mix that is to be grouped into a known number of cells. To do so, a modified cell formation methodology and two mathematical models, (MP1 and MP2), which can determine the machine composition of each cell, have been developed. If such models can be fully solved, one will actually have made a real and optimal CM structure selection because they consider all major costs and factors affecting production. The assumptions listed below isolate and describe the nature of the problem considered.

3.1 ASSUMPTIONS

Key Assumptions:

1. Most machines can perform more than one type of operation, but usually not all types of operations.

2. The same operations usually take different amounts of time on different machines. The fixed cost of each machine is correlated to its ability to perform a given number of operations. Generally, a higher fixed cost of a machine means that the variable costs related to that machine will be lower than some other machines with lower fixed costs.

3. Processing rate of a machine is inversely correlated to its ability to perform an increasing number of different types of operations.

4. The facility does not exist beforehand and a RC is permitted whether it is used or not. Pre-empting and lab phasing of the jobs are not allowed, but job splitting is permitted.

5. Each single operation of a job (for all demands for that job) will be completed on the same machine as is selected by the mathematical model, so the same operation on a given job may not be split between cells or two different machines in the same cell. Each cell may well have more than one of the same machine type if dictated by the mathematical model (parallel processors case allowed).

6. Each cell will usually not have every type of available machine and the RC has at least one of each type of available machine as determined by the mathematical model.

7. If a job is to be transported to the RC, it must return to its originally assigned cell assuming that the job needs more processing. In other words, a job will not get its next operation at the RC while it is already there (unless dictated by the mathematical model).

8. Once selected, each job will be processed using only one lot size and this will not change between machines and operations. There is a new set-up required for each single operation regardless of the possibility that the next opera-

tion may also be performed on that same machine. Each job may need one of every possible operation, but two of the same operation may not be needed by any job. A job, once assigned to a cell, has all the machines available so that the job can be fully processed in that cell.

Secondary Assumptions:

1. No machine failure or downtime is allowed. The system is at steady state and all variables are deterministic. Scrap or rework is disregarded. Jobs are independent of each other.

2. Job types, routings and, the number of cells are already known. Cells operate as MFS, the RC operates as a JS.

3. Machines or machine groups are laid out in a serial fashion in each cell and in parallel when there is more than one machine of the same kind.

4. Demand for parts and the related costs are known. The production rate is fixed. Also the total work assigned to each cell can not exceed the capacity of that cell.

5. All other classical scheduling and GT assumptions are implied.

General Cost Modelling

Most manufacturing operations use some form of a model to evaluate the effectiveness and profitability of ongoing and/or future production. Cost models, as explained in the next section, usually focus on cost items such as variable, fixed, investment, set-up and material handling related costs. Once cost items are determined, then one goal is to find a production level, tools, and machining rates that minimize the sum of all related costs. On the other hand, some cost models are used to maximize the profit of production by also considering the total revenue generated by sales, and deducting the total cost from the revenue. Cost minimization and profit maximization are closely related to each other and frequently one of them is directly related to the other one. However, there may be cases in which these two objectives may not necessarily support each other, such as a case when the unit revenue is a variable.

3.2 DEFINITION OF TERMS

MP1: Mathematical program 1.

MP2: Mathematical program 2.

RC : Remainder cell

Indices

i:index used to label machine types.	$i=1,2,3.....m$
j:index used to label cells.	$j=1,2,3.....n_c$
k:index used to label Jobs(products).	$k=1,2,3.....JN$
n:index used to label operations.	$n=1,2,3.....n_{mx}$
b:index used to label lot sizes.	$b=1,2,3.....lt$

Variables To Be Determined by the Mathematical Models

in MP1:

M_{ij} : Number of type i machines in cell j.

X_{ikn}: 1 if operation n of job k, is to be processed on machine i.

0 Otherwise.

Q_{bk} : 1 if job k is to be processed in lots of size b

0 otherwise

in MP2:

R_{ij} : 0 if fractional M_{ij} value is rounded down.

1 if rounded up

T_{ijkn}: Fraction (percent) of the unmet demand for operation n of job k (due to rounding down of the number type i machines in cell j) to be satisfied by using the available capacity in RC.

N_I : Number of machines of the i th kind that that should be placed in RC. (e.g,. I=2 means that RC will have two machines of type i)

Known Constants To Be Supplied by the Decision Maker:

In MP1:

FC_i : Fixed cost (per day) of machine i.

FC_i^R : Fixed cost (per day) of a machine i at the RC.

VC_{ikn}: Daily per unit cost of processing operation n of job k using machine i.(variable cost)

D_k : Daily demand of job k.

SC_{iknb}: Set-up cost of job k's operation n to be performed on machine i in lots of size b.

HC_{bk} : Handling (travel) cost of job k if processed in lots of size b.

NO_k : Number of different operations needed to complete job k.

t_{ikn} : Processing time of operation n of job k if processed on machine i

ST_{iknb}: Set-up time required for operation n of job k when processed on machine i in lots of b.

T : Machine hours avaiable per day (8,16,or 24 hrs/day)

IC_{ij} : Investment cost of machine i.

IC_{ij}^{RC} : Investment cost of machine i at RC.

$\$C$: Capital available to purchase all machines at the time of planning.

In MP2:

b_k : Already selected lot size for job k.

U_{ij} : Undercapacity (in machine terms) when rounding down occurs to the number of machine i's (M_{ij}) in cell j.

F_{ij} : Fraction (or percent) of the demand for that can not be met because of rounding down of a particular M_{ij} value.

UD_{ijk} : Number of job k (parts) that can not be manufactured when rounding down of the related M_{ij} value obtained from MP1.

RHC_k : Remainder handling cost incurred for each job (part) k if it is sent to and from RC.

P_{ij} : 1 if machine i needed by job k is the last machine (or in the last paralell processor group) in cell j, 2 otherwise.

SCC_{kn}: Subcontracting cost for operation n of job k.

IDC_i : Idle cost coefficient for machine i, when a particular fractional M_{ij} value is rounded up.

M_{ij}^R : Rounded up value of the fractional value of a particular M_{ij} value determined in MP1.

E_{ij} : Excessive capacity of machine i in cell j when a particular fractional value of M_{ij} determined in MP1 is rounded up.

\$C2 : Capital available to transport all jobs to and from RC.

\$C3 : Capital available to purchase machines for RC.

3.3 MATHEMATICAL MODELS

3.3.1 MP1

This model determines the machine types and the quantities that should be placed in a cell that has a given number of jobs already assigned for processing. Since each machine is capable of performing certain operations at varying times and costs, a selection is to be made to determine the minimum cost combination of machines that can still meet the specified daily demand.

When MP1 is solved, if all X_{ikn} values turn out to be 0 or 1, it will indicate that it is best to assign each operation of each job to one machine instead of splitting. However, some of the M_{ij} values (number of machines of each type) may well turn out as noninteger, indicating that fractional machine assignments are needed. The formulated form of MP1 is shown in Figure 3. Term A1 is the total daily fixed cost incurred as a result of the LP selection. Term B1 is total daily variable cost. Term C1 stands for the total daily set up cost for all k jobs processed in lots of size b between each operation n on every machine i. D1 is total daily handling cost for all jobs processed in lots of size b. MP1 is based on the expected (long run) demand for each job so that the production can progress smoothly.

$$\text{Min } Z_1 = \underbrace{\sum_i \sum_j FC_i \cdot M_{i,j}}_{A1} + \underbrace{\sum_i \sum_n \sum_k D_k \cdot VC_{i,k,n} \cdot X_{i,k,n}}_{B1} + \underbrace{\sum_i \sum_k \sum_n \sum_b D_k \cdot SCB_{i,k,n,b} \cdot Q_{b,k} \cdot X_{i,k,n}}_{C1} + \underbrace{\sum_k \sum_b HCB_{b,k} \cdot Q_{b,k}}_{D1}$$

s.t.

1) $X_{i,k,n} = \{0,1\} \quad \forall\ i,k,n$

2) $Q_{b,k} = \{0,1\} \quad \forall\ b,k$

3) $M_{i,j} \geq 0 \quad \forall\ i,j$

4) $\sum_k D_k \sum_n [t_{i,k,n} + (\sum_b S_{i,k,n,b} \cdot Q_{b,k})] \cdot X_{i,k,n} \leq T \cdot M_{i,j} \quad \forall i\ \forall j$ (Machine capacity constraint)

5) $\sum_i X_{i,k,n} = 1 \quad \forall k,\ \forall n$ (Operation assignment constraint)

6) $\sum_b Q_{b,k} = 1 \quad \forall\ k$ (Lot size selection constraint)

Investment Function (Special Constraint)

$$\sum_i \sum_j IC_{i,j}\, M_{i,j} \leq \$C$$

where:

$$SCB_{i,k,n,b} = \frac{SC_{i,k,n,b}}{b}$$

$$HCB_{b,k} = \frac{HC_{b,k} \cdot NO_k \cdot D_k}{b}$$

$$S_{i,k,n,b} = \frac{ST_{i,k,n,b}}{b}$$

Figure 3. Mathematical Model I (MP1)

3.3.2 MP2

In MP2, shown in Figure 4, A2 indicates a decision as to round up or down a given fractional number of machine type i in cell j. B2 is total daily remainder handling cost incurred for the portion of the unmet demand for job k that is to be met using the RC. Term C2 is the portion of the unmet demand for job k that is to be subcontracted. Term D2 is the total daily subcontracting cost, and the term E2 is the total daily fixed cost at the RC. Finally, G2 and F2 express the total daily fixed idle cost incurred at the RC when a fractional number of machines resulted from MP1 are rounded up.

This secondary model is used only when fractional (thereby impossible) number of machine assignments are made by MP1. Whenever such fractional assignments arise, the decision maker faces two choices.

1) Round up all fractional machine assignments, meet the demand and incur some machine idle cost.
2) Round down all fractional machine assignments and become unable to meet the demand for some jobs.

$$\text{Min } Z_2 = \left\{ \sum_i \sum_j (1 - R_{i,j}) \left[\sum_n \sum_k \left((UD_{i,j,k} \cdot T_{i,j,k,n} \cdot RHC_k \cdot P_{i,j}) + ((1 - T_{i,j,k,n}) \cdot SCC_{k,n} \cdot UD_{i,j,k}) \right) \right] + FC_i^{RC} (N_i - 1) \right\} + \sum_i \sum_j R_{ij} \cdot IDC_i \sum_k (E_{i,j,k} \cdot FC_{i,j})$$

A2 B2 C2 D2 E2 F2 G2

s.t. 1) $R_{i,j} = [0,1] \quad \forall i, \forall j$

2) $T_{i,j,k,n} \geq 0$

3) $T_{i,j,k,n} \leq 1$ $\quad \forall i,j,k,n$

4) $\sum_n \sum_k \sum_j T_{i,j,k,n} \cdot U_{i,j} \leq N_i \quad \forall i$ (RC Machine capacity constraint)

5) $N_i \geq 1$ and integer $\forall i$

Investment Functions:

1) $\sum_i \sum_j \sum_k \sum_n UD_{i,j,k} \cdot T_{i,j,k,n} \cdot RHC_k \cdot P_{i,j} \leq \$C2$

2) $\sum_i IC_i^{RC} \cdot N_i \leq \$C3$

where:

$U_{i,j} = M_{i,j} - [M_{i,j}]$

$E_{i,j} = M^R_{i,j} - M_{i,j}$

$F_{i,j} = \frac{U_{i,j}}{M_{i,j}}$

$UD_{i,j,k} = D_{i,j,k} \cdot F_{i,j}$

Figure 4. Mathematical Model 2 (MP2)

Using the X_{ikn} values resulting from MP1, one can keep track of which job's demand is threatened with the fractional assignment that will be rounded down. So, the jobs, whose demand will not fully be met, is known when MP1 is solved. To improve this undercapacity situation:

a) Transport some of these jobs to the RC as long as the RC has capacity to process them.
b) Do not meet all of the demand and subcontract the demand that cannot be met.
c) Reach a compromise between (a) and (b) by meeting a portion of the unmet demand at the RC while incurring subcontracting cost for the other portion.

There would be no direct need to have MP2 if all fractional assignments (M_{ij}) values were restricted to only integer values in MP1. This, however, would potentially create under or excess capacity cases for some of the integer number of machines of each type assigned to cells. Therefore, MP2 is needed not only as a secondary model, but also to help one make very real and necessary decisions related to rounding up or down situations.

3.4 PROBLEM SIZE, VARIABLES, AND CONSTRAINTS

Size of the Problem

Maximum Number of Variables

MP1: This model is composed of five different variables each having one or more subscripts ranging from one to the maximum value as shown earlier. Here, the total number of the variables is the combination of all of these individual variables.

[(no.of cells)X(no.of jobs)X(max.op/job)X(no.of machines)X(no.of lot sizes)]

$$= [(n_c)X(JN)X(n_{mx})X(m)X(lt)]$$

MP2: Using the same reasoning, the maximum number of variables is the combination obtained from,

[(no.of cells)X(no.of jobs)X(no.of machines)]

$$[(n_c)X(JN)X(m)]$$

Discussion of the Constraints

MP1:

Constraint No.1: 0-1 restriction for X_{ikn}.

