GROUP TECHNOLOGY DECISION AIDS FOR THE DESIGN OF CELLULAR MANUFACTURING SYSTEMS - AN EXPERT SYSTEMS APPROACH

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ABSTRACT

Group Technology Decision Aids for the Design of Cellular Manufacturing Systems - an Expert Systems Approach

Venkatesh Govindarajan

The study develops a methodology for the design of a cellular manufacturing system (CMS) utilizing the group technology output. The design process is built into an expert system (ES) and a framework of the ES has been developed in this research A new algorithm for forming a groupable matrix using alternate process plans is also developed. This algorithm increases the chances of obtaining a well defined grouping of machines and parts. The application of group technology to the binary incidence matrix generates machine - part groupings and by considering a different set of process plans alternate groupings are obtained. An advantage of the new approach is it gives alternatives at various stages which can be evaluated and a solution can be selected by the user. The ES consists of a knowledge base i. e production and expert rules, database, algorithms and an inference engine. It aids the user in choosing a feasible set of layouts and material handling systems (MHSs) for each cell and the overall manufacturing system. A new method for the joint selection of layout and MHS is also proposed. Knowledge base rules evaluate the feasibility of these layout and MHS combinations. The alternative cell and cellular manufacturing system designs

generated are evaluated by simulation to select the best design The complete design procedure is built into a heuristic which forms the inference engine of the ES Unlike other researches in this area, which deal only with the grouping of machines and parts, a practical methodology for the design of a CMS is proposed in this thesis

Dedicated To My Parents

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CHAPTER 1

1.1 PROBLEM DEFINITION

Group Technology is a philosophy which can be applied to a manufacturing system by exploiting the similarities that occur between the processing of different types of parts on different machines The machines required to process the similar parts are grouped into machine cells and parts are grouped into part families The shop floor is divided into cells and the layout is called a Group Technology layout or group layout [13] Group Technology when implemented in a batch manufacturing system can lead to benefits in reduced work-in-process and tooling, improved productivity, reduced material handling, better management and control The application of Group Technology to the manufacturing system results in a layout which is also known as a Cellular manufacturing System (CMS) The name CMS highlights the fact that the formation of cells is fundamental to the application of this concept.

The design problem of a CMS involves forming machine cells and part families, layout selection, determining the relative allocation of the machines and layout of the cells, material handling system selection for the cells and the manufacturing system, selecting a combination of layout and material handling system for the cell and scheduling of the parts in the cells. A vast majority of literature published in this area has been concentrated over the formation of machine cells and part families, and numerous algorithms have been suggested for that purpose. There is no approach in literature which considers the complete design problem of a CMS. In this study an Expert System approach to the desigr of a CMS is presented The group technology output forms an input to the design process The consideration of layout of machines and the material handling system is important for the practical application of the group technology concept Any approach to the design of a CMS must generate alternatives so that the user may select the one most suitable to his/her application Alternative process plans for each part are considered and a new algorithm for the formation of a matrix which has a higher chance of forming a well defined grouping of parts and machines is also presented If the group technology output is not feasible to be implemented then the effort in grouping the parts is futile In this study a framework for the complete design of a cellular manufacturing system is considered which includes material handling selection and layout selection A literature review is presented in the next section, following which we list the objectives of this research and a new methodology is proposed for the design of a Cellular Manufacturing System

1.2 LITERATURE REVIEW

An important part of the design process of a CMS is the formation of machine cells and part families There are many methods available for grouping machines and parts, which are broadly divided into two categories, 1) Classification and Coding systems and 2) Cluster Analysis methods. The classification and coding system assigns a unique alpha-numeric code to each part in the system based on part parameters, regardless of the origin or use of the part. Then part families are formed taking into consideration similar process routing of the parts. The classification and coding systems were popular initially, because each part had a unique code and tracing the part from raw material to finished product stage and inventory became easier and more structured. But recently, cluster analysis methods have been used more widely in research and industry for group technology applications because they are less expensive, less time consuming to implement and the methods are based on route card information, which is readily available in any manufacturing organization. The clustering methods are based on one or a combination of the three formulations that have been discussed in literature, namely 1) Matrix formulation 2) Mathematical programming formulation and 3) Graphical formulation. The commonly cited methods under matrix formulation are, similarity coefficient method (SCM)[20], rank order clustering (ROC)[10], bond energy algorithm (BEA)[16], single linkage cluster analysis (SLCA)[15], modified rank order clustering (MODROC)[4]. A few approaches to the grouping of machines and parts have been reviewed in this research. The matrix formulation methods use route card information to construct the machine-part incidence matrix. The non-zero entries in the matrix indicate the processing of the part on the corresponding machine. Much attention has been focused on the machine and part grouping, and very few approaches [14,17,21,22] deal with the other issues like layout, MHS and scheduling, in the design of cellular manufacturing systems.

The similarity coefficient method [20] groups machines based on a measure of similarity between the machines, which is dependent on the number of parts processed by both the machines. The machines which process parts in two or more cells and cannot be allocated to a unique cell are called bottleneck machines. Seiffodini[20] suggests that the bottleneck machines be duplicated based on the number of inter-cellular moves (ICM) The machine resulting in the largest number of intercellular moves is duplicated first, followed by the next. By setting the lower limit on the inter-cellular moves alternative solutions with varying number of inter-cellular moves are produced. The groupings are different only in the ICM levels and do not generate alternative groupings and solutions for the design process. Like many other approaches to cellular manufacturing the study limits itself to the grouping of parts and machines.

King [10] developed a method called "rank order clustering (ROC)" The method starts by assigning binary weights to the rows and columns in the matrix, and calculating their equivalent decimal weights by multiplying the weights with the respective entries in the matrix. The rows and columns are rearranged, resulting in a matrix with distinct (if possible) groups of machines and parts. The method tries to reduce bottleneck machines as part of the algorithm, but results in addition of duplicate machines A modification to this algorithm was proposed by Chandrashekar et al [4], which they called Modified ROC or MODROC. The procedure is in three stages It starts with the ROC algorithm, then in stage two, blocks with all '1's adjacent are identified and output to stage three of the algorithm. Stage three forms the groups of machines and parts Bottleneck machines are not given special consideration. ROC and MODROC both generate unique groupings of machines and parts which may not necessarily be feasible in practical applications.

Wei and Kern [23] presented an algorithm for forming machine cells by using a commonality score of machines producing a family of parts. This algorithm considers bottleneck machines automatically without giving any special consideration.

Kusiak [11], described a method for forming machine cells and part families considering all the process plans available for each part to be grouped into a part family. This method uses both the matrix formulation and the integer programming model. Kusiak showed that considering alternative process plans results in improved quality of grouping of machines and parts In another study Kusiak and Chow [12] developed a cluster identification algorithm (CIA) for the grouping of parts and machines. The generation of alternative groupings which can be evaluated later based on certain criteria was also introduced in the study [12]. However, they have not outlined the criteria for the evaluation of alternative groupings and have not considered cell layout and part routing which are important for the design of a cellular manufacturing system.

Rajamani et al. [19] considered alternative process plans for each part. They used an integer programming formulation to select a process plan and then group the machines and parts. The binary nature of the formulation used by Rajamani restricts the size of the problem that can be solved by their models. Choobineh [7] also suggested the use of two alternative process plans for each part in the matrix. The process plans are treated as independent parts and grouped into families. This results in the identification of two cells which might produce the part. The parts can be assigned to the cell which produces it most economically. Choobineh considered part routing or the sequence of operations. His approach includes the routing information in the calculation of the similarity coefficient and identifies the natural part families. Harhalakis et al. [8] considered part routing and non-consecutive operations on the same machine. The two step method starts by a bottoms-up aggregation of machines into cells to minimize "normalized inter-cell traffic." The part routing information is used in the calculation of the inter-cell traffic The second step attempts to improve the solution by validating the inclusion of each machine to the cell. The method reduces bottle-neck machines but does not give alternative solutions to select the best for the specific application.