There will be a maximum of ((m)X(JN)X(n_{mx})) of these constraints if all machines can perform all of the operations. If not, the number of constraints of this type can be found as follows (the normal case) :

MCA_{ikn} = 1, If job k needs operation n and machine i can perform operation n,

0, otherwise

Total Constraints: $\sum_{n} MCA_{ikn} \quad \forall (i,k)$

Constraint No.2: 0-1 restriction for Q_{bk}.

There will be a maximum of [(lt)X(JN)] of these constraints if all jobs can be processed in every available lot size. However, if there are any technical reasons which prohibit certain (job-lot size) combinations, then the total number of constraints (of this kind) for a given MP1 has to be found in the following manner :

$LOT_{bk} = 1,$ if job k is compatible with lot size b

0, otherwise

Total Constraints: $\sum_b LOT_{bk} \; \forall k$

Constraints No.3 and No. 4: Nonnegative machine assigments and machine capacity restrictions.

Constraint 3 states the obvious fact that the number of machines of type i assigned to any cell j must be nonnegative. Constraint 4, on the other hand, indicates that each machine assigned to a cell means an additional T hours of machine capacity; hence, the amount of processing time and set up time associated with jobs to be loaded to that machine can not exceed this limit. Again, there would be (mxn) of each of these two constraints if all cells were to have at least one of each type of machine. However, this conflicts with the fundamentals of the CM design which is built on special cell ideas. The actual number of each of these constraints is found below.

$MCC_{ij} = 1,$ if cell j has machine i

0, otherwise

Total Constraints: $2(\sum_i MCC_{ij}) \; \forall j$

Constraint No.5: Operation - Machine assigment restriction.

This dictates that each operation of a job will only be processed at one machine. There can be a maximum of (JN X n) of this type constraints if all jobs need all operations. Otherwise:

$$N_{kn} = \begin{cases} 1, & \text{if job k needs operation n} \\ 0, & \text{otherwise} \end{cases}$$

Total constraints: $\sum_{n} N_{kn} \quad \forall k$

Constraint No.6: Lot size assignment restriction.

Here, it is required that each job be processed in only one of the lt available lot sizes until all the demand for that job is met. There will always be JN of these types of constraints in every MP1.

Investment Function No.1: Budget restriction.

This last constraint limits the total number of machines of all types that can be purchased given a fixed amount of capital available to spend for all machines. Each MP1 contains only one such constraint which imposes a severe restriction on the machine selection process while making the whole problem more realistic.

MP2

Constraint No.1: 0-1 restriction for R_{ij} .

This constraint requires that a decision be made on all fractional machine assigments resulting from MP1 as to either rounded up or down to reach an integer number of machines in each cell. Each MP2 will contain (m X n) of this constraint type.

Constraints No.2 and 3: Restrictions on T_{ijkn} .

The number of these constraints is the same as those for constraint No. 4 of MP1. Here, it is required that all possible T_{ijkn} be fractions (0 to 1) so that they can represent a portion of the unmet demand.

Constraint No.4: RC Capacity restriction.

MP2 has m of these constraints, each of which indicates how much machine capacity is available at the RC.

Constraint No.5: Non-negativity and integer restrictions.

There are m of these constraints which indicate that the number of machines of each type, placed in the RC, must be nonnegative and integer.

Investment Function No.1: Transport-Budget restriction.

One such constraint contained in MP2 limits how much money can be used to send jobs to and from the RC to satisfy the extra capacity needs that can not originally be met due to the rounding down of fractional machine numbers. In a sense, here the number of jobs that would be sent to the RC is limited with a budget constraint.

Investment Function No.2: RC investment restriction

This limits the number of machines that can be assigned to the RC. Such a constraint is needed when there is a real budget limit on the amount of money that can be spent for machines in the RC.

Weaknesses and Difficulties Forseen in Both Models:

1) As it is, it would be intractable to attempt to solve this problem even for a very small sized system using combinatorial search or branch and bound methods as can be seen in the discussion of the number of variables and constraints.

2) Available methods for solutions of nonlinear programs are not applicable because, in most cases, there are no continous functions so that convexity and concavity concepts can be used.

3) Available LP and IP packages can not directly be used because both objective functions contain nonlinear terms.

4) The objective function of MP1 assumes that there are as many job handling activities as the number of operations needed by each job. This actually overstates the total handling cost per job because it ignores the fact that certain operations are processed subsequently on the same machine thus eliminating the need to transport the part (job) to the next machine in the cell.

5) Both models state that a job can only be processed either in its original cell or at the RC. So, any residual capacity that may result in other cells is not utilized when there is a need in a given cell.

A heuristic solution methodology has been developed to solve both models in a sequential manner. A set of simplifying, but still realistic, assumptions were made in order to obtain a good solution. The assumptions and the method along with an example are presented in Chapter IV.

Chapter IV

A SOLUTION PROCEDURE

Possible Relaxations of the Overall Model

The objective of the modeling contained in Chapter III was to express the problem as fully and realistically as possible. However, certain relaxations may well be needed in order to obtain a solution.

Use of MP2 makes it possible to remove the integer restrictions in MP1 because MP2 simply takes over whenever a fractional number of machines of any type is selected by MP1. On the other hand, there is no assurance that the assignments of MP1 (X_{ikn} variables) will always be 0 or 1. However, there is considerable similarity between this 0-1 case and a set of other general problems such as transportation/assigment, quadratic assigment, and fixed charge warehouse location problems. So, it will later be shown that X_{ikn} values will typically be either 0 or 1.

Both mathematical models can be solved if some, or all, of the followings are considered.

1) Set up consideration (time and cost) is disregarded, and if one agrees on a suboptimal result by rounding all machine assignments (M_{ij} values) to the nearest integer. (This means that MP2 is not needed at all.)

2) MP2 becomes easier if the rounding-up or-down cases are investigated separately thus eliminating the nonlinearity caused by R_{ij} . (This means MP2 is divided into two LPs with no integer or 0-1 restrictions.)

3) Fixing the value of N_I in MP2; thus eliminating an important integer restriction.

4.1 HEURISTIC SOLUTION METHOD FOR MP1

The function of the 0-1 variable Q_{bk} is to select the optimal lot size (b) for the production of job (k). Typically, lots would be made of 10, 20, 30, or 40 parts and have different set-up cost (SC_{iknb}) for each different lot size. It can be argued that if the SCB_{iknb} (SC/b) for an average manufacturing company are plotted against the lot sizes, it would result in a non-increasing, and probably a decreasing, function. Therefore, it can be assumed that the selection of the largest available lot size would normally minimize the total per part set-up time (and cost) needed to meet the daily demand. So, it is reasonable to ignore Q_{bk} as a variable from the objective function, making it possible to drop term D1 from the objective function.

Consequently, one can combine terms C1 and B1 by redefining the variable cost as follows:

$$VC'_{ikn} = VC_{ikn} + SCB_{iknb}$$

Since variable Q_{bk} of the term C1 is dropped, terms C1 and B1 can be summed together once this variable is no longer used. The above simplifications cause elimination of constraint No. 6 and the modification of constraint No. 4 by redefining the operation time as follows:

$$t'_{ikn} = t_{ikn} + S_{iknb}$$

and rewriting the constraint No. 4 as

$$\sum_k D_k \sum_n (t'_{ikn}) \cdot X_{ikn} \leq T \cdot M_{ij} \quad \forall i \quad \forall j$$

Now, MP1 becomes a mixed integer 0-1 program with variables X_{ikn} and M_{ij}. Since variables X_{ikn} are restricted to be 0-1, a possible way to solve MP1 is one of the available 0-1 solution methods which would be very hard and cumbersome even for a small sized CM design problem.

Instead, this problem is solved as a regular linear program by ignoring the 0-1 restriction. It is observed that all X_{ikn} values always turn out to be 0-1, especially when the investment function is not included as a constraint. Even with the inclusion of that function, a great majority of the X_{ikn} values still turn out to be 0-1. So, the final stage of the solution of MP1 is accomplished by solving MP1 as a regular LP and assuming that all 0-1 assignments will result. This assertion is of vital importance in the solution procedure because it makes MP1 much easier to solve. Therefore, it is shown below that such an assumption is valid.

MP1 is closely related to the following three classical models. These models are given for comparison purposes and without any detailed explanation since they can be readily found in many sources [See references 18 and 20]

Transportation Problem (TP)

$$\text{MIN} \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} T_{ij} \quad \text{subject to:}$$

1) $\sum_{j=1}^{n} T_{ij} \leq b_i \quad i=1,2.....m$

2) $\sum_{i=1}^{m} T_{ij} \geq d_j \quad j=1,2.....n$

3) $T_{ij} \geq 0$

4) $b_i \geq 0$

5) $d_j > 0$

Fixed Charge Warehouse Location Problem (FCWLP)

$$\text{MIN} \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} d_{ij} + \sum_{i=1}^{m} FC_i \cdot X_i \qquad \text{subject to :}$$

1) $\sum_{i=1}^{m} d_{ij} = b_j \qquad j=1,2.....n$

2) $\sum_{j=1}^{n} d_{ij} - h_i \cdot X_i \leq 0 \qquad i=1,2.....m$

3) $X_i = 0 \text{ or } 1 \quad \forall\ i$

4) $d_{ij} \geq 0 \quad \forall i \quad \forall j$

General Assignment Problem (GAP)

$$\text{MIN} \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} X_{ij} \qquad \text{subject to :}$$

1) $\sum_{j=1}^{n} X_{ij} = A_i \qquad i=1,2,....m$

2) $\sum_{i=1}^{m} X_{ij} = 1 \qquad j=1,2.....n$

3) $X_{ij} = 0 \text{ or } 1$

4) $A_i > 0$

MP1 is the least similar to TP, but GAP is a special form of TP and MP1 is highly related to GAP and FCWLP, so all four models are interrelated. All objective functions are roughly the same because their goals are always minimization of all the costs considered. Further similarities can be outlined as follows.

1) VC_{ikn} of MP1 is equivalent to C_{ij} that appears in other models.

2) FC_i of MP1 and FC_i of FCWLP are identical.

3) X_{ikn} of MP1 is analogous to X_{ij} of GAP and X_i of FCWLP.

4) Operation k in MP1 is equivalent to item i of GAP, customer j of FCWLP and the destination j of TP.

5) Machine i in MP1 is equivalent to grid j of GAP, warehouse i of FCWLP and the source i of TP.

6) Constraint No.4 (after simplification) of MP1 and constraint No.2 of FCWLP are identical.

7) Constraints No.1 and No.2 of TP, No.1 of FCWLP, and No. 1 of GAP are all analogous to the simplified form of the constraint No. 4 of MP1.

8) Variable M_{ij} of MP1 serves a role similar to X_i of FCWLP by indirectly indicating that machine i will be used. (Assuming that a single cell environment is the same as the total FCWLP environment). Since MP1 is more complex than

the FCWLP, the information conveyed by X_i of FCWLP is already built into the variable M_{ij} of MP1.

9) Constraints No. 2 and 6 of MP1 become null after the simplifying assumptions are made. That is why only constraint No. 5 of MP1 has no match in other models. However, this extra constraint, not applicable in the other models, still does not reduce the high correlation among the models.

Conclusion:

FCWLP, GAP and indirectly TP are all 0-1 type models that yield 0-1 results when restricted as such. If MP1, when solved as a LP, yields all 0-1 assignments (without such a restriction), then MP1 will always yield 0-1 results. So, there is no need to use a IP-Balas type solution methodology to reach the desired goal of assigning each operation of a given job to one and only one machine in a cell. However, the same argument is not valid when investment function No.1 is used as an active constraint. Then, 0-1 structure deteriorates as the budget available decreases.

4.2 EXAMPLE PROBLEM

Consider a CM system that has to manufacture seven different jobs (parts) (A, B, C, D, E, F, H), each of which may need a maximum of 8 different operations as shown in the job-characteristic matrix of Table A-1 in Appendix A. It is assumed that each job needs operations in the order listed across the row (roughing to finishing operations). Also, let there be 6 available machines (P, J, K, N, W, Z), each of which is capable of performing certain operations, shown on the machine capability matrix of Table A-2 in Appendix A where the daily fixed cost and the investment cost of each machine are also indicated on Table A-3.

Furthermore, let it be desired that 3 production cells (C1, C2, C3) be used in meeting a daily demand of 120, 100, 140, 80, 200, 100, and 180 of each of the corresponding jobs (parts). However, it should be emphasized that it is not assumed that jobs are already grouped, so the first task in the CM design is to group the jobs into a specified number of cells using the GT concepts.

Job Grouping Methodology:

The idea of job similarity coefficients of MAPEC [33] and other CM literature is improved and used by introducing some modifications. Here, a job characteristic matrix is constructed in more detail by using jobs and operations (not machines); a machine capability matrix is constructed to supplement the grouping process. Once these two matrices are constructed, the following steps are taken :

1) Calculate the commonality of each job with other jobs by using $SM_{ij} = N_{ij} /(N_i + N_j - N_{ij})$ where N_{ij} is the number of operations needed both by job i and job j, N_i is the number of operations needed by Job i only, and N_j is the number of operations needed by job j only. SM_{ij} lies between 0 (no similiarity at all) and 1 (both need identical operations). For example, consider Job F vs Job B. So, $N_{BF} = 3$ (they both need operations 3, 6, 8), $N_F = 5$, $N_B = 5$ and $SM_{BF} = 3/(5 + 5 - 3) = 0.43$. All other SM_{ij} coefficients are calculated and recorded on the similarity coefficients matrix as shown in Table 1.

2) Calculate the range of SM_{ij} values. Range 0.60 - 0 = 0.60

3) Divide the range into a given number of cells and assign a score for each level (0.60/3 = 0.20)

Level	Score	Comment
0.00-0.19	1	Dissimiliar
0.20-0.39	2	Fairly Similiar
0.40-0.60	3	Similiar

4) Determine which level each SM_{ij} belongs to and assign a proper score in the upper triangular portion of the similarity coefficients matrix as shown in Table 1.

Table 1

Similarity Coefficients Matrix

JOBS

	A	B	C	D	E	F	G
A	x	2	3	3	1	3	3
B	0.25	x	2	2	1	3	3
C	0.50	0.29	x	2	0	3	3
D	0.50	0.29	0.33	x	0	2	2
E	0.17	0.17	0	0	x	1	0
F	0.43	0.43	0.50	0.29	0.17	x	3
G	0.50	0.50	0.60	0.33	0	0.50	x

5) Using the similarity scores, collect jobs into a given number of groups (cells) as explained below.

The goal is to obtain as high an overall cellular similarity mean as possible. Here, $SM_{AF} = 3$, $SM_{FH} = 3$, and $SM_{AH} = 3$, so jobs A, F, and H should be grouped together in C1, yielding a cellular similarity mean of (3+3+3)/3 = 3. Actually, this grouping process is arbitrary and not necessarily an optimal method because one first picks a group that yields the maximum individual cellular mean and then tries to group other jobs that yield reasonably high individual means. Next, jobs C and D are grouped together for C2 giving a mean of 2/1= 2 (score of 2 for a single interaction examined). Finally, jobs B and E go to C3 with a mean of 1. Here, the overall cellular similarity mean is (3+2+1)/3 = 2.

Other Inputs

A cost and operation time matrix (Table A-5 in Appendix A) is constructed using the available manufacturing data in a format so that cells and jobs are listed as rows while machines and the pertinent operations of each machine are listed in columns.

MP1 Expansion :

MP1 has to be written out using the above input data. The expanded form of MP1 turns out to be a large LP. A portion of the objective function and portions of each of the constraints are shown in Figure A-1 of the Appendix A for illustration purposes. This LP is solved using MPS on an IBM-370. The output is shown in the same appendix (Figure A-2). The following assignment matrix shows the machines at which each operation of a given job will be processed. This assigment matrix (Table 2) is constructed using the same format as the variable cost operation time matrix (input) which lists all of the possible selections for a given job, cell and operation. Here, 29 X_{ikn} variables have been selected (as ones) out of 68 possible selections, giving total cost of $5725.92 a day.

Machine Assignment Results:

Table 3 contains machine assignments (M_{ij} values) as determined by MP1. As expected, almost all of the M_{ij} values are fractional leading to a need to use MP2. It is noted that no machine type Z was selected for this example.

Table 2

Job Operation Assignment Matrix

MACHINES/OPERATIONS

		P				J		K			N			W			Z			
		1	4	5	7	6	8	2	3	7	1	4	8	2	3	6	3	5	7	8
C1	A					x				x	x	x		x						
	F					x	x	x	x			x								
	H	x						x	x							x				
C2	C					x			x	x				x						
	D						x			x	x			x						
C3	B			x		x	x		x		x									
	E			x								x								

Table 3

Results of MP1

		Machines					
		P	J	K	N	W	Z
CELLS	C1	1.125	2.20	4.30	1.875	2.375	0
	C2	-	2.00	2.875	0.83	1.08	0
	C3	2.29	2.29	1.04	2.70	-	0

Calculation of Effect of Fractional Machine Assignments:

Using the results obtained from MP1, U_{ij}, E_{ij} and unmet demand UD_{ijk} must be calculated so that MP2 can be written out in a complete form. Tables 2 and 3 contain the information needed to perform these calculations. The following example is given for machine P in cell 1.

From Table 3, M_{P1} = 1.125 machines. Since an integer assignment is needed, this 1.125 must either be rounded up to 2 (M^R_{ij}) or rounded down to 1 [M_{ij}], resulting in a possible excess capacity of 0.875 (2 - 1.125) or an under - capacity, U_{ij} of 0.125 (1.125-1). If the rounding down choice is made, then (0.125/1.125)x100 = 11% of the jobs, assigned to cell 1 that also needs to use machine P, will not be fully processed and left unfinished due to atleast one operation.

Table 2 is used to identify the jobs whose one or more operations will be affected with the rounding decision of the machine considered. It is observed that only operation No.1 of Job H is to be performed on machine P in cell 1. The daily demand for Job H is 180 parts, so 20 parts of Job H (0.11 x 180) will be unfinished (UD_{P11}) if the round down choice is adopted for this cell-machine combination. The same set of calculations are performed for every entry shown on Table 2. It is important to note that there could be more than one UD_{ijk} calculated for a given job because any two operations of a job can be assigned to the same machine. In this case, two separate entries are used in the Fortran code shown in Appendix B because the subcontracting cost (SCC_{kn}) is based on a job and each of its operations. For example, Job C needs machine K for its operations No.3 and 7 A rounding down decision here means that 44 parts of Job C ($UD_{k,2,}$3/7) will not receive these operations. If, later, these parts are to be subcontracted, then operation 3 will cost (44 x $1.9) and operation 7 will cost (44 x $2.4) for all 44 parts of C. Table A-6 of Appendix A contains subcontracting costs.

4.3 HEURISTIC SOLUTION OF MP2

As indicated in Chapter III, MP2 is a mixed integer, zero-one, and also a nonlinear program, which would be quite intractable to solve. The method illustrated below is characterized by the following modifictions applied to MP2.

1) Decompose and investigate MP2 in two parts: rounding each M_{ij} up and down.

2) Convert T_{ijkn} to a 0-1 variable instead of letting it range from 0 to 1. In the example shown above, UD_{ijk} is 20 (due to operation 1), so setting T_{ijkn} to either 0 or 1 indicates that either all 20 unfinished parts of Job H should be sent to the RC for processing (set to 1), or all 20 should be subcontracted only for operation No. 1. (It should be remembered that T_{ijkn} is used only after the rounding down decision is made.) In the original MP2, the complex model was expected to indicate what fraction of these 20 parts should be subcontracted and subsequently (1-fraction) of them sent to RC. Figure 5 below illustrates the decomposition concept. Rounding up any fractional machine designation involves incurring idle cost for each machine assignment (M_{ij}) because some excess capacity results, so there should be a penalty factor for the unused resource. On the contrary, rounding down a given fractional

machine assignment means that either subcontracting cost or the remainder cell cost (RCCOST) must be incurred for that fractional assignment (M_{ij}). RCCOST consists of two components. First is the cost of transport of parts to and from the RC and the set up cost at the RC (called remainder handling and set up cost, RHSC). The second cost component is made up of the fixed cost and possible idle cost at RC.

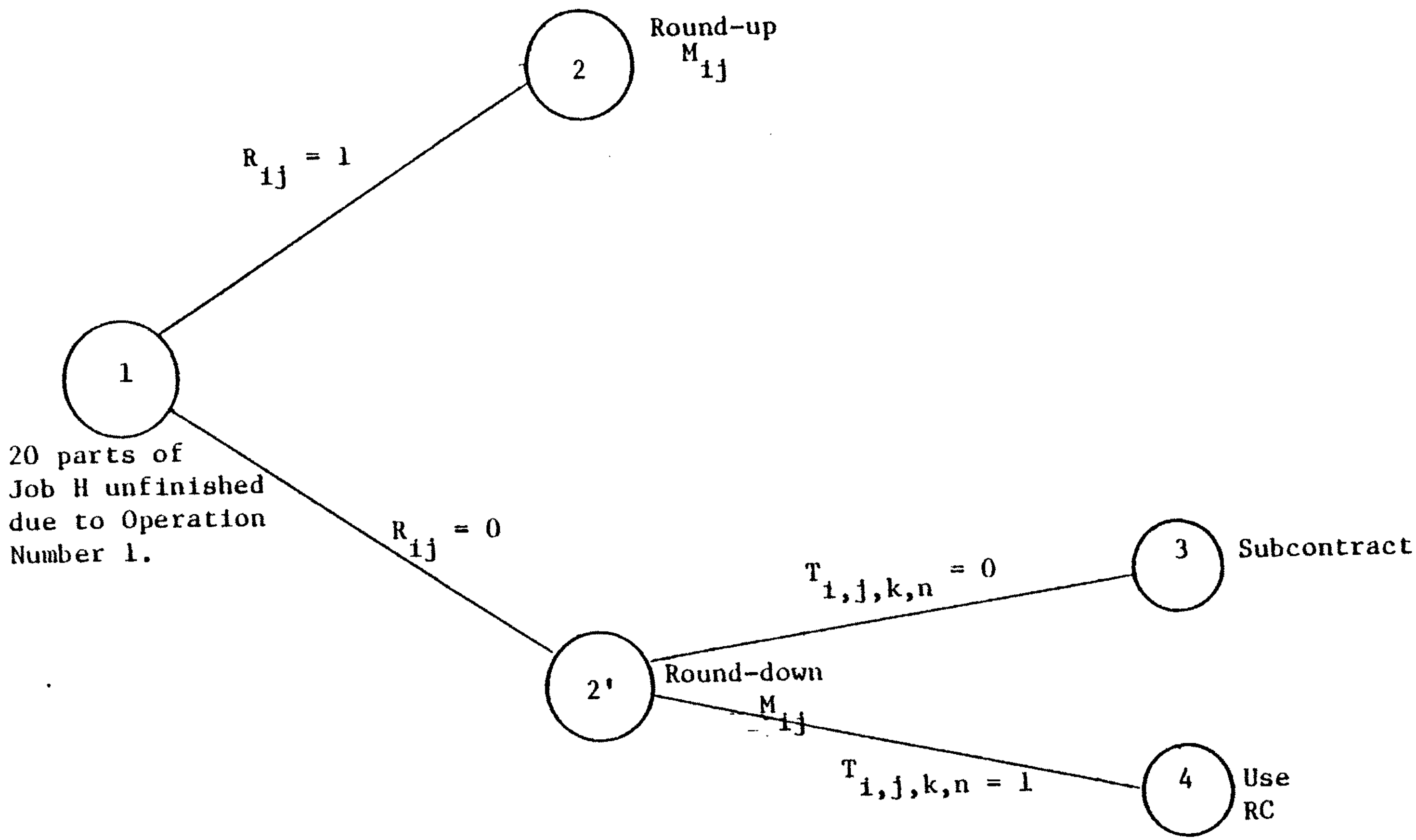

Figure 5. Decomposition of MP2.

4.4 ADDITIVE - RESIDUAL METHOD FOR MP2

This method starts by calculating all costs corresponding to nodes 2,3, and 4 of Figure 5, so all possible 0-1 combinations of the variables R_{ij} and T_{ijkn} are tested. Whenever a fractional machine assignment is confronted, then there are two options: round up or down as discussed earlier. But, it is possible that two or more cells may have fractional assignments of the same machine type. The goal is to add (pool) the total need for a given machine type, over all cells, and use a common source, RC, to meet the needs. Doing so will not always prove to be the best action because sometimes the aggregate need over all cells may exceed 1.0 machines to be placed in the RC and another machine will be required (even though most of the second machine may not be used). To account for such cases, a method, which makes an incremental steepest descent search (discrete first order gradient approximation), is developed and shown below.

First, each machine type, in all cells, is listed in order of decreasing idle cost (cost of rounding up of a fractional machine). The machine-cell combination that is most costly to round up is ranked first because that machine has the highest chance of justifying the use of the RC. If it does not, and the combined machines ranked No. 1 , No. 2, etc. do not, then no other machine of same type, ranked lower, can justify the use of the RC.

Idle Cost Calculation (Round Up Cost):

This is done by multiplying the excess capacity E_{ij} and the daily fixed cost of the machine considered. Also, an idle cost factor (IDC_i), unique to each machine type, is attached as a penalty factor. For machine P in cell 1:

$$(E_{ij})\cdot(1+IDC_i)\cdot FC_i$$

$$(0.875)x(1+0.2)x97 = \$101.85/day.$$

Remainder Handling and Set-up Calculation (RHSC):

Table A-4 of Appendix A shows how much it costs to transport and return (RHC_k) one part to and from the RC. Normally, those UD_{ijk} number of parts to be sent to the RC would be multiplied with the appropriate RHC_k values. However, there may occasionally be a case when the same part may have to use machine types contained in the RC in a nonconsecutive manner. For example, Table 2 indicates that Job A uses machine N for operations No. 1 and No. 4 while Job A also uses machine W for operation No. 2. In this case, if Job A ever needs to use the RC, then it will be transported twice to the RC since operation 2 must precede operation 4. Using Table 1, Table 4 showing which jobs may be subject to double transport charges is generated.