A survey of literature related to the design of CMS shows very few studies that deal with the complete design of a CMS. There exist few approaches in recent years which address these issues. Leskowsky et al. [14] introduced a new algorithm for part-machine family formation based on similarity measures and present a procedure for the allocation of machines in cells and cells in the plant area using the CRAFT algorithm. The procedure attempts to reduce intra-cellular and inter-cellular material handling The plant layout procedure first calculates layout of machine cells in the plant area, then attempts to layout the machines in the cells. The disadvantage of this approach is that the machines have to be allocated in the cell area which is already fixed This might lead to under utilization of the floor space, and it might not be possible to allocate all the machines in the layout The reason is, the layout of cells produces irregular shapes and it would be difficult to allocate machines of fixed dimensions in the area provided, thus resulting in unused areas. Leskowski et al. have not addressed the issue of MHS selection, part routing, and the problem of bottleneck machines. Vakharia et al [22] presented a new method for grouping parts and machines using operation sequences of parts. The utilization of machines is used as a measure. The study also discusses the interaction of bottleneck machines and cells. Their approach does not discuss the layout of machines and the MHS which are important components of the design of CMS. Tam [21] has presented an algorithm for layout of cells in the manufacturing system. The approach starts with the plant area then sequentially divides the area for the cells. The method can be extended to allocate machines in the cell. The effect of material handling on the layout is not considered and suffers from the same limitation as Leskowsky's approach, that is the cellular layout is calculated before allocating machines in the cell.

Table 1 1 summarises a few approaches to group technology. They are compared with respect to the method or principle of the grouping algorithm, consideration of part routing, alternative process plans, cell layout, bottleneck machines, alternate solutions and the type of grouping. Type of grouping is 'simultaneous' if the grouping of machines and parts is done jointly and it is 'machine' if the grouping of machines is performed first and parts are assigned to cells after.

Table 1.1 Comparison of approaches to group technology

Clustering Algorithms	Grouping Technique	Consid Part Routing	Consid Alt Process Pl	Consid Cell Lay out	Consid Bot-tleneck m/c	Results in Alt Groups	Type of grouping
Choobineh, 1988	SC+LP	Yes	Yes	No	No	Yes	Simultaneous
Seiffodini, 1986	SCM	No	No	No	Yes	Yes	Machine
King et. al ,1981	ROC	No	No	No	Yes	No	Simultaneous
Chandrsekar, 1986	MODROC	No	No	No	No	No	Simultaneous
McAuley, 1972	SLCA	No	No	Yes	No	No	Machine
McCormik et al 1986	BEA	No	No	No	No	No	Simultaneous
Kusiak, 1987, 1990	CIA & IP	No	Yes	No	Yes	Yes	Simultaneous
Rajagopalan, 1975	GRAPHIC	No	No	No	No	Yes	Machine
Rajamani et. al 1990	SC + IP	No	Yes	No	Yes	No	Simultaneous
Harhalakis et al , 1990	MP	Yes	No	No	Yes	No	Machine

SC: Similarity Coefficient
IP: Integer Programming
MP: Mathematical Programming
LP: Linear Programming
CIA: Cluster Identification Algorithm
BEA: Bond Energy Algorithm
SLCA. Single Linkage Cluster Analysis
MODROC: Modified Rank Order Clustering
SCM: Similarity Coefficient Method
ROC: Rank Order Clustering

1.3 OBJECTIVES OF THE STUDY

The implementation of the design of a cellular manufacturing systems (CMS) extends much beyond the formation of groups of machines and parts. Reviewing current literature indicates the limitations of the existing approaches to the design of CMS. The actual design process should result in the selection of a material handling system (MHS) and cell layout, cellular CMS and layout, part routing and the production schedule of the parts A comprehensive approach which will combine the present body of knowledge in Group Technology and other aspects of the design process is much needed. The approach should present a useful methodology to the industry for the complete design of a Cellular Manufacturing System (CMS). The research highlights the problems encountered in the design process and suggests a systematic methodology incorporating the important factors already mentioned. Alternative process plans for each part are considered. A new heuristic has been developed which first forms a groupable matrix then it applies the grouping algorithm to get machine cells and part families. The proposed heuristic offers a better chance of obtaining a block diagonal form of grouping with distinct cells and part families. The method generates alternative solutions at various levels, providing the designer an opportunity to use his/her judgement and incorporating specific requirements or limitations of the problem. The design process is achieved in three major steps. The first step deals with the formation of the groupable matrix and grouping the matrix. The second step is the cell design, and checking the feasibility of the cell design. The third step is cellular manufacturing system design and the evaluation of the feasibility of the

CMS design. The new method is suggested for the design of a CMS which is built into an expert system providing easier user input and using expert judgement at various stages The experts' knowledge is built into the system as knowledge base rules. In this study the framework of an expert system will be presented along with some sample knowledge base rules.

1.3.1 Grouping machines and parts

A part can be manufactured using more than one process plan with a slight variation in cost. Two or more process plans will be selected for each part The process plans are placed along the columns and machines form the rows in the incidence matrix A new heuristic has been developed which first generates a matrix which has a higher chance of obtaining distinct cells or fewer bottle-neck machines and sub-contracted parts. To this matrix the grouping algorithm developed by Abdou [1] is applied and machine cells and part families are obtained.

1.3.2 Cell design and checking the feasibility of cells

The design of a cell involves forming machine cells and part families, evaluating the cell layout, selecting a material handling system for the cell and part scheduling A new methodology is introduced in this research for the joint selection of layout and MHS for the cell. In the grouping for each cell all feasible layout and MHSs are selected using this method. The grouping output by the algorithm will be evaluated for feasibility based on the following constraints : part routing, part schedule, production volume required for the part, machine utilization and intercellular movement. The complete design for each cell, with the material handling system and layout is evaluated using simulation. If a cell is not feasible the whole grouping is rejected and an alternative grouping is evaluated.

1.3.3 Cellular Manufacturing System design and checking the feasibility of the design

The feasible cells are input to the CMS design stage. The layout and MHS for the complete system is determined and design of the CMS is evaluated by simulation.

1.3.4 Steps taken :

1 Develop a heuristic for a groupable matrix formation considering alternative process plans

2. Develop a methodology for cell design including selection of the layout structure, MHS and scheduling of parts.

3. Develop a methodology for the joint selection of layout and MHS for each cell.

4. Establish criteria and methodology for the evaluation of the cell design.

5. Develop a methodology for CMS design, which would include layout of cells or cellular layout and a MHS.

6. Establish criteria and methodology for the evaluation of the CMS design.

7. Develop a framework for the proposed methodology for the design of CMS.

8. Demonstrate the methodology by applying to case studies selected from literature.

CHAPTER 2

FRAMEWORK FOR THE DESIGN OF CELLULAR MANUFACTURING SYSTEMS

Group Technology tries to bring the parts requiring similar processing together into a part family such that a family of parts can be produced on a set of machines grouped into a machine cell. The manufacturing environment of today is rapidly changing from mass production to small or medium batch production, because of customer's demand for variety in products. In a batch manufacturing environment the application of group technology and cellular manufacturing results in drastic improvements in productivity and easier control of the system. In the design of cellular manufacturing systems there are two distinct stages in the design process, the cell design stage and the CMS design stage The various factors that should be considered for the cell design stage are listed below

2.1 *Factors for the Cell Design Stage* :

1. Alternative process plans
2. Sequence of operation
3. Cell Layout
4. MHS selection
5. Production schedule
6. Processing time of parts
7. Alternatives in the design of a cell

2.1.1 Alternative Process Plans

In a manufacturing plant there are machines which perform similar operations and can substitute for one another in processing requirements. For example a turret lathe can do most of the work as a CNC lathe, but it might take more time and the cost might vary and thus a part can be produced by using different process plans. Kusiak [11], Rajamani [19] and Choobineh [7] have considered alternate process plans in their initial incidence matrix and have shown that by considering alternative process plans there are better chances of obtaining a diagonalized matrix with well defined machine cells and part families. Alternative process plans also help in the generation of alternative solutions if the solution first obtained is not feasible.

2.1.2 Sequence of Operations

Part routing consists of two types of information, the machines to be used in the processing of the part and the sequence of the operations. The grouping methods use route card information to construct the binary incidence matrix, but the sequence of operation is neglected in most grouping algorithms. The sequence of operation changes the material handling time depending on the relative allocation of the machines. Choobineh [7] and Harhalakis [8] have considered the sequence of operation in their grouping algorithms. By considering the sequence of operations while calculating the relative allocation of machines, material handling time and costs can be reduced. The importance of sequence of operation is illustrated by an example. The example is adopted from Asfahl [3]. There are three machines in the system B, C and D, each with processing times of 2.0, 1 0 and 2 6 respectively. A is the input buffer and E is the output buffer. The parts are transported by a robot R. The gripper pickup time is 0.1 and gripper release time is 0.1. The transportation time in minutes are given in table 2 1 The layout is shown in figure 2.1.