Table 4

RC Transport Charge Coefficients

Jobs

Machines	A	B	C	D	E	F	H
P	0	1	0	0	1	0	1
J	1	1	1	1	0	1	0
K	1	1	2	1	0	1	1
N	2	1	0	1	1	1	0
W	1	0	1	1	0	0	1

Description of the Solution Method:

Basically, cost of rounding up (UPCOST) and the cost of using RC (RCCOST) are compared in a cumulative manner. If RCCOST is less than UPCOST, then RC is used (Corresponding M_{ij} is rounded down). Otherwise, the same M_{ij} is rounded up given that it meets the conditions disscussed below.

Steps of the Solution and an Example

Table 3 and Figure B-1 of Appendix B indicate that machine K is used in all 3 cells and a fractional number of (4.3, 2.875, and 1.04) machine type K have been assigned for each cell. The cost of rounding up each machine K is $63/day in C1, in C2 $11.25 and $86.40 in C3.

1) Rank order rounding up costs in decreasing order and refer to the corresponding cell as a ranked cell, also enter the corresponding under capacity (U_{ij}).

U_{ij}	COST	
0.040	86.40	C3 becomes No. 1 ranked cell-machine K
0.300	63.00	C1 becomes No. 2 ranked cell-machine K
0.875	11.25	C2 becomes No. 3 ranked cell-machine K

2) Calculate the cost of using RC (RCCOST) for the first ranked case. This cost consists of a fixed cost of having

the machine, amount charged for the idle portion of the machine, and remainder handling and set-up cost (RHSC) of transport of the parts. Here, Figure B-1 of Appendix B indicates that RHSC is only \$2.4/day, $FC_{k3} = 75$, and $U_{k3} = 0.04$. Then, 1-0.04 = 0.96 of machine K will be idle.

$$RCCOST = (1 + 0.2\ (0.96))75 + 2.4 = \$91.8/day.$$

3) a- If the total RCCOST is less than the round up cost (both for a given cell-machine case), use RC for that case.

b- Otherwise, no decision is reached and the cumulative process begins.

4) For next highest ranked cell-machine combination, try to use the residual capacity at RC.

a- Compare the current U_{kl} with the residual. If sufficient, then there is no need for another machine. Deduct idle cost for the portion of the machine still unused from the cumulative RCCOST to compensate for the fact that the same machine is now less idle and to prevent double counting.

b- Otherwise, incur another FC and repeat the calculations.

Here, $U_{kl} = 0.30$ and is less than the residual (leftover) capacity of 0.96. Now 0.30 of the 0.96 unused capacity can be utilized ; leaving 0.96-0.30 = 0.66 of the machine still idle. The RHSC of case 2 is $19.4. So, the cumulative RCCOST is 91.8-(0.2(0.66)X75))+19.4 = $101.3/day. The cumulative roundup cost is 86.4+63 = $149.4/day. Since RCCOST is less than UPCOST, the decision is to use the RC for both No.1 and 2 ranked cell-machine combinations.

5) Whenever a decision to use RC is reached, all cumulative costs are set to 0 and the same process is started with the next combination that belongs to the cell considered. However, the residual capacity is kept while steps 2,3, and 4 are repeated. Here, the No.3 ranked cell-machine case (machine K in C2) is the last one to consider. The UPCOST is $11.25/day, U_{k2} = 0.875 (the need for machine K) while the residual capacity is 0.66. Therefore, the present single machine K at RC is not enough and a second one is needed if the need of C2 for machine K must be met using RC. The amount by which the first machine is short is 0.875-0.66 = 0.215 machine K. This is also the portion of the second machine that will be used and 1-0.215 = 0.785 is the portion of the second machine that will stay idle (steps 4-6). The RHSC is $54.60, the RCCOST is:

(1+0.2(0.785)) x 75 + 54.60 = $140.88/day.

Since $11.25 is less than $140.88 and there are no more cells that have machine K, machine K in No. 3 ranked cell should be rounded up to 3 (from 2.875).

6) Once RC use (or round up) decisions are made, all round up decisions are further tested against the option of subcontracting using Figure A-5 of Appendix A. It is important that the variable cost must first be deducted from subcontracting cost before comparison, because variable cost must be incurred if the round up decision remains intact. Here, the difference of subcontracting and variable cost is $101. Since $11.25 is also less than $101, the rounding up decision still holds.

The above procedure is used as an independent test for each of the different machine types.

All other fractional assignments shown on Table 3 were examined, as in the above example, and the results are given in Table 5 below. The second Fortran code of Appendix B and the flowcharts, Figures 6 and 7, also describe the procedure.

Table 5

Results

MACHINES		CELLS C1	C2	C3
	P	RC	-	RC
	J	RC	-	RC
	K	RC	UP	RC
	N	UP	SC	UP
	W	RC	RC	-
	Z	-	-	-

RC : Use RC for that combination

UP : Round up for that combination

SC : Subcontract for that combination

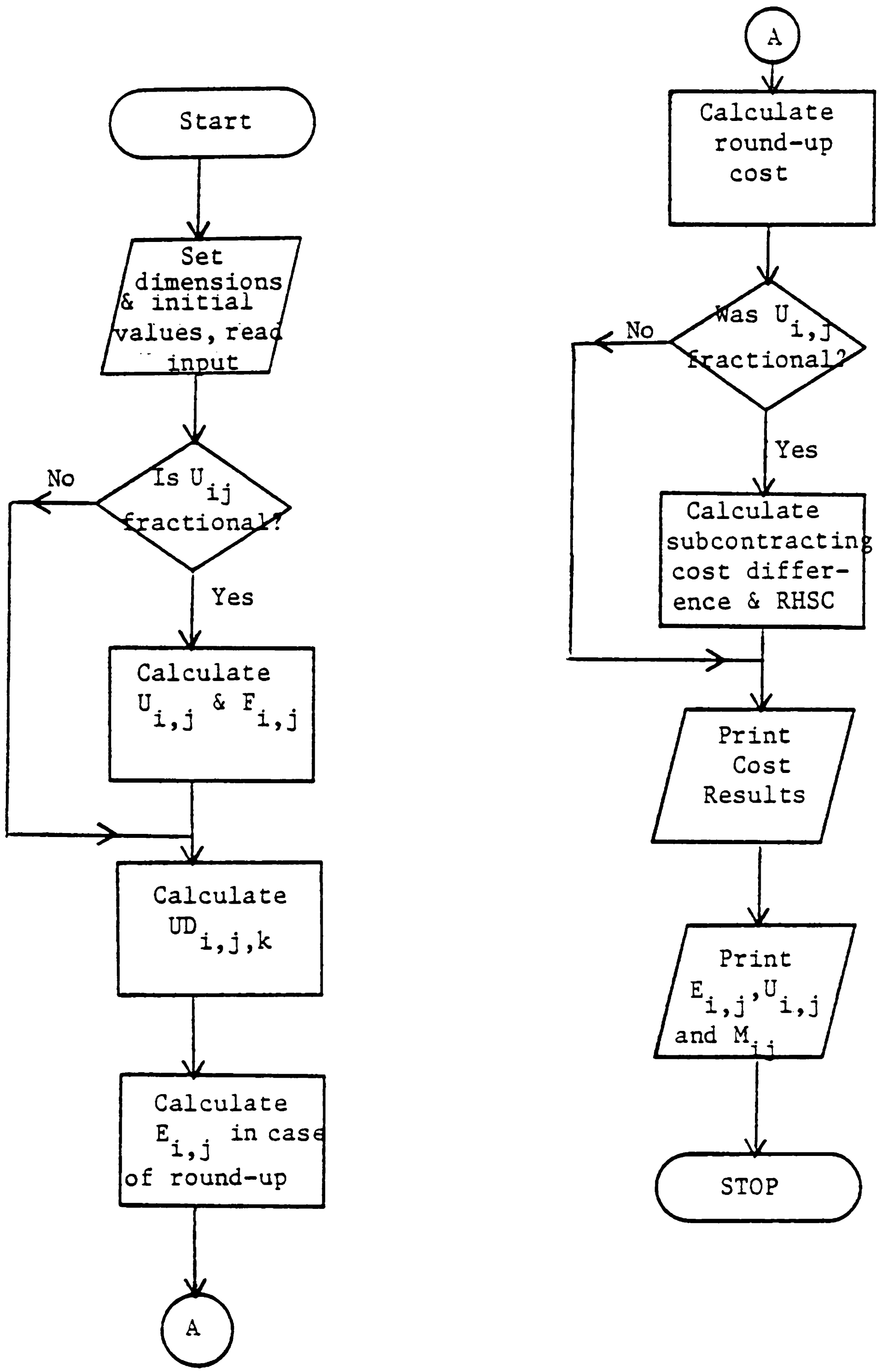

Figure 6. Flowchart of Program No. 1

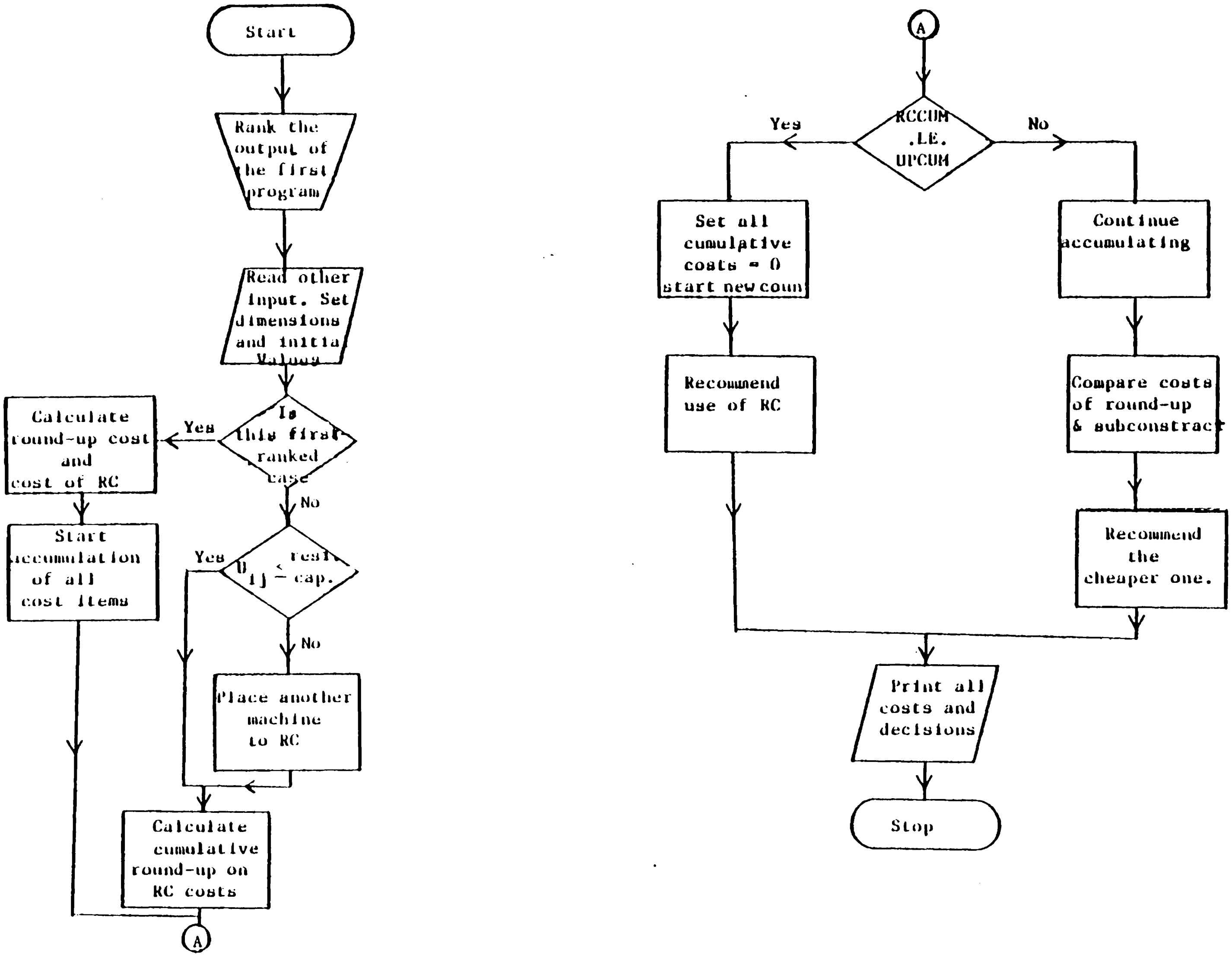

Figure 7. Flowchart of Heuristic Decision Method

So far, the first two stages of CM design : job grouping, and capacity planning, have been made. The third step in this example is to find a serial layout for each cell that accomplishes a given objective. The final step is the scheduling of jobs in each cell. Scheduling, however, is not addressed in this particular research since step 2 has ensured that there would be enough capacity to meet the daily demand for each job. Since jobs are demanded at the end of the day, completion time of any given job order does not affect the cost or the profit of the company. Layout design is discussed below as the last segment of the total heuristic method for the example.

LAYOUT DESIGN

Here, the goal is taken as the minimization of the amount of backtracking made by all jobs in each cell. To do so, the following simple procedure is followed:

1) List all the cells and their assigned jobs, machines, and daily demand for each job.

For C1 jobs: A (120), F (100), H (180)

Machines : P,J,K,N,W

2) Write out each job's order of use of these machines.

A : N W N J K   F : K N J   H : P K W

Create an order of machines which will yield the minimum possible number of backtrackings while giving priority to the job with the highest demand in that cell. Then, any unused machines are added in the sequence in such a way that the job with the second priority has as few backtrackings as possible. The above procedure is repeated until all jobs have been considered. Here, Job H has the highest demand (180) and needs machines P, K and W. Initially place machines in the following order :

P K W : no backtracking for H.

Job A uses all machines assigned to that cell, so machines N and J should be inserted somewhere in the initial sequence. By inspection, the following order results :

P K N W J : 2 backtrackings for A

All machines needed by Job F are already placed and 100 parts of Job F will not have to backtrack. (Forward skipping is acceptable). Figure 8 illustrates the results of the layout and overall CM system considered in this example. In Figure 8, each smaller circle has two parameters which indicate the machine and operation(s) to be performed on the specific number of parts sent to that station. Also, if the circle does not have RC in it, then that machine is in a regular cell. The same layout procedure was utilized for cells 2 and 3 and their layouts are as follows:

C2: N W K J　　　　C3: N K P J

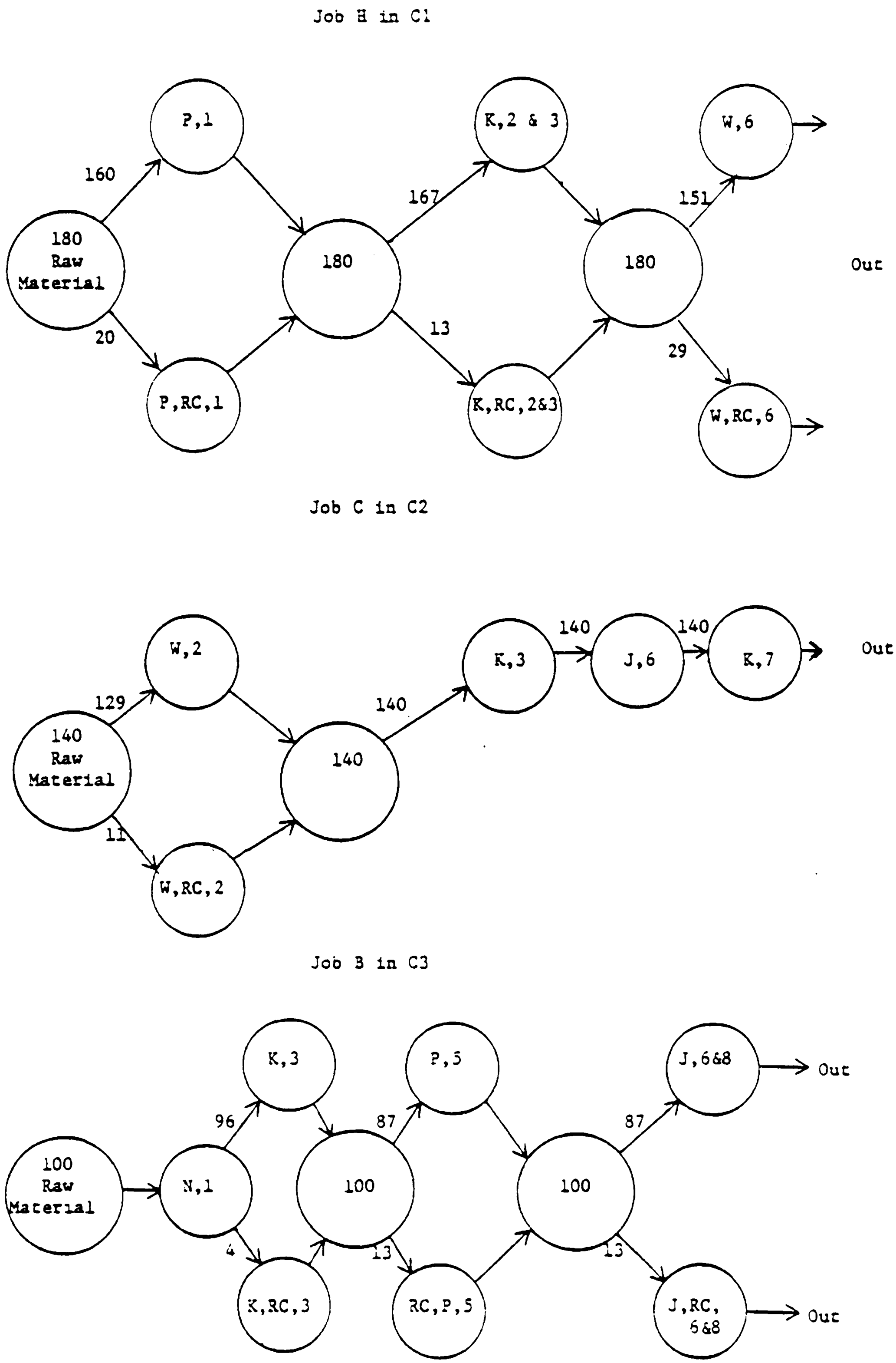

Figure 8. Partition and Flow of Jobs

Chapter V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This research was undertaken to provide a basis for determining the machine requirements in a CM system, with the goal of incurring the minimum total cost of installation. First, a two part mathematical model was proposed as the ideal basis for a solution. However, it was argued that a direct solution of the model would be impractical; so a heuristic alternative solution method was developed. It was shown to be a good way of approximating a solution to the initial models.

This method needs the following input : fixed and variable cost of the available machines, jobs and the operations needed by each job, operation times, demand for each job, and the number of cells to be used. First, the input is used to formulate a LP which normally yields fractional number of machines to be assigned to each cell while no fractional machine is possible in reality. Later, the method determines which fractional machine assignments should be rounded up and which ones rounded down. In case of rounding down, a remainder cell or a subcontractor is used to create additional capacity so that the demand can always be met.

Fortran codes and flow charts that describe the solution method were also developed for the ease of the planner who may require some assistance in designing a complete CM system. Moreover, a modified job grouping and cell formation methodology, independent of the primary model and the heuristic solution method, based on GT principals was introduced as a means of handling the first stage of a CM design.

Possible extensions of the present research are suggested in order to improve the planning tools needed to design an actual CM system. These are given below.

Recommendations

The CM concept, models,and methods presented in this thesis can be improved. The present research should be considered as the seed of a fully comprehensive production design using CM and GT concepts. The assumptions listed in the previous chapters had a limiting effect on the scope of the CM design problem so that certain goals could be accomplished.

CM production design can be improved by implementing any one, some, or all of the following extensions. However, it should be noted that some of the improvements suggested require extensive research before they can be used. So, the goal is to cite possible ways of enhancing the present research without protracted explanations. Some of the improvements formulated in Appendix C are direct extensions of MP1 and MP2.

5.1 POSSIBLE IMPROVEMENTS

1) Production using overtime :

Since each machine purchased, and its related fixed cost, are actually applicable to a 24 hour day, it may be a good idea to use all or some of the machines for periods longer than 8 hours a day. This will undoubtly result in the purchase of fewer numbers of machines while incurring higher variable cost of production due to higher cost of labor and overhead during the overtime shifts. Appendix C contains the necessary formulation that could be added to MP1.

2) Available space in each cell and the area covered by each machine type :

This is also formulated as an addition to MP1 and shown in the Appendix C. In a real life CM environment, the designer should certainly consider this aspect because there is always a fixed number of square feet of area available in each cell that can be covered by machines.

3) Total Available plant space and space to be allocated for each cell:

Again, this is another issue that should be dealt with especially if the number of cells is not fixed in advance and the existence of a RC is not required.

4) Cell Size Penalty:

A cost penalty that discriminates against having too many machines should be included in the objective function of MP1. The rationale for such a penalty can be derived from the fundamental CM concepts, which favor as little material handling as possible between the production centers. This addition is valid because, in the context of this research, it is possible to select different sets of machines that have almost equal processing capacities, while incurring different cost levels. (See Appendix C)

5) Inclusion of work-in process inventory considerations.

6) Use of Existing Equipment:

Possible low cost acquisition or takeover of used and older machines with low performance levels should be considered. The effect of these on the overall machine selection process, and inclusion of machine replacement concepts should be investigated.

7) Time Value of Money:

Inclusion of salvage value of each machine type, time value of money, and capital formation concepts along with the introduction of planning horizon in order to include the interest effect should be considered.

8) Machine operating rates:

The present research assumes that there is only one rate at which each machine type can be operated for each operation. Obviously, a better model would select the optimum rate for each machine type in every individual cell. Furthermore, given the fact that each cell may contain more than one of each of the machine types (called machine groups), the ultimate rate selection process should be based not only on each machine type in a given cell, but also on each of the machines of the same type in each individual cell. (See Appendix C)

9) Profit Maximization:

It should be possible to alter MP1 in such a way that it could be easily converted into a profit maximization model when the unit revenue is a variable based on the demand and the production.

10) Testing multiple cellular layouts:

Presently, a layout is obtained by placing each machine (or machine group) in a serial fashion in each cell. But other layouts such as circular, square, and triangular ones should be investigated as viable alternatives since they may help reduce backtracking in each cell while increasing the width of the cell. An ideal MP1 should include all of the possible layouts as 0-1 variables and select the best layout for each cell.

11) Introduction of Probabilistic Variables:

Thus far, all variables considered have been deterministic. On the other hand, in actual production, variables such as demand and operation times should be expressed as random variables with probability distribution functions. Machine failures, down times, due dates, lead times and scrap rates should be considered and ideally all built into a complex mathematical model. Subsequently, a good but hard to reach goal in the CM design would be the development of a simulator that considers all of the possible CM design aspects.

12) Alternative Grouping of Jobs:

The grouping procedure described in Chapter IV is quite arbitrary because it largely depends on initial inspection by a designer and lacks the surety that the best grouping combinations have been reached. Average cellular rating (ACR) [43] that considers similarities, material handling requirements and the total processing times of all jobs is a better measure than the simple grouping score used to group jobs in this research. Moreover, even when using only the grouping score of this research, a cell-group formation program should be coded to calculate the grouping score (and/or the ACR) for all possible job-cell combinations so that the best possible job groups can be identified. Finally, the ideal job grouping should be part of a solution when the number of cells is also a variable to be determined by MP1.

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Appendix A

DATA

Table A-1

Job-Chracteristic Matrix

		Operations							
		1	2	3	4	5	6	7	8
JOBS	A	x	x		x		x	x	
	B	x		x		x	x		x
	C		x	x			x	x	
	D	x	x					x	x
	E				x	x			
	F		x	x	x		x		x
	H	x	x	x			x		

Table A-2

Machine-Capability Matrix

Machines

OPERATIONS		P	J	K	N	W	Z
	1	x			x		
	2			x		x	
	3			x		x	x
	4	x			x		
	5	x					x
	6		x			x	
	7	x		x			x
	8		x		x		x

Table A-3

Cost of Machines

	Machines					
	P	J	K	N	W	Z
FC ($/day)	97	61	75	80	83	101
FC ($/day)	97	61	75	80	83	101
IC ($)	14K	6K	11K	9K	8K	13K
IC ($)	15K	7K	12K	11K	10K	14K
IDC	0.2	0.1	0.2	0.2	0.1	0.3

Table A-4

Remainder Handling Costs of Jobs

	jobs						
	A	B	C	D	E	F	H
RHC ($/part)	.7	.6	.4	.8	1.1	.8	.6

Table A-5

Variable Cost and Operation Time Data

Machines/Operations

	P 1	P 4	P 5	P 7	J 6	J 8	K 2	K 3	K 7	N 1	N 4	N 8	W 2	W 3	W 6	Z 3	Z 5	Z 7	Z 8	
A	6 / 0.5	5 / 1.5		5 / 1.8	3 / 1.0		6 / 1.2		4 / 1.1	3 / 0.6	3 / 1.1		5 / 1		5 / 1.4			3 / 2		
F		6 / 3			5 / 1.5	3 / 1.6	3 / 0.5	2 / 0.8			3 / 2.3	4 / 2.1	4 / 0.7	6 / 1.0	3 / 2	8 / 1.5			5 / 1.9	C1
H	3 / 1.2				4 / 1.2		3 / 1.5	3 / 0.7		4 / 1.8			5 / 1.8	4 / 1.1	3 / 1.0	5 / 1.2				
C				5 / 1.3	4 / 0.8		5 / 0.7	4 / 1.1	3 / 1.2				3 / 0.8	5 / 1.2	5 / 1.2	6 / 1.3		6 / 1.8		
D	6 / 0.6			7 / 0.9		5 / 1.2	4 / 1.1		5 / 0.7	5 / 0.8		6 / 1.6	3 / 0.9					6 / 1.1	7 / 2.1	C2
B	3 / 0.8		5 / 0.6		5 / 1.2	6 / 0.7		5 / 0.5		5 / 0.9		7 / 1.2		4 / 0.6	8 / 1.7	5 / 0.4	4 / 0.8		8 / 1.0	
E		5 / 1.3	3 / 0.8								4 / 1.3						2 / 1.1			C3

Legend:

t i, k, n/per part per operation (Minutes)
VC ,i, k,n/per part per operation. ($)