Table 2.1 Movement time between stations

			TO		
FROM	A	B	C	D	E
A	-	0.3	0.6	0 9	1.2
B	0.3	-	0.3	0 6	0 9
C	0.6	0.3	-	0.3	0.6
D	0.9	0.6	0.3	-	0 3
E	1.2	0.9	0.6	0 3	-

The part routing is B-C-D in the first case. The cycle time is 4 4 minutes and robot cycle time is 4.4, thus the robot utilization is 100%. Now when the routing of the part was changed to C-B-D the cycle time is increased and robot utilization is reduced to 72% This simple example clearly indicates that the routing of the parts is very important and should be accounted for in the design of a CMS.

2.1.3 Cell Layout

The layout of the machines in the cells that are formed has not been considered in most approaches to the design of a cellular manufacturing system. The layout of the machine affects the utilization of the floor area, controls the flow of parts and determines the material handling time and cost. If the machines are laid out after considering the sequence of operations, the flow of parts would be smoother and there would be less backtracking of parts The system would be easier to control and would result in reduced work in process (WIP) The importance of considering the layout is illustrated by an example There are two parts to be manufactured numbered 1 & 2, with processing times of 2 0, 1.0 & 2.6 and 9.1, 9.0 & 5 0 on machines B, C and D respectively. The movement times are the same as in table 2.1. A queuing station or work in process 'W' is added between machines B & C as shown in figure 2.1. Movement of part from B-W takes .2 and from W-C takes .1 minutes. The parts enter the system in the sequence 1-2-1-2 . When the layout was ABWCDE the cycle time was 9.4 and robot utilization was 96 8% When the layout was changed to ACWBDE the cycle time went up to 10.4 and robot utilization came down to 94%. A change in layout produced a change in cycle time and decreased robot utilization. So the design of a CMS should include, layout of machines and the layout of cells in the system when there is intercellular movement, as the throughput and utilization levels are significantly affected by the layout of system.

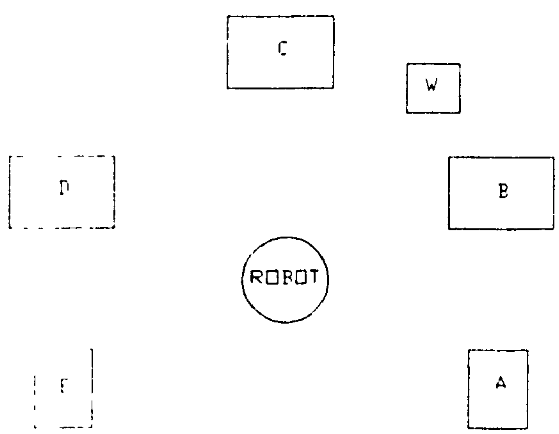


Figure 2 1 Layout of cell

2.1.4 Material Handling System

The MHS being used determines the cost and time of movement of parts It has a significant effect on the throughput and the cost of production. The issue of MHS selection has not been considered in any of the approaches to CMS design. The type of MHS selected also has a profound effect on the layout of machines, for example if the material handling system is a unidirectional conveyor the layout has to be linear. Thus the MHS selection is an important aspect of the design of a CMS.

2.1.5 Production Schedule

The part schedule or the sequence in which the parts enter the manufacturing system determines the cycle time, production rate and the utilization of machines and material handling system. Scheduling under cellular manufacturing requires a slightly different approach, instead of having one single schedule for the system, each cell will have its own schedule of parts and there is a schedule of parts between cells generating inter-cellular movement. The effect of part schedule on the throughput and the utilization of machines and the MHS is illustrated by an example. There are three machines B, C and D, WIP W between machines B and C, and WIP X between machines C and D as shown in figure 2.2 The robot takes 0.2 & 0.1 minutes to travel from machines C and D respectively. Two parts 1 & 2 are fed into the system first in the sequence 1-2-1-2-. , and then in the sequence 2-1-2-1-2.... . The processing time of part '1' is 2 0, 1 0 and 2.6, and for part '2' it is 9.1, 9.0, and 5.0 minutes on machines B, C and D respectively. The effect of the two different schedules is illustrated in table 2 2

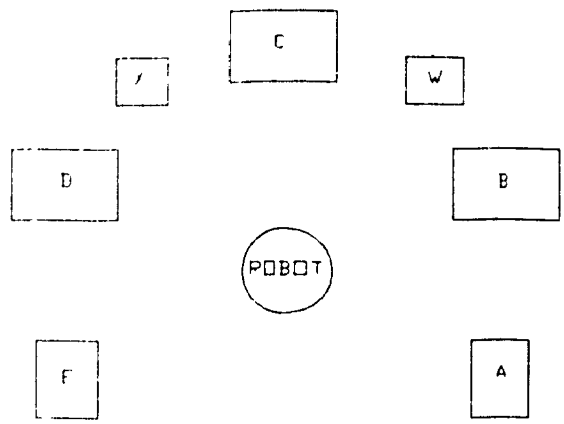


Figure 2 2 New layout for the cell

Table 2.2 Effect of part schedule

Schedule of parts	Cycle Time	Production Rate	Robot Cycle Time
1-2-1-2-1-2 ..	24.5 Minutes	2.45 parts/hr	10.8 Minutes
2-1-2-1-2-1 ..	14.2 Minutes	4.22 parts/hr	7.7 Minutes

2.1.6 Processing time of parts

The processing time of the part affects the throughput, material handling system utilization and machine utilization. Kusiak [11] considered the processing time of the part in the incidence matrix, instead of the binary 0s and 1s. He showed that by doing this we directly get the machine utilization and availability. The effect of processing time is illustrated with an example. Consider the system shown in figure 2.1 and the data given in table 2.1. When the processing time of the part is 2.0, 1.0 and 2.6 on machines B, C, and D respectively the cycle time was 4.4 minutes and production rate was 13.6 units/hr.

The robot utilization was 100% of the cycle time When the processing time is changed to 9.1, 9.0, and 5.0, the cycle time becomes 10.7 and production rate is 5.6 units/hour. The robot utilization is decreased to 41% of the cycle time.

2.1.7 Alternatives in the design of a cell

The presence of alternatives is very important in the design of a CMS. Alternatives can be generated at various stages in the design process Alternative groupings can be generated by using a different set of process plans and applying the grouping algorithm. The different layout and MHS combinations selected for each cell can produce alternatives in the design stage. A single combination of layout and MHS will produce one alternative design for the cell. When the design process is applied to a grouping, if the grouping is not feasible then another grouping is selected and the design process is applied to it

2.2 Factors for the Cellular Manufacturing System Design Stage

The expert systems approach to cell design outlined a new methodology for the layout of machines, MHS selection and scheduling of parts under cellular manufacturing In the cell design stage parts and machines were grouped into part families and machine cells, feasible layout and material handling system combinations were produced. The feasibility of these combinations was evaluated dynamically by simulating each cell independently. In isolation each cell might be feasible but the entire manufacturing system with all the cells put together might not be feasible due to constraints discussed later in the chapter. The design of a cellular manufacturing system cannot be implemented until the feasibility of the entire system has been evaluated. The second stage of the design process is called CMS design. CMS design involves combining all the cells from stage 1 (cell design), evaluating their layout or relative allocation in the manufacturing system, selecting a MHS for the system to transport parts from cell to cell and from buffers to cells. The group technology output brings to light the exceptional elements in the machine-part grouping, which are bottleneck machines and parts which have processing requirements in more than one cell. These exceptional elements lead to inter-cellular movement The layout and material handling equipment selection is dependent on this frequency of inter-cellular movement and must be considered in the design stage. The important factors that have to be addressed in the CMS design stage are :

1) Formation of functional cell

2) Layout of the cells in the manufacturing system

3) Inter-cellular movement

4) MHS for the system

5) Knowledge Base Rules for various aspects of CMS design

6) Evaluating the feasibility of the entire manufacturing system dynamically

A literature survey related to the design of CMS shows very few studies which deal with this part of the design of a CMS. Leskowsky et al. [14], Vakharia et al. [22] and Tam [21] have considered the layout of the cells in the system, but the drawbacks in their studies were highlighted in the literature review. The detailed methodology of CMS design after cell design is outlined in the section on Inference Engine.