Table A-6

Subcontracting Cost ($/part/operation)

Operations

	1	2	3	4	5	6	7	8
A	1.1	1.6	X	2.0	X	1.9	2.6	X
B	1.2	X	0.7	X	0.8	2.2	X	X
C	X	1.1	1.9	X	X	1.5	2.4	X
D	1.0	1.5	X	X	X	X	1.3	2.4
E	X	X	X	1.9	1.5	X	X	X
F	X	0.9	1.3	4.0	X	2.6	X	2.7
H	2.2	2.7	1.2	X	X	1.5	X	X

Minimize:

$$97M_{p,1} + 61M_{j,1} + \cdots + 80M_{n,3} + 93M_{w,3} + 101M_{z,3}$$

$$+ D_a(0.5\, X_{p,a,1} + 1.5\, X_{p,a,4} + \cdots + 1.4\, X_{w,a,6} + 2\, X_{z,a,2})$$

$$+ D_f(3\, X_{p,f,4} + \cdots + 2.3\, X_{n,f,4} + \cdots + 1.9\, X_{z,f,8})$$

$$\vdots$$

$$+ D_e(1.3\, X_{p,3,4} + 0.8\, X_{p,e,5} + 1.3\, X_{n,e,4} + 1.1\, X_{z,e,5})$$

Subject to:

$$X_{p,a,2}, X_{p,a,4}, \ldots, X_{n,d,1}, \ldots X_{z,e,5} \geq 0$$

$$M_{p,2}, M_{j,1}, \ldots, M_{n,2} \ldots M_{z,3} \geq 0$$

$$D_a(4X_{p,a,1} + 5X_{p,a,4} + 5X_{p,a,7}) + D_f(6X_{p,f,4}) + D_h(3 \cdot X_{p,h,1}) \leq 8 \cdot M_{p,1}$$

$$\vdots$$

$$D_b(5X_{z,b,3} + 4X_{z,b,5} + 8X_{z,b,8}) + D_e(2X_{z,e,5}) \leq 8 \cdot M_{z,3}$$

$$X_{p,a,1} + X_{n,a,1} = 1$$

$$\vdots$$

$$X_{p,a,7} + X_{k,a,7} + X_{z,a,7} = 1$$

$$\vdots$$

$$X_{j,b,8} + X_{n,b,8} + X_{z,b,8} = 1$$

Figure A-1 Open LP Form of the Modified MP1

Partial Output of the MPS Used in Solving Modified MP1

Figure A-2

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..
49	MP1	BS	1.12500	97.00000
50	MJ1	BS	2.20833	61.00000
51	MK1	BS	4.29167	75.00000
52	MN1	BS	1.87500	80.00000
53	MW1	BS	2.37500	83.00000
54	MZ1	LL	.	101.00000
55	MP2	LL	.	97.00000
56	MJ2	BS	2.00000	61.00000
57	MK2	BS	2.87500	75.00000
58	MN2	BS	.83333	80.00000
59	MW2	BS	1.08333	83.00000
60	MZ2	LL	.	101.00000
61	MP3	BS	2.29167	97.00000
62	MJ3	BS	2.29167	61.00000
63	MK3	BS	1.04167	75.00000
64	MN3	BS	2.70833	80.00000
65	MW3	LL	.	83.00000
66	MZ3	LL	.	101.00000
67	XWA6	LL	.	168.00000

68	XPA1	LL	.	60.00000
69	XPA4	LL	.	180.00000
70	XPA7	LL	.	216.00000
71	XJA6	BS	1.00000	120.00000
72	XKA2	LL	.	144.00000
73	XKA7	BS	1.00000	132.00000
74	XNA1	BS	1.00000	72.00000
75	XNA4	BS	1.00000	132.00000
76	XWA2	BS	1.00000	120.00000
77	XZA7	LL	.	240.00000
78	XPF4	LL	.	300.00000
79	XJF6	BS	1.00000	150.00000
80	XJF8	BS	1.00000	140.00000
81	XKF2	BS	1.00000	50.00000
82	XKF3	BS	1.00000	80.00000
83	XNF4	BS	1.00000	230.00000
84	XNF8	LL	.	210.00000
85	XWF2	LL	.	70.00000
86	XWF3	LL	.	100.00000
87	XWF6	LL	.	200.00000
88	XZF3	LL	.	150.00000
89	XZF8	LL	.	190.00000
90	XPH1	BS	1.00000	216.00000
91	XJH6	LL	.	216.00000
92	XKH2	BS	1.00000	270.00000

93	XKH3	BS	1.00000	126.00000
94	XNH1	LL	.	324.00000
95	XWH2	LL	.	324.00000
96	XWH3	LL	.	198.00000
97	XWH6	BS	1.00000	180.00000

BUFFA

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..
98	XZH3	LL	.	216.00000
99	XPC7	LL	.	196.00000
100	XJC6	BS	1.00000	112.00000
101	XKC2	LL	.	98.00000
102	XKC3	BS	1.00000	154.00000
103	XKC7	BS	1.00000	168.00000
104	XWC2	BS	1.00000	112.00000
105	XWC3	LL	.	168.00000
106	XWC6	LL	.	168.00000
107	XZC3	BS	.	182.00000
108	XZC7	LL	.	252.00000
109	XPD1	BS	.	48.00000
110	XPD7	LL	.	72.00000
111	XJD8	BS	1.00000	96.00000
112	XKD2	LL	.	88.00000
113	XKD7	BS	1.00000	56.00000
114	XND1	BS	1.00000	64.00000
115	XND8	LL	.	128.00000

116	XWD2	BS	1.00000	72.00000
117	XZD7	LL	.	88.00000
118	XZD8	LL	.	168.00000
119	XPB1	LL	.	80.00000
120	XPB5	BS	1.00000	60.00000
121	XJB6	BS	1.00000	120.00000
122	XJB8	BS	1.00000	70.00000
123	XKB3	BS	1.00000	50.00000
124	XNB1	BS	1.00000	90.00000
125	XNB8	LL	.	120.00000
126	XWB3	BS	.	60.00000
127	XWB6	LL	.	170.00000
128	XZB3	LL	.	40.00000
129	XZB5	BS	.	80.00000
130	XZB8	LL	.	100.00000
131	XPE4	LL	.	260.00000
132	XPE5	BS	1.00000	160.00000
133	XNE4	BS	1.00000	260.00000
134	XZE5	LL	.	220.00000

Appendix B

PROGRAMS

Input and Explanation of Program No.1

Number of machines, cells, jobs, operations and entries in Table 2 (as ones)

6,3,7,8,29

Remainder Handling and set up cost per job

0.7,0.6,0.4,0.8,1.1,0.8,0.6

Demand for each job

120,100,140,80,200,100,180

Subcontracting Cost (Table A-6)

1.1,1.6,0,2,0,1.9,2.6,0

1.2,0,0.7,0,0.8,2.2,0,1.6

0,1.1,1.9,0,0,1.5,2.4,0

1,1.5,0,0,0,0,1.3,2.4

0,0,0,1.9,1.5,0,0,0

0,0.9,1.3,4,0,2.6,0,2.7

2.2,2.7,1.2,0,0,1.5,0,0

C Variable Cost entered using Table A-5 and Table 2

0.60,1.0,0,1.1,0,1.0,1.10,0

0.90,0,0.5,0,0.6,1.20,0,0.70

0,0.80,1.1,0,0,0.8,1.20,0

0.8,0.9,0,0,0,0,0.7,1.20

0,0,0,1.3,0.80,0,0,0

0,0.5,0.8,2.30,0,1.50,0,1.4

1.2,1.50,0.7,0,0,1.1,0,0

Idle Cost coefficient of each machine type

0.2,0.1,0.2,0.2,0.1,0.3

Fixed Cost of each machine at RC

97.,61.,75.,80.,83.,101.

MP1 output : number of machines and the fixed cost of each machine in every cell

1.125,97.,2.2,61.,4.3,75.,1.875,80.,2.375,83.,0.,101.

0.,97.,2.,61.,2.875,75.,0.83,80.,1.08,83.,0.,101.

2.29,97.,2.29,61.,1.04,75.,2.7,80.,0.,83.,0.,101.

MP1 assignments (Table 2), RC transport charge coefficients (Table 4) entered. For example, (2,1,1,6,1,1) means that operation No.6 of job 1 is assigned to machine No.2 in cell 1.
For this combination, the RC transport charge coefficient is 1.

1,1,7,1,1,1

2,1,1,6,1,1

2,1,6,6,1,1

2,1,6,8,1,1

3,1,1,7,1,1

3,1,6,2,1,1

3,1,6,3,1,1

3,1,7,2,1,1

3,1,7,3,1,1

4,1,1,1,1,2

4,1,1,4,1,2

4,1,6,4,1,1

5,1,1,2,1,1

5,1,7,6,1,1

2,2,3,6,1,1

2,2,4,8,1,1

3,2,3,3,1,2

3,2,3,7,1,2

3,2,4,7,1,1

4,2,4,1,1,1

5,2,3,2,1,1

5,2,4,2,1,1

1,3,2,5,1,1

1,3,5,5,1,1

2,3,2,6,1,1

2,3,2,8,1,1

3,3,2,3,1,1

4,3,2,1,1,1

4,3,5,4,1,1

PROGRAM NO. 1

```
1       $JOB      WATFIV
   1          DIMENSION RHLSC(15),FC(10,10),FCARC(10),FR(10,10),IM(10,10),RNDUP(
             110,10),E(10,10),L(10,10,15),UD(10,10,15),IN(10,10,15),DEMAND(15),U
             1(10,10),UPCOST(10,10),RCFC(10,10),TRCOST(10,10),NMTRIP(10,15),
             1TOTRCC(10,10),SUB(10,10,15,15),SUBCON(10,10),SCDIFF(15,1
             15),SCC(15,15),VC(15,15),IL(10,10,10,10)
        C
   2          REAL M(10,10),IDLECF(10),L
   3          INTEGER DEMAND,UD,BJK
        C
   4          READ,NMACH,NCELLS,NJOBS,NOPER,NCOMB
        C
        C*********************************************************************
        C         DEFINITION OF THE TERMS
        C*********************************************************************
        C    I          :INDEX USED FOR MACHINES
        C    J          :INDEX USED FOR CELLS
        C    K          :INDEX USED FOR JOBS
        C    N or KN    :INDEX USED FOR OPERATIONS
        C    NMACH      :NUMBER OF MACHINE TYPES AVAILABLE
        C    NCELLS     :NUMBER OF CELLS
        C    NJOBS      :NUMBER OF JOBS
        C    NOPER      :MAXIMUM NUMBER OF OPERATIONS PER JOB
        C    NCOMB      :NUMBER OF ASSIGMENTS MADE BY MP1
        C    RHSC       :REMAINDER AND SET UP COST PER JOB
        C    FC         :FIXED COST OF A MACHINE
        C    FCARC      :FIXED COST OF A MACHINE AT RC
        C    FR         :FRACTION OF THE DEMAND THAT CAN NOT BE MET
        C    IM         :INTEGER OR ROUNDED DOWN VALUE OF A MACHINE ASSIGMENT
        C                (IF FRACTIONAL)
        C    M          :NUMBER OF MACHINES ASSIGNED
        C    IDLECF     :IDLE COST COEFFICIENT OF A MACHINE
        C    RNDUP      :ROUNDED UP VALUE OF FRACTIONAL NUMBER OF MACHINES
        C    E,U        :EXCESS AND UNDER CAPACITY
        C    UD         :NUMBER PARTS THAT CAN NOT BE FINISHED DUE TO ROUNDING DOWN
        C    DEMAND     :DAILY DEMAND
        C    UPCOST     :COST  ROUNDING UP OF A GIVEN M VALUE (IF FRACTIONAL)
        C    TRCOST     :TOTAL RHLSC FOR ALL OPERATIONS OF A GIVEN JOB PER MACHINE
        C    TOTRCC     :SUM OF ALL TRCOST VALUES THAT CORESSPOND TO A GIVEN CELL
        C                AND MACHINE COMBINATION.
        C    SCC        :SUBCONTRACTING COST PER OPERATION PER JOB
        C    VC         :VARIABLE COST (MACHINE/JOB/OPERATION)
        C    SUB        :COST OF SUBCONTRACTING (MACHINE/JOB/OPERATION/CELL)
        C    IL         :INDICATOR THAT TELLS WHETHER A PARTICULAR (I,J,K,N)
        C                COMBINATION EXISTS (1) OR NOT (0)
        C    IN         :INDICATOR THAT TELLS WHETHER A PARTICULAR (I,J,K)
```

```
C             COMBINATION EXISTS (1) OR NOT (0)
C   NUMTRIP  :RC TRANSPORT CHARGE COEFFICIENT
C**********************************************************************
C**********************************************************************
C
      PRINT 1,NMACH,NCELLS,NJOBS,NOPER,NCOMB
    1 FORMAT(3X,'THE CM SYSTEM IS MADE OF ',2X,I2,1X,'MACHINES',4X,I2,1X
     1,'CELLS',4X,I2,1X,'JOBS',4X,'WITH MAX OF',1X,I2,1X,'OPERATIONS PER
     1JOB',4X,'AND',2X,I2,1X,'ENTRIES'///)
C
C*****************READ THE INPUT**************************************
C**********************************************************************
         READ,(RHLSC(K),K=1,NJOBS)
C
         READ,(DEMAND(K1),K1=1,NJOBS)
C
      DO 70 K3=1,NJOBS
      READ,(SCC(K3,KN),KN=1,NOPER)
   70   CONTINUE
             DO 74 K3=1,NJOBS
C
      READ,(VC(K3,KN),KN=1,NOPER)
   74   CONTINUE
C
      DO 76 KX=1,NJOBS
      DO 76 JL=1,NOPER
C
C   DIFFERENCE BETWEEN SUBCONTRACTING AND THE VARIABLE COST FOUND
C
      SCDIFF(KX,JL)=SCC(KX,JL)-VC(KX,JL)
C
    76  CONTINUE
C
C
C
         READ,(IDLECF(I),I=1,NMACH)
         READ,(FCARC(I1),I1=1,NMACH)
C
      DO 40 J=1,NCELLS
C
   40   READ,(M(I3,J),FC(I3,J),I3=1,NMACH)
C
      DO 37 I6=1,NMACH
       DO 37 J=1,NCELLS
        DO 37 KK=1,NJOBS
C
C   SET ALL INDICATORS TO ZERO
C
      NMTRIP(I6,KK)=0
      IN(I6,J,KK)=0
```

```
C
            DO 37 KN=1,NOPER
         IL(16,J,KK,KN)=0
C
      37   CONTINUE
C
C*************************************************************************
C
            DO 48 II=1,NCOMB
C
C     TABLE 2 INFORMATION IS NOW ENTERED : ALL JOB-CELL-MACHINE-OPERATION
C     ASSIGNMENTS ARE READ IN AS ONES (1)
C     NOTE THAT COMBINATIONS  NOT ASSIGNED AS ONES REMAIN AS ZEROS
C     BECAUSE OF THE INITIALIZATION MADE PREVIOUSLY
C
         READ,I,J,K,KN,IVAL,BJK
C
                 IL(I,J,K,KN)=IVAL
                 IN(I,J,K)=IVAL
C     TABLE 4  THAT GIVES RC TRANSPORT CHARGE COEFFICIENTS IS READ IN
C     AS A MATRIX.
C
                 NMTRIP(I,K)=BJK
      48   CONTINUE
C
         DO 36 I4=1,NMACH
                 DO 36 J1=1,NCELLS
C
         TOTRCC(I4,J1)=0
         SUBCON(I4,J1)=0
C
C     FRACTIONAL MACHINES ARE ROUNDED DOWN ;  FRACTIONAL DEMAND THAT CAN
C     NOT BE MET IS CALCULATED.
C
         IF(M(I4,J1).NE.0)  GO TO 12
         U(I4,J1)=0
         FR(I4,J1)=0
         GO TO 25
      12       IM(I4,J1)=INT(M(I4,J1))
C
         IF(IM(I4,J1).EQ.M(I4,J1))          THEN DO
         U(I4,J1)=0
         FR(I4,J1)=0
                                              ELSE DO
         U(I4,J1)=M(I4,J1)-IM(I4,J1)
         FR(I4,J1)=U(I4,J1)/M(I4,J1)
                                              END IF
      25 CONTINUE
C
C     CALCULATE NUMBER OF JOBS THAT WILL NOT BE FINISHED.
```

```
C
      DO 88 KK=1,NJOBS
C
      L(I4,J1,KK)=DEMAND(KK)*FR(I4,J1)*IN(I4,J1,KK)
C
      UD(I4,J1,KK)=(INT(L(I4,J1,KK))+1)*IN(I4,J1,KK)
C
C   CALCULATE EXCESS CAPACITY IN CASE OF ROUNDING UP
C
              IF(U(I4,J1).GT.0)                          THEN DO
                   RNDUP(I4,J1)=INT(M(I4,J1))+1
                   E(I4,J1)=RNDUP(I4,J1)-M(I4,J1)
                                                         ELSE DO
                   E(I4,J1)=0
                                                         END IF
C
C   CALCULATE THE COST OF ROUNDING UP OF A FRACTIONAL
C   MACHINE ASSIGNMENT
C
      UPCOST(I4,J1)=(1+IDLECF(I4))*E(I4,J1)*FC(I4,J1)
C
      IF(U(I4,J1).EQ.0)  GO TO 88
C
          DO 98 KN=1,NOPER
C
C   CALCULATE THE COST OF SUBCONTRACTING FOR NUMBER
C   OF JOBS THAT CORRESPOND TO A SPECIFIC
C   OPERATION-JOB-CELL-MACHINE COMBINATION
C
      SUB(I4,J1,KK,KN)=UD(I4,J1,KK)*SCDIFF(KK,KN)*IL(I4,J1,KK,KN)
C
C   SUM UP COMBINATIONS TO REDUCE THEM TO
C   CELL-MACHINE COMBINATION LEVEL
C
      SUBCON(I4,J1)=SUBCON(I4,J1)+SUB(I4,J1,KK,KN)
C
   98   CONTINUE
C
C   CALCULATE THE RHSC COSTS ON MACHINE-JOB BASIS
C
      TRCOST(I4,KK)=UD(I4,J1,KK)*RHLSC(KK)*NMTRIP(I4,KK)
C
1 C   SUM UP RHSC COSTS SO THAT THEY ARE CONVERTED
C   TO CELL MACHINE BASIS
C
      TOTRCC(I4,J1)=TOTRCC(I4,J1)+TRCOST(I4,KK)
C
   88   CONTINUE
   36   CONTINUE
C
```

```
C
C    PRINT ALL RESULTS
C
C
         DO 26 I4=1,NMACH
         DO 26 J1=1,NCELLS
C
         PRINT 30,I4,J1,UPCOST(I4,J1),TOTRCC(I4,J1),SUBCON(I4,J1)
   30     FORMAT(5X,'MACHINE:',1X,I1,1X,'IN CELL:',I1,5X,'UPCOST:$',F7.2,5X,
        1'RC-HANDLING&SET-UP COST:$',F7.2,5X,'(SCC-VC):$',F7.2//)
C
   26     CONTINUE
C
         DO 56 I=1,NMACH
            DO 56 J=1,NCELLS
C
         PRINT 151,I,J,U(I,J),E(I,J),M(I,J)
  151     FORMAT(15X,'MACH:',I2,2X,'IN CELL:',I2,5X,'UNDER CAPACITY.:',F5.3,
        13X,'EXCESS CAPACITY.:',F5.3,5X,'FROM MP1',F5.2,1X,'MACHINES'//)
   56     CONTINUE
         STOP
         END
```

OUTPUT OF PROGRAM NO.1

NOTE : FOLLOWING NOTATION IS USED

UPCOST : COST OF ROUNDING UP OF A FRACTIONAL MACHINE
RHSC : REMAINDER HANDLING AND SET UP COST
SB : COST OF DIFFERENCE BETWEEN THE SCC AND VC

THE CM SYSTEM IS MADE OF 6 MACHINES 3 CELLS 7 JOBS

WITH MAX OF 8 OPERATIONS AND 29 SEPERATE ASSIGNMENTS

MACHINE: 1	IN CELL:1	UPCOST:$ 101.85	RHSC:$ 12.00	SB:$ 20.00
MACHINE: 1	IN CELL:2	UPCOST:$ 0.00	RHSC:$ 0.00	SB:$ 0.00
MACHINE: 1	IN CELL:3	UPCOST:$ 82.64	RHSC:$ 36.40	SB:$ 20.80
MACHINE: 2	IN CELL:1	UPCOST:$ 53.68	RHSC:$ 15.70	SB:$ 33.90
MACHINE: 2	IN CELL:2	UPCOST:$ 0.00	RHSC:$ 0.00	SB:$ 0.00
MACHINE: 2	IN CELL:3	UPCOST:$ 47.64	RHSC:$ 7.80	SB:$ 24.70
MACHINE: 3	IN CELL:1	UPCOST:$ 63.00	RHSC:$ 19.70	SB:$ 41.90
MACHINE: 3	IN CELL:2	UPCOST:$ 11.25	RHSC:$ 54.40	SB:$ 101.00
MACHINE: 3	IN CELL:3	UPCOST:$ 86.40	RHSC:$ 2.40	SB:$ 0.80
MACHINE: 4	IN CELL:1	UPCOST:$ 12.00	RHSC:$ 116.00	SB:$ 158.30
MACHINE: 4	IN CELL:2	UPCOST:$ 16.32	RHSC:$ 64.80	SB:$ 16.20

1

MACHINE: 4 IN CELL:3 UPCOST:$ 28.80 RHSC:$ 72.80 SB:$ 39.00

MACHINE: 5 IN CELL:1 UPCOST:$ 57.06 RHSC:$ 30.70 SB:$ 23.00

MACHINE: 5 IN CELL:2 UPCOST:$ 84.00 RHSC:$ 9.20 SB:$ 6.90

MACHINE: 5 IN CELL:3 UPCOST:$ 0.00 RHSC:$ 0.00 SB:$ 0.00

MACHINE: 6 IN CELL:1 UPCOST:$ 0.00 RHSC:$ 0.00 SB:$ 0.00

MACHINE: 6 IN CELL:2 UPCOST:$ 0.00 RHSC:$ 0.00 SB:$ 0.00

MACHINE: 6 IN CELL:3 UPCOST:$ 0.00 RHSC:$ 0.00 SB:$ 0.00

CAPACITY INFORMATION AND ECHO PRINT OF MP1 RESULTS

MACH: 1 IN CELL: 1 UNDER CAP.:0.125 EXCESS CAP.:0.875 M(I,J) : 1.13

MACH: 1 IN CELL: 2 UNDER CAP.:0.000 EXCESS CAP.:0.000 M(I,J) : 0.00

MACH: 1 IN CELL: 3 UNDER CAP.:0.290 EXCESS CAP.:0.710 M(I,J) : 2.29

MACH: 2 IN CELL: 1 UNDER CAP.:0.200 EXCESS CAP.:0.800 M(I,J) : 2.20

MACH: 2 IN CELL: 2 UNDER CAP.:0.000 EXCESS CAP.:0.000 M(I,J) : 2.00

MACH: 2 IN CELL: 3 UNDER CAP.:0.290 EXCESS CAP.:0.710 M(I,J) : 2.29

MACH: 3 IN CELL: 1 UNDER CAP.:0.300 EXCESS CAP.:0.700 M(I,J) : 4.30

MACH: 3 IN CELL: 2 UNDER CAP.:0.875 EXCESS CAP.:0.125 M(I,J) : 2.88

MACH: 3 IN CELL: 3 UNDER CAP.:0.040 EXCESS CAP.:0.960 M(I,J) : 1.04

MACH: 4 IN CELL: 1 UNDER CAP.:0.875 EXCESS CAP.:0.125 M(I,J) : 1.88

1 MACH: 4 IN CELL: 2 UNDER CAP.:0.830 EXCESS CAP.:0.170 M(I,J) : 0.83

MACH: 4 IN CELL: 3 UNDER CAP.:0.700 EXCESS CAP.:0.300 M(I,J) : 2.70

MACH: 5 IN CELL: 1 UNDER CAP.:0.375 EXCESS CAP.:0.625 M(I,J) : 2.38

MACH: 5 IN CELL: 2 UNDER CAP.:0.080 EXCESS CAP.:0.920 M(I,J) : 1.08

MACH: 5 IN CELL: 3 UNDER CAP.:0.000 EXCESS CAP.:0.000 M(I,J) : 0.00

MACH: 6 IN CELL: 1 UNDER CAP.:0.000 EXCESS CAP.:0.000 M(I,J) : 0.00

MACH: 6 IN CELL: 2 UNDER CAP.:0.000 EXCESS CAP.:0.000 M(I,J) : 0.00

MACH: 6 IN CELL: 3 UNDER CAP.:0.000 EXCESS CAP.:0.000 M(I,J) : 0.00

Input and Explanation of Program No.2

Number of machines and cells (NCELL)

6,3

Fixed cost at RC for each machine type

97,61,75,80,83,101

Idle cost coefficient of each machine type

0.2,0.1,0.2,0.2,0.1,0.3

Results of the first program after they are manually ranked in descending UPCOST order. Here, every NCELL number of lines of input corresponds to each machine type that may or may not (zero) exist in each cell.