2.2.1 *Formation of Functional Cell*

The parts which are to be processed on machines in different cells are either sent from cell to cell creating inter-cellular movement(ICM), or are subcontracted to avoid ICM. The machines which process parts in two or more cells and could not be allocated to any one cell are called bottleneck machines. To resolve the problem of bottleneck machines many approaches to the design of CMS suggest that a duplicate of the machine be purchased and placed in the secondary cell, thus eliminating ICM This approach is only feasible when the cost of machine is not high and comparable to the savings in material handling costs. Another method to resolve the problem of bottleneck machines is to transfer the bottleneck machine to a new cell called "functional cell", where parts from both cells are carried for their respective operations on the machines This approach creates ICM and the parts are carried by the system MHS In a practical application there might be some more machines which have to be duplicated, because of higher requirement for capacity and production volume of parts. These additional machines have to be accommodated in the existing cell layout as all their operations are within one cell, but because of space constraints, these machines might have to be placed in a functional cell. In this research it is assumed that these machines are placed in the cell in which all its operations are performed and the bottleneck machines are placed in the functional cell

2.2.2 Cellular Layout

Once the machine cells have been formed they have to be allocated in the manufacturing system. Leskowski e.. al. [14] first evaluate the layout of cells then find the relative allocation of the machines in the cells In our approach we first evaluated the relative allocation of the machines in the cell design stage and now in the CMS design stage attempt to layout the cells in the plant area. The cellular layout can be determined irrespective of the MHS selection and the joint selection of the Layout and MHS is not required Since the system MHS, unlike the cell MHS, does not impose any constraints on the layout, for example, if the cell MHS is a robot the layout of machines has to be circular Further a change in the path of the MHS system (AGV, Forklift, or Conveyor etc.) would accommodate the change in layout of cells. The cellular layout is generated by considering the ICM and using the CRAFT algorithm.

A new method for generating the cellular layout including the functional cell is presented here. The input required by the CRAFT algorithm is, number of departments, area of each department, volume of material flow between the departments and the material handling cost between the departments. Each cell is considered as a department and each machine in the functional cell is identified as an independent department. To assure that all the machines in the functional cell are together, a very close relationship is defined between the machines. This is achieved by defining the inter-department material flow and material handling costs very high relative to rest of the system. The relative allocation of the machines in the functional cell is automatically generated by the CRAFT algorithm, which is dependent on the cellular layout in the system. The machine with the most interaction with a cell is assigned a position close to it, so as to avoid a MHS within the functional layout. The volume of material flow between the departments is determined by the ICM level. The relative allocation of machines in the functional cell are affected by the ICM level and sequence of operations If a part has one intermediate operation that is performed in a secondary cell and all other operations in the primary cell then this will necessitate two trips for each batch between the cells. But if only the last operation is performed in a secondary cell, then there is only one trip required By defining a close relationship between the bottleneck machine and the cells in which it processes parts we are assured that the bottleneck machine is placed between the cells and parts can be moved by the cell MHS itself.

2.2.3 Inter-Cellular Movement (ICM)

The exceptional elements in the grouped matrix like bottleneck machines and subcontracted parts create ICM when the parts are machined in the system and moved from cell to cell for their processing requirements The level of ICM affects the cellular layout. The cells having the largest flow of parts between them are placed adjacent The ICM also affects the selection of the MHS, if the ICM is very high a dedicated MHS like a conveyor would be suitable otherwise a Forklift or AGV would serve the purpose. Inter-cellular movement determines the material handling time and cost for the parts, if ICM is high then more time is required for material handling and throughput would be lower.

2.2.4 Material Handling System

The selection procedure for the MHS is similar to the procedure outlined for the selection of MHS for the cell. In CMS design the ICM plays an important role in the selection of MHS. If the ICM is high a conveyor is selected and if ICM is low a forklift truck is selected A list of MHSs available for the system is shown in table 3.1. Depending on the user requirement and criteria a MHS is selected for the system.

CHAPTER 3

FRAMEWORK OF THE EXPERT SYSTEM

The design process of a Cellular Manufacturing System (CMS) is complex and requires expert judgement at various stages of the design problem. An expert system which would include all the experience based knowledge from the expert would be most suitable for the design problem on hand. The real life problem of the design of CMS is not confined to the formation of machine cells and part families, it includes material handling selection, layout of machines in the cells, layout of the cells in the system etc. Each part of the design is a complete problem in itself. Expert Systems have been developed for MHS selection and for machine layout. The design of a CMS is a one time problem i.e. once a design is implemented, it cannot be changed beyond the flexibility built into the design. So the designer should observe caution and design the system as close as possible to the optimal. The expert systems approach suggested might appear to be time consuming and expensive, but the advantages derived from obtaining a better design outweigh these drawbacks. The suggested approach generates alternative solutions at various levels incorporating user's requirements and judgement. Since a lot of experience based knowledge is required for the design process, the problem can effectively be solved by using an expert system. In this study a framework of the Expert System for the design process is developed. Figure 3.1 shows the structure of the expert system. The main components as in any expert system are : 1) Database 2) Knowledge base 3) The Inference Engine.

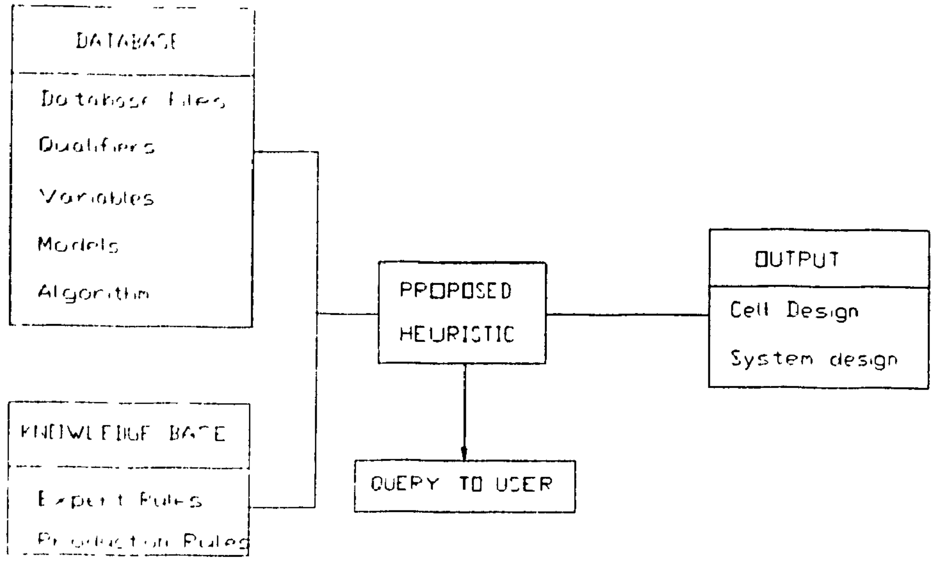


Figure 3.1 Expert System Structure

3.1 Database

The expert system requires a lot of information to generate alternatives for the user to make a decision. Some data are directly given by the user, while other data are extracted implicitly from an external program and input to the expert system.

The database consists of

(i) Database files

(ii) Qualifiers

(iii) Variables

(iv) Models and Algorithms

(v) External programs for data searching and calculations

3.1.1 Database files

The characteristics and properties of the different items used in the problem are listed in the database files. The material handling systems that have been considered in this study are listed in tables 3.1 and 3.2. The tables shows the relationship of the material handling system and the various factors and criteria that affect the selection process. The corresponding entry in the table shows the value the parameter takes or is the preferred value for the particular MHS. Table 3.3 shows the relationship of the 5 types of layout structures considered with respect to the factors, criteria and the flexibility derived by choosing the particular layout. The layout structures suitable are affected by the number of machines in the cell, part variety and the production volume required for the part Figure 3.2 and 3.3 illustrate the relationship between them.

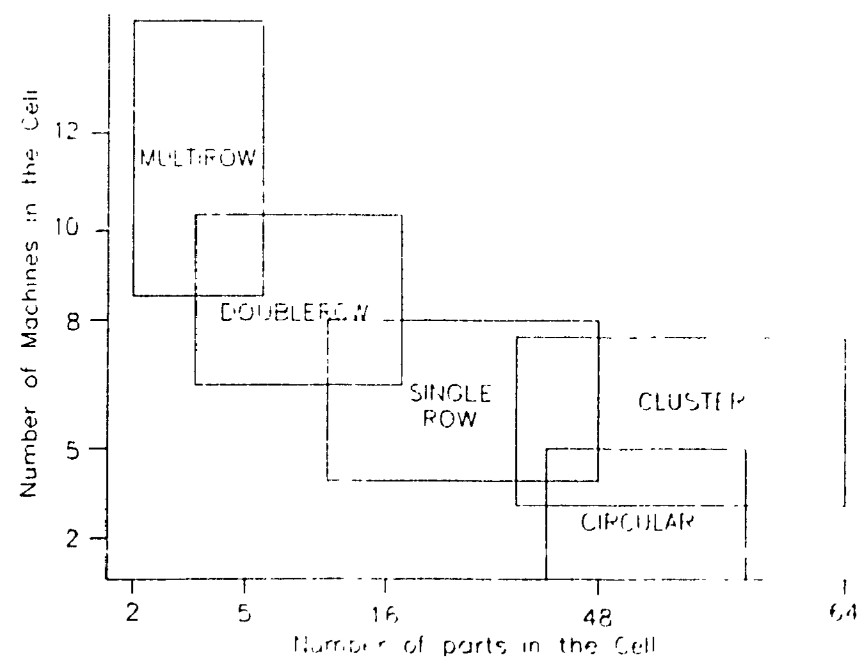


Figure 3.2 Relationship between layout and number of machines and parts

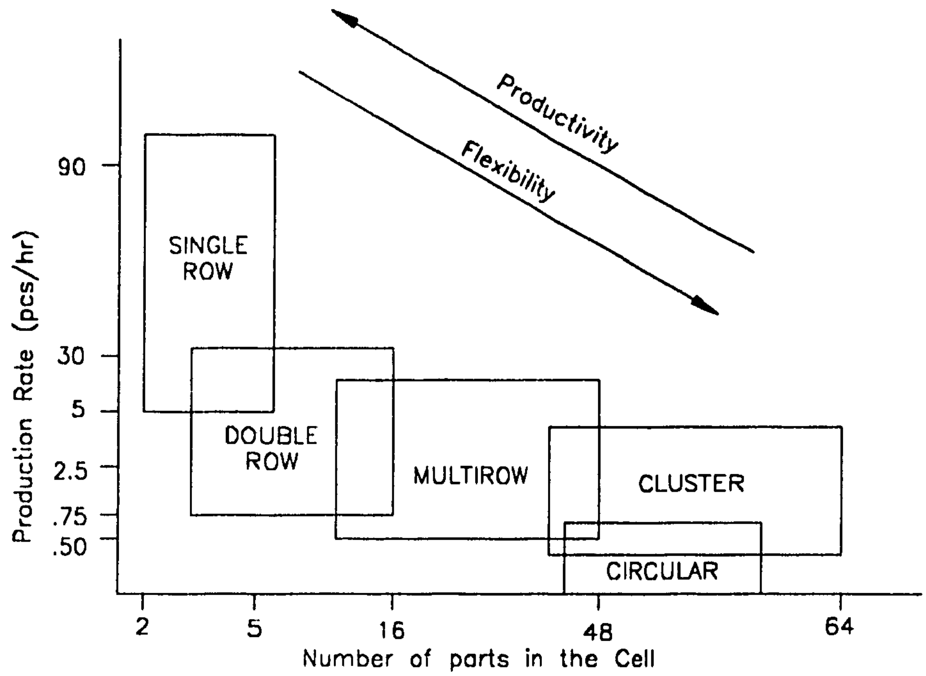


Figure 3.3 Relationship between layout structure, production rate and number of parts in the cell

Figure 3.2 helps in the selection of a layout structure, for example, if the number of machines in the cell is 5, then depending on the part flexibility required a layout structure can be selected from single row, cluster or circular. The number of parts in the cell is also influenced by the MHS for the cell. But, by making a selection of a layout structure we limit the types of MHS selected. For example, if the layout is circular, the MHS will probably be a robot and if layout is single row then conveyor might be the MHS. Figure 3.3 shows a relationship between production rate, number of parts in the cell and the layout structures A single row layout would be similar to a flowline and gives the highest production rate, whereas the cluster and circular layouts have the lowest production rate but are highly flexible to accommodate maximum number of parts.

Figures 3.2 and 3.3 are used to generate knowledge base rules which will be used in the selection of a layout for the cell. The knowledge base rules are listed in IF-THEN-ELSE format, and whenever a decision is to be made the expert system checks the IF premise of the rules, if it finds a match then the rule is fired and the THEN result is output The rules are listed in the Appendix A.

Table 3 1 MHSs, their factors and criteria for a cell

MHS TABLE	FACTORS								FLEXIBILTY		CRITERIA		
	Wt Load	Speed Unif	%Hand -ling	Mech attach	Part Size	Part Volm	Unman -ned	L of A utomn.	M/c LT	Part Route	Space Utiln	Safety	Opm Cost
Fork Lift Truck	H	N	M	Y	B	L	N	L	H	H	L	M	H
Tractor Trailer	H	Y	M	N	B	L	N	L	H	H	L	M	M
AGV Tugger+Trailer	H	E	M	N	M	M	Y	H	H	H	L	H	L
Unit Load AGV	H	E	H	Y	M	M	Y	H	H	H	L	H	M
Monorail Conveyor	H	E	M	N	M	H	N	L	M	L	H	H	V
Power&Free Convey	H	N	H	N	M	H	N	L	M	L	H	H	V
Roller Conveyor	M	Y	H	Y	M	H	N	L	L	L	M	L	M
Chain Conveyor	L	Y	H	Y	S	H	N	L	M	L	M	L	M
Tow Line	H	Y	H	N	S	H	Y	M	L	L	L	H	V
Robot	L	Y	L	Y	S	L	Y	H	L	H	H	L	L
Gantry Robot	L	Y	L	Y	S	L	Y	H	H	H	L	M/H	L

Table 3 2 MHSs, their factors and criteria for the system

MHS TABLE	FACTORS								FLEXIBILTY		CRITERIA		
	Wt Load	Speed Unif	%Hand -ling	Mech attach	Part Size	ICM Level	Unman -ned	L of A utomn	Cell LT	Part Route	Space Utiln	Safety	Oprn Cost
Fork Lift Truck	H	N	M	Y	B	L	N	L	H	H	L	M	H
Tractor Trailer	H	Y	M	N	B	L	N	L	H	H	L	M	M
AGV Tugger+Trailer	H	E	M	N	M	M	Y	H	H	H	L	H	L
Unit Load AGV	H	E	H	Y	M	M	Y	H	H	H	L	H	M
Monorail Conveyor	H	E	M	N	M	H	N	L	M	L	H	H	V
Power&Free Convey	H	N	H	N	M	H	N	L	M	L	H	H	V
Roller Conveyor	M	Y	H	Y	M	H	N	L	L	L	M	L	M
Chain Conveyor	L	Y	H	Y	S	H	N	L	M	L	M	L	M
Tow Line	H	Y	H	N	S	H	Y	M	L	L	L	H	V

Table 3.3 Layout structures, their factors and criteria

LAYOUT TABLE	FACTORS					FLEXIBLITY		CRITERIA		
	Part Vrty	Part Volm	#m/c in Cell	MHS Effect	L of Autn.	LT Flex	Adapt ability	%spce Utln.	Ease S & C	Saf-ety
Linear Single Row	M	H	M	H	L	L	L	L	H	H
Circular	H	L	V	H	H	L	H	H	H	L
Linear Double Row	M	H	H	M	M/H	M	M	M	L	M
Multirow	M	H	H	M	M/H	M	M	H	L	M
Cluster Layout	H	L	L	L	H	H	H	H	M	L

3.1.2 Qualifiers

The data to be input for the problem is entered by prompting the user to enter the numerical value of the data and choose one of the alternatives for the qualitative data. Qualifiers represent the data to be incorporated qualitatively. Tables 3.4 and 3.5 represent the qualifiers to be used which will be replaced for the values selected by the user in the production rules.