101.85,12,20,0.125,0.875

82.64,36,20.8,0.29,0.71

0,0,0,0,0

53.68,15.7,33.9,0.2,0.8

47.64,7.8,24.7,0.29,0.71

0,0,0,0,0

86.4,2.4,0.8,0.04,0.96

63,19.7,41.9,0.3,0.7

11.25,54.4,101,0.875,0.125

28.8,72.8,39,0.7,0.3

16.32,64.8,16.2,0.83,0.17

12,116,158.3,0.875,0.125

84,9.2,6.9,0.08,0.92

57.06,30.7,23,0.375,0.625

0,0,0,0,0

0,0,0,0,0

0,0,0,0,0

0,0,0,0,0

PROGRAM No.2

```
1       $JOB     WATFIV
    1         DIMENSION UPCOST(10,10),E(10,10),U(10,10),TOTRCC(10,10),FCARC(10),
             1SUBCON(10,10),RC(10,10),PARTRC(10,10),TEM(10,10),UN(10,10),RCCUM(1
             10),UPCUM(10),RC2(10,10),UP2(10,10),EX(10,10)
        C
    2         REAL M(10,10),IDLECF(10)
        C
        C
        C    ****NOTE****WHENEVER A USE-RC DECISION IS DISPLAYED IN THE OUTPUT,
        C    IT IS A CUMULATIVE DECISION.  IT REPLACES THE PREVIOUS CONDITIONAL
        C    DECISION WITH USE OF RC IN EVERY INDIVIDUAL MACHINE GROUP.
        C
        C
        C***********************************************************************
        C               DEFINITION OF THE TERMS
        C***********************************************************************
        C    UPCOST,TOTRCC,FCARC,E,M,U,IDLECF,NMACH,NCELLS,SUBCON : SAME AS THE
        C                                                            PREVIOUS
        C                                                            DEFINITIONS
        C    UPCUM     :CUMULATIVE ROUND UP COST
        C    RCCUM     :CUMULATIVE COST OF USE OF RC
        C    EX        :RESIDUAL CAPACITY
        C    TEM       :AMOUNT BY WHICH THE RESIDUAL CAPACITY IS SHORT OF MEETING
        C               THE NEXT RANKED COMBINATION'S UNDER CAP.
        C    UN        :AMOUNT OF CAPACITY THAT WILL BE IDLE IF A
        C               SECOND OR EXTRA MACHINE IS ADDED TO RC
        C***********************************************************************
        C***********************************************************************
        C
        C               INPUT IS READ IN
        C***********************************************************************
        C
    3         READ,NMACH,NCELLS
        C
    4         READ,(FCARC(I),I=1,NMACH)
        C
    5         READ,(IDLECF(I),I=1,NMACH)
        C
    6         PRINT 4
    7      4  FORMAT(20X,'THE RESULTS OF THE ADDITIVE-RESIDUAL SOLUTION METHOD A
             1RE GIVEN BELOW'//////)
        C
    8          DO 1 I=1,NMACH
        C
        C    RESULTS OF THE FIRST PROGRAM ARE READ IN.  IT IS TO BE NOTED THAT
        C    THESE COSTS MUST FIRST BE RANKED IN DESCENDING ROUND UP COST  ORDER
```

```
      C
      1    READ,(UPCOST(I,J),TOTRCC(I,J),SUBCON(I,J),U(I,J),E(I,J),J=1,NCELLS
          I)
      C
      C**********************************************************************
      C
                   DO 18 I=1,NMACH
                   DO 17 J=1,NCELLS
      C
           IF(J.EQ.1)   PRINT 23
        23   FORMAT(34X,'NEXT MACHINE'//)
      C
           IF(J.GT.1)                 GO TO 16
      C
           UPCUM(I)=0
           RCCUM(I)=0
      C
      C   START ACCUMULATING ROUND UP COSTS
      C
           UPCUM(I)=UPCUM(I)+UPCOST(I,J)
      C
      C   CALCULATE AND ACCUMULATE COST OF USING THE RC
      C
           IF(UPCOST(I,J).EQ.0)   RC(I,J)=0
           IF(UPCOST(I,J).GT.0)   RC(I,J)=(1+(IDLECF(I)*E(I,J)))*FCARC(I)+TOT
          IRCC(I,J)
      C
           RCCUM(I)=RCCUM(I)+RC(I,J)
      C
           IF(J.EQ.1) GO TO 27
      C
        16   KK=J-1
      C
      C   COMPARE THE RESIDUAL CAPACITY AT RC WITH THE CURRENT NEED (U(I,J))
      C
           IF(U(I,J).LE.E(I,KK))                       THEN DO
      C
           EX(I,J)=E(I,KK)-U(I,J)
           E(I,J)=EX(I,J)
           PARTRC(I,J)=IDLECF(I)*EX(I,J)*FCARC(I)
      C
           IF(TOTRCC(I,J).EQ.0)  RC(I,J)=0
      C
           IF(TOTRCC(I,J).GT.0)      RC(I,J)=TOTRCC(I,J)-PARTRC(I,J)
      C
           RCCUM(I)=RCCUM(I)+RC(I,J)
           UPCUM(I)=UPCUM(I)+UPCOST(I,J)
      C
                                                        ELSE DO
      C
```

```
         TEM(I,J) =U(I,J)-E(I,KK)
         UN(I,J)=1-TEM(I,J)
         E(I,J)=UN(I,J)
C
         IF(TOTRCC(I,J).EQ.0)  RC(I,J)=0
C
         IF(TOTRCC(I,J).GT.0)   RC(I,J)=((1+(IDLECF(I)*UN(I,J)))*FCARC(I))
        ITOTRCC(I,J)
C
         RCCUM(I)=RCCUM(I)+RC(I,J)
         UPCUM(I)=UPCUM(I)+UPCOST(I,J)
C
                                                 END IF
C
C
      27   IF(RCCUM(I).LE.UPCUM(I))              THEN DO
         RC2(I,J)=RCCUM(I)
         UP2(I,J)=UPCUM(I)
C
         RCCUM(I)=0
         UPCUM(I)=0
C
         IF(UP2(I,J).EQ.0.OR.UPCOST(I,J).EQ.0)  PRINT 91,J,I,I
      91   FORMAT(3X,'FOR',1X,'#',I2,2X,'RANKED CELL- MACHINE #',I2,3X,'METHO
        ID NOT APPLICABLE - NO FRACTIONAL MACHINE TYPE',1X,I2,2X,'WAS ASSIG
        INED'/)
C
         IF(UP2(I,J).GT.0)    PRINT 33,J,I,UP2(I,J),RC2(I,J)
      33   FORMAT(3X,'FOR',1X,'#',I2,2X,'RANKED CELL- MACHINE #',I2,3X,'UP:$'
        I,F7.2,2X,'RC:$',F7.2,2X,'FOR THAT MACHINE IN THIS CELL ***USE RC**
        I*'/)
C
                                                 ELSE DO
C
         RC2(I,J)=RCCUM(I)
         UP2(I,J)=UPCUM(I)
C
C    IN CASE OF ROUND UP, COMPARE COST OF ROUNDING UP AND SUBCONTRACTING
C
         IF(SUBCON(I,J).LT.UP2(I,J))   PRINT 35,J,I,UP2(I,J),RC2(I,J),SUBCO
        IN(I,J)
      35   FORMAT(3X,'FOR',1X,'#',I2,2X,'RANKED CELL- MACHINE #',I2,3X,'UP:$'
        I,F7.2,2X,'RC:$',F7.2,2X,'SUB:$',F7.2,6X,'SUBCONTRACT IF NO (USE-RC
        I) FOLLOWS'/)
C
         IF(SUBCON(I,J).GE.UP2(I,J))    PRINT 34,J,I,UP2(I,J),RC2(I,J),SUBC
        ION(I,J)
      34   FORMAT(3X,'FOR',1X,'#',I2,2X,'RANKED CELL- MACHINE #',I2,3X,'UP:$'
        I,F7.2,2X,'RC:$',F7.2,2X,'SUB:$',F7.2,6X,'ROUND UP IF NO (USE-RC)
        IFOLLOWS'/)
```

```
C
                                            END IF
   17   CONTINUE
C
    18  CONTINUE
C
        STOP
        END
0      $ENTRY
```

OUTPUT OF PROGRAM NO.2

THE RESULTS OF THE ADDITIVE-RESIDUAL SOLUTION
METHOD ARE GIVEN BELOW

NOTE : FOLLOWING NOTATION IS USED

DEC : DECISION
S : SUBCONTRACT IF NO (USE RC) FOLLOWS
R : USE RC
UP : ROUND UP IF NO (USE RC) FOLLOWS
NF : NO FRACTIONAL MACHINE TYPE WAS ASSIGNED

NEXT MACHINE

FOR # 1 RANKED CELL- MACHINE # 1	UP:$ 101.85	RC:$ 125.97	SUB:$ 20.00	DEC : S
FOR # 2 RANKED CELL- MACHINE # 1	UP:$ 184.49	RC:$ 150.63		DEC : R
FOR # 3 RANKED CELL- MACHINE # 1	METHOD NOT APPLICABLE - NF			

NEXT MACHINE

FOR # 1 RANKED CELL- MACHINE # 2	UP:$ 53.68	RC:$ 81.58	SUB:$ 33.90	DEC : S
FOR # 2 RANKED CELL- MACHINE # 2	UP:$ 101.32	RC:$ 86.27		DEC : R
FOR # 3 RANKED CELL- MACHINE # 2	METHOD NOT APPLICABLE - NF			

NEXT MACHINE

FOR # 1 RANKED CELL- MACHINE # 3	UP:$ 86.40	RC:$ 91.80	SUB:$ 0.80	DEC : S
FOR # 2 RANKED CELL- MACHINE # 3	UP:$ 149.40	RC:$ 101.60		DEC : R
FOR # 3 RANKED CELL- MACHINE # 3	UP:$ 11.25	RC:$ 141.17	SUB:$ 101.00	DEC : UP

NEXT MACHINE

FOR # 1 RANKED CELL- MACHINE # 4	UP:$ 28.80	RC:$ 157.60	SUB:$ 39.00	DEC : UP

FOR # 2 RANKED CELL- MACHINE # 4 UP:$ 45.12 RC:$ 309.92 SUB:$ 16.20 DEC : S

FOR # 3 RANKED CELL- MACHINE # 4 UP:$ 57.12 RC:$ 515.44 SUB:$ 158.30 DEC : up

NEXT MACHINE

FOR # 1 RANKED CELL- MACHINE # 5 UP:$ 84.00 RC:$ 99.84 SUB:$ 6.90 DEC : S

FOR # 2 RANKED CELL- MACHINE # 5 UP:$ 141.06 RC:$ 126.01 DEC : R

FOR # 3 RANKED CELL- MACHINE # 5 METHOD NOT APPLICABLE - NF

NEXT MACHINE

FOR # 1 RANKED CELL- MACHINE # 6 METHOD NOT APPLICABLE - NF

FOR # 2 RANKED CELL- MACHINE # 6 METHOD NOT APPLICABLE - NF

FOR # 3 RANKED CELL- MACHINE # 6 METHOD NOT APPLICABLE - NF

Appendix C

IMPROVEMENTS

1) Production Using Overtime :

Following terms are used to expand MP1

$SH1_j$ = 1, If cell j operates for 1 shift a day (8 hours)

0, Otherwise

$SH2_j$ = 1, If cell j operates for 2 shifts a day (16 hours)

0, Otherwise

$SH3_j$ = 1, If cell j operates for 3 shifts a day (24 hours)

0, Otherwise

e : Factor of increase of VC during the 16 hour shift as compared to 8 hour shift

f : Factor of increase of VC during the 24 hour shift as compared to 8 hour shift

Term B1 of MP1 is changed to :

$$\sum_j \sum_k \sum_i \sum_n D_k \cdot VC_{ikn} \cdot X_{ikn} (SH1_j + e \cdot SH2_j + f \cdot SH3_j)$$

Following constraints are added to MP1

$$SH1_j + SH2_j + SH3_j = 1 \qquad \forall\ j$$

(Each cell can operate only at one of the three shifts)

$$SH1_j , SH2_j , SH3_j = [0,1]$$

Right hand side of constraint No.4 is modified as follows:

$$.......... \leq (8 \cdot SH1_j + 16 \cdot SH2_j + 24 \cdot SH3_j) \cdot M_{ij} \quad \forall i \quad \forall j$$

2) Available space in each cell and area covered by each machine :

Define :

MA_i : Number of square feet covered by machine i

CA_j : Total cell area available for mounting machines

This improvement only requires the following additional constraint and no change in the objective function

$$\sum_i MA_i \cdot M_{ij} \leq CA_j \quad \forall j$$

4) Cell size penalty :

Term bp is defined as the "bigness penalty" ($/machine) and included in the term A1 of MP1 as follows :

$$\sum_i \sum_j (FC_i + bp) \cdot M_{ij}$$

5) Machine Operating Rates :

In MP1, variable cost (VC) and the operation time (t) are based on machine, job, and operation (i,k,n). Here, another subscript (r) is added to VC and t. Now, there can be different variable cost and operation times unique to each possible machine, job, operation, and rate (r) combination (i,k,n,r). Also :

R_{ijr} = 1, if machine i in cell j is run at the rate of r

0, Otherwise

t_{ikn} of constraint No.4 becomes t_{iknr} and a summation sign over r ($\sum_r$) is added to that constraint.

Term B1 of the objective function is rewritten as follows:

$$\sum_i \sum_n \sum_k \sum_j \sum_r \quad D_k . VC_{iknr} . X_{ikn} . R_{ijr}$$

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MACHINE REQUIREMENTS PLANNING FOR CELLULAR MANUFACTURING SYSTEM

by

Hüseyin Sarper

(ABSTRACT)

This thesis presents an approach for solving the problem of determining a near optimal number of machines in order to minimize total cost in a Cellular Manufacturing System. In addition, all aspects and design of a Cellular Manufacturing System are discussed along with other related topics such as Group Technology and Plant Layout as applied to Cellular Manufacturing.