Table 3.4 Qualifiers for the layout problem

QUALIFIER	CHOICE
Shape of space available	Rectangular/L-shaped
Level of automation	High/Medium/Low
Layout flexibility desired	High/Medium/Low
Layout adaptability desired	High/Medium/Low

Table 3.5 Qualifiers for MHS selection

QUALIFIER	CHOICE
Weight Load	High/Medium/Low
Uniform Speed	Yes/No
Mechanism Attached	Yes/No
Unmanned	Yes/No
Level of Automation	High/Medium/Low
Layout Flexibility	High/Medium/Low
Part Routing Flexibility	High/Medium/Low

3.1.3 Variables

The quantitative data to be incorporated into the problem is represented as variables. The table 3.6 lists the variables to be used for our design problem.

Table 3.6 List of variables

Variables for Parts	Variables for Machines
Processing time of parts	Number of machines
Sequence of operations	Type of machines
Part Variety	Size of machines
Part Volume	
Part Rate required	
Setup times	
Production schedule	

3.1.4 Algorithms

The various procedures for calculating the different steps in the design process are listed under algorithms. These algorithms are the external programs which will provide data for the various stages of the design process. Each algorithm is defined independently with a flow chart explaining the logic of the algorithm and supported by examples to illustrate the method of applying the algorithms.

3.1.4 a) The Groupability Algorithm

The formation of the machine cells and part families is the first step in the implementation of group technology. Most algorithms for grouping are sensitive to the nature of the machine-part matrix and might not result in a matrix with distinct cells and part families. To derive maximum benefits from the application of Group Technology we should have fewer bottleneck machines and subcontracted parts By considering alternate routings there is a better chance of obtaining well defined cells, which has also been shown by Kusiak [11]. A new algorithm is introduced here which uses alternate process plans for each part and generates a matrix of parts and machines which has a higher chance of obtaining distinct block diagonal form. The algorithm has been appropriately called the Groupable Matrix Formation Algorithm (**GMF Algorithm**) The new algorithm is based on the Groupability index suggested by Chandrasekharan [5]. The index analyses the properties of the matrix by a measure of similarity or dissimilarity and the Jaccard similarity coefficient 'S_j', which has been found most suitable for the analysis of a matrix for group technology applications. The two measures of the index are σ_{sj}, the variance of the similarities and X, the mean of the similarities. The method is demonstrated by an example. The initial matrix for the example is taken from Kusiak [11]. The method is an iterative procedure lending itself to be solved on a computer. A program for the algorithm was written in 'C' and the code is presented in appendix B.

RATIONALE

The machine-part incidence matrix is assumed to be represented by two vectors in space The machines give the row vector in n-dimensional space, process plans/parts form the column vector in m-dimensional space. The relative location of these vectors in space determines the existence of clusters. The groupability of data may depend on the statistical nature of the inter-point distances between the vectors. The inter-point distance is analogous to the similarity coefficient. Therefore a statistical study (average & standard deviation) of the distribution may enable us to check whether the data is groupable or not.

PROCEDURE

The procedures are as follows :

Step 1. Input the machine-part matrix.

The machine-part matrix has the machines along the rows and the process plans for the parts along the columns.

Step 2. Calculate the Jaccard similarity coefficient (S_J)

The Jaccard similarity coefficient (S_J) is defined as the ratio of the number of pairs in which both elements are non-zero to the number of pairs in which either of the elements is non-zero. The Jaccard similarity coefficient (S_J) is calculated between all rows and all columns separately.

Step 3. Find the average and standard deviation (σ_{SJ}) of the similarity coefficients (S_J) calculated

The average of the S_J is simply the addition of the values over the number of values. The standard deviation is the square root of the deviation of the values from the mean value.

Step 4. Check if the matrix is groupable

If σ_{sj} lies between 0 2 and 0.35, it can be concluded the matrix might be groupable. Otherwise the matrix has a low probability of leading to a good grouping. The rejected matrix may have more number of '1s' in the off-diagonal places. These off-diagonal '1s' lead to intercellular movements, which should be minimized as far as possible.

Step 5. If the matrix is not groupable the .move the process plans which consist of only one operation. Calculate the similarity values again, check if the matrix is groupable.

Step 6. If the matrix is not groupable, then select the set of machines with the lowest similarity coefficient value and delete the process plan with processing requirements on both machines. This reduces the similarity coefficient between the two machines and increases the standard deviation of the matrix, thus improving the groupability. Calculate the similarity values, if the matrix is still not groupable apply step 6 again, till the value of the standard deviation is within the groupable limits. If the value of standard deviation is not within the limits after successive iterations, then reject the grouping as not groupable.

Example :

This example illustrates the different Jaccard similarity values obtained for three matrices generated using alternative process plans, then determining the groupability of the matrices. The initial matrix shown in figure 3.4 has 5 parts and 4 machines. By selecting one process plan for each part we can have many different matrices but only one or a few will be groupable. To illustrate this a sample three matrices are formed by selecting one process plan for each of the 5 parts as shown in figure 3.5. The Jaccard similarity coefficient S_j is calculated for the machines and the values are shown in figure 3.6.

Part #		1			2		3		4		5	
Process Plan #		1	2	3	4	5	6	7	8	9	10	11
Machine #	1			1		1	1		1	1		1
	2		1	1	1			1				
	3	1			1	1				1	1	
	4	1	1				1	1	1		1	

Figure 3.4 Input matrix for example

	2	5	7	9	11
1		1		1	1
2	1		1		
3		1		1	
4	1		1		

(a)

	1	5	7	8	10
1		1		1	
2			1		
3	1	1			1
4	1		1	1	1

(b)

	3	4	6	9	10
1	1		1	1	
2	1	1			
3		1		1	1
4			1		1

(c)

Figure 3.5

	1	2	3	4
1	-	0	.67	0
2		-	0	1
3			-	0
4				-

(a)

	1	2	3	4
1	-	0	.25	.2
2		-	0	25
3			-	4
4				-

(b)

	1	2	3	4
1	-	.25	.2	.25
2		-	.25	0
3			-	.25
4				-

(c)

Figure 3.6

The coefficient denoted by S_j is defined as the ratio of the number of machine pairs having both non-zero entries, to the number of machine pairs with either having non-zero entries. The groupability of a matrix is related to the standard deviation σ_{sj}, and the mean S_j of the Jaccard similarity coefficient. Chandrasekharan [5] have shown that if the value of σ_{sj} lies between 0.2 and 0.35 the matrix has a higher chance of being groupable The σ_{sj} and S_j values for the 3 similarity matrices are :

(a) $\sigma_{sj} = 0.4045$, $S_j = 0.2783$

(b) $\sigma_{sj} = 0.1433$, $S_j = 0.1833$

(c) $\sigma_{sj} = 0.0913$, $S_j = 0.2$

These values indicate that only one of the matrices (a-c) namely (a) might be groupable, and by applying the grouping algorithm we find that the matrix (a) is groupable into two mutually exclusive cells The upper limit on σ_{sj} might not be restrictive and is relaxable The grouped matrix obtained is the same as obtained by Kusiak [11].

3.1 4 b) The Scheduling Algorithm

The sequence of loading the parts on machines or the parts schedule is to be calculated before simulation. Schedule for each cell is generated separately There are few methods available for scheduling n-machines and m-parts. The methods are heuristics which lead to good solutions. The heuristic selected is by Kusiak [13], which leads to a good solution rather than the optimum. The heuristic is demonstrated by applying it to the example problem from Nagi et al. [17]. In the heuristic an operation is selected using the following priority rules. Select an operation in the following priority sequence -

P1 : with the largest number of successive operations

P2 : belonging to a part with the minimum number of schedulable operations

P3 : with the largest number of immediate successive operations

P4 : belonging to a part with the largest number of unprocessed operations

P5 : with the shortest processing time

P6 : belonging to a part with the corresponding shortest slack time

P7 : random

Example :

The initial part-machine matrix is shown in Figure 5.6. it shows the sequence of operation for individual parts The processing times of parts on machines are shown for individual cells. The grouped matrix is generated by the Nagi et al algorithm [17]. Each cell is considered separately and part schedule is generated.

CELL 1

Parts 2 : 1[12]-2[9]-3[7] Machine numbers are in brackets

4 : 4[7]-5[12]-6[1]

6 : 7[1]-8[9]-9[12]-10[7]

8 : 11[1]-12[12]-13[7]

9 . 14[9]-15[1]-16[12]

Problem : Schedule 16 operations on 4 machines

Part #	2			4			6				8			9		
Opn. #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
M/c. #	12	9	7	7	12	1	1	9	12	7	1	12	7	9	1	12
M/c. Time	.1	.2	.1	.1	.1	.1	.1	.2	.1	.1	.1	1	.2	.1	.2	1

Iteration 1.

Step 1: Time t = 0

Schedulable operations = [1,4,7,11,14]

Parts Available = [2,4,6,8,9]

Machines available = [1,7,9,12]

Step 2 & 3:

Start Operations 1 on m/c 12 Finish t=0.1

Start Opn. 4 on m/c 7 Finish t=0 1

Start Opn. 14 on m/c 9 Finish t=0 1

Schedule Opn. 7 & 11 on m/c 1.

Rule P4. Start Opn. 11 on m/c 1 Finish t=0.1

Step 4: Set t = 0.1

Completed operations = [1,4,14,7]

Iteration 2.

Step 1: Time t = 0.1

Schedulable operations = [2,5,8,11,15]

Parts available = [2,4,6,8,9]

Machines available = [1,7,9,12]

Step 2 & 3:

Start Opn. 5 on m/c 12 Finish t=0.2

Schedule Opn. 2 & 8 on m/c 9

Rule P4. Start Opn. 8 on m/c 9 Finish t=0.3

Schedule Opn. 11 & 15 on m/c 1

Rule P4. Start Opn. 11 on m/c 1 Finish t=0.2

Step 4.

Set t = 0 2

Completed operations = [1,4,14,7,5,11]

Proceeding along the same lines after seven iterations the results obtained are :

Completed operations = [1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16]

The final schedule is :

Machines 1 : 7[6]-11[8]-15[9]-6[4]

7 : 4[4]-13[8]-3[2]-10[6]

9 · 14[9]-8[6]-2[2]

12 : 1[2]-5[4]-12[8]-9[6]-16[9]

CELL 2

Using the procedure illustrated for cell 1 we come up with the schedule for cell 2.

The final schedule is :

Machines 2 : 15[28]-12[27]-3[12]-10[21]

5 · 4[19]-2[12]-17[28]

6 · 1[12]-9[21]-7[19]-18[28]-14[27]

16 . 11[27]-5[19]-8[21]-16[28]

20 6[19]-13[27]

CELL 3

The final schedule is .

Machines 3 : 5[33]-2[30]-10[36]

8 · 1[30]-6[33]-9[36]

11 : 8[36]-3[30]

18 · 7[33]-4[30]-11[36]

CELL 4

The final schedule is

Machines 4 : 4[50]-2[49]-8[51]

13 : 1[49]-5[50]

15 . 7[51]-3[49]-6[50]

CELL 5

The final schedule is ·

Machine 10 : 1[40]-9[46]-7[43]-13[48]

14 : 12[48]-3[40]-10[46]

17 : 11[48]-6[43]-4[40]

19 : 5[43]-8[46]-2[40]

3.1.4 c) Algorithm for the grouping of machines and parts

The algorithm was developed by Abdou [1]. It is applied to the binary machine-part matrix. The salient feature of this algorithm is that it scans only non-zero entries in the matrix and thus has a lower CPU time. The flow chart of the algorithm is shown in figure 3.7. The algorithm consists of the following steps :

Step 1 : Set family number, FN = 1, and row number, R = 1

Step 2 : Scan row R

Step 3 : Locate the non-zero entries in row R

Step 4 : Scan each column with a non-zero entry in row R

Step 5 : For each non-zero entry scanned, if both the corresponding row and column are scanned, assign the part (column j) and machine (row i) to FN

Step 6 : For each non-zero entry scanned along the column, scan the corresponding rows

Step 7 : If there are any rows not scanned with non-zero entries, set R = R+1 and FN = FN+1, and go to step 2.

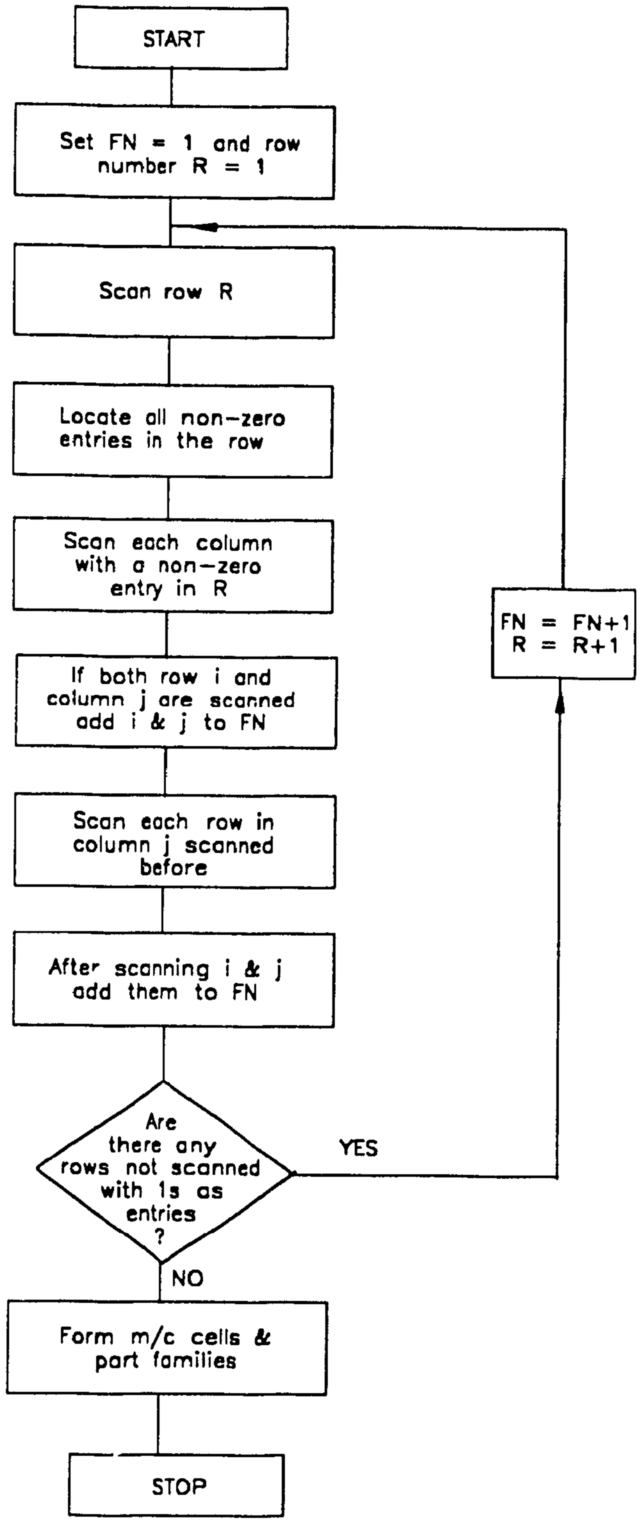


Figure 3 7 Flow chart for the grouping algorithm

3.1.4 d) Algorithm for MHS selection

The material handling equipment selection requires an extensive knowledge of the factors involved and the interactions between them. The process involves many criteria, (as illustrated in table 3.1) and might require to satisfy multiple objectives. The model for the material handling equipment selection is presented here. It has been adopted from Abdou [2] with slight modifications. The flow chart represents the procedure in general terms for MHS selection. The first step is to identify and input the task factors according to the user's requirements. The value of each criteria is determined based on rules described in the knowledge base section. Table 3.1 (MHS table) lists 11 types of MHSs. Each MHS is matched with user's task factors and alternative MHSs are generated. The alternatives are numerically evaluated to select the best 2-3 alternatives.

3.1.4 e) Algorithm for the layout structure selection

Layout structures of 5 types are considered. Table 3.3 lists the 5 types of layout with the criteria and factors for the selection. The type of layout structure which suits the user's requirements is selected by the procedure shown in the flow chart. The user inputs the task factors depending on the problem requirements and using rules from the knowledge base the value of each criterion is determined. Each layout is matched with user's task factors, if they are satisfied the layout is accepted as an alternative. Each alternative layout is associated with a probability value. All alternative layouts generated are evaluated and the best 2 or 3 are retained.

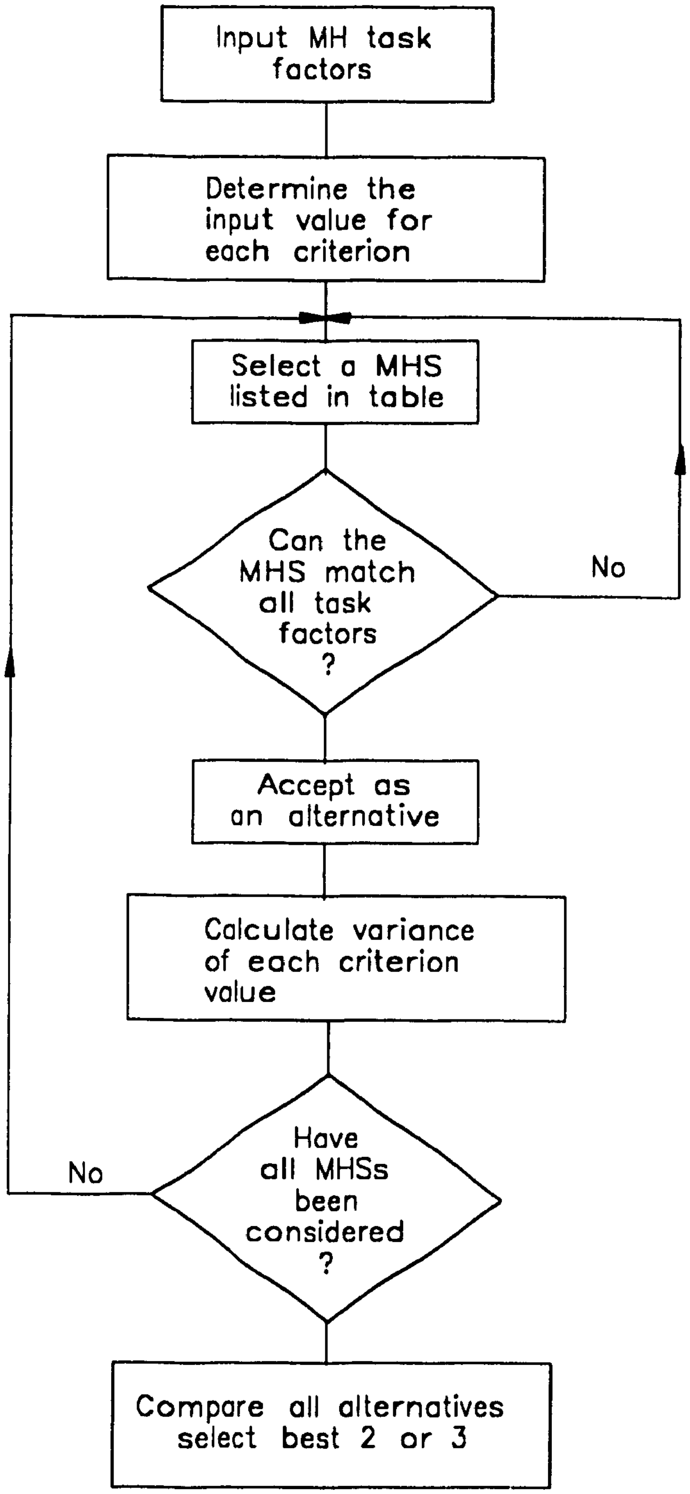


Figure 3.8 Flow Chart for MHS selection

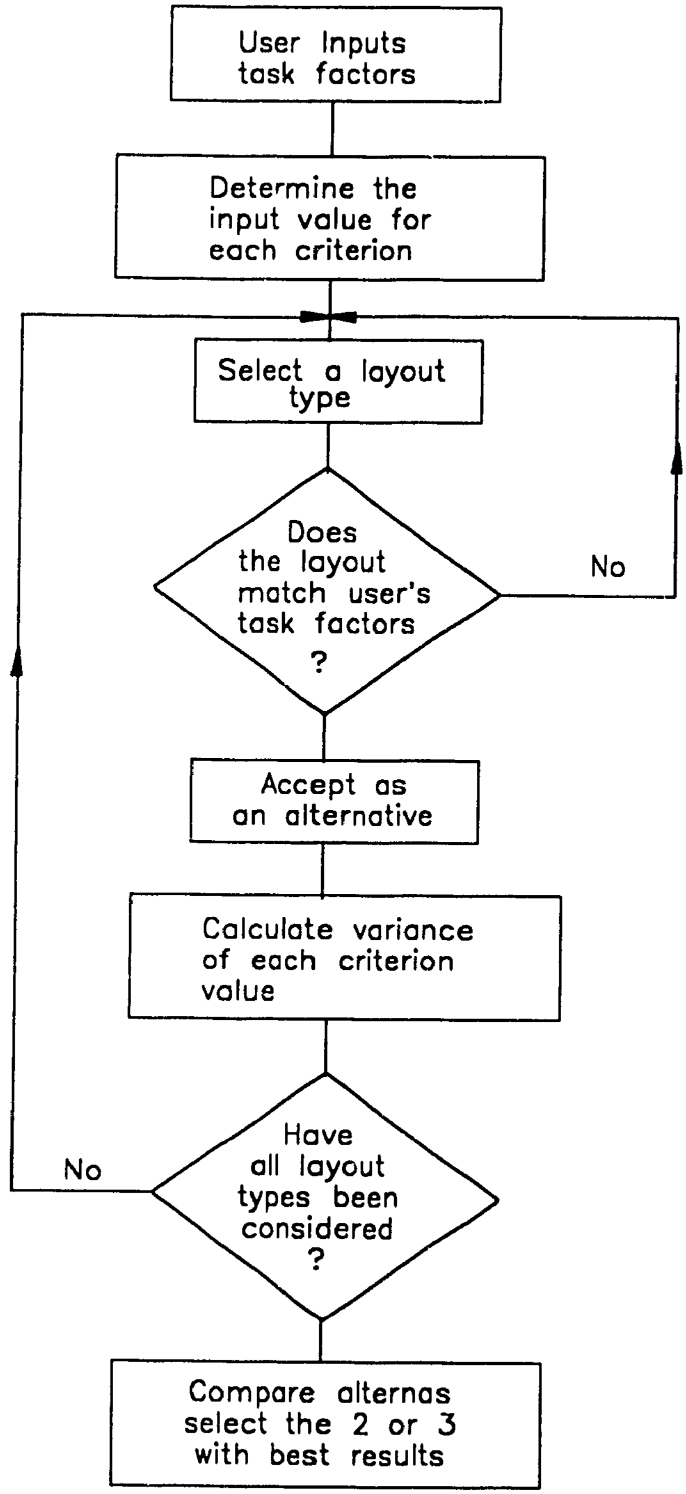


Figure 3.9 Flow chart for layout selection

3.1.4 f) Algorithm for joint selection of layout and MHS for a cell

The selection of layout and material handling system is interdependent, i.e one cannot be selected without affecting the choice of the other. The algorithms for the selection of layout require that the MHS be selected before hand and the algorithms for MHS selection assume the type of layout is already known. A new method for the joint selection of layout and Material handling system is presented here.

The algorithm for material handling systems (MHS) selection, selects all possible MHS for each cell Having selected the MHSs the types of layout structures that can be adopted are selected using the knowledge base rules and database files This forms a tree shown in figure 3 10b. It indicates that first the MHS is selected then based on that information the feasible layouts are selected Using the layout selection algorithm select the feasible layout structures Applying the knowledge base rules the feasible alternative MHSs feasible for the types of layout are selected. With this we form a second tree The two trees are studied together and if the same combination of layout and MHS exists in both trees, it is selected as a feasible combination. The procedure is illustrated by a hypothetical example. The application of layout selection algorithm for selecting a layout for cell (say)X results in the selection of two layouts, Linear single row L1, and multi-row L2. The knowledge base rules then choose the MHSs compatible with these types of layout and user requirements The MHSs chosen are Roller conveyor MH1, and Towline MH3. The layout L2 takes MHSs AGV + tugger MH2, Fork lift truck MH5 and Unit load AGV MH7. Simultaneous selection of the MHS first results in the identification of 3 MHSs, roller conveyor MH1, AGV + tugger MH2, and Towline MH3 MH1 according to the knowledge base rules can take L1 and L2, MH2 can take L2 and Cluster layout L3, MH3 takes L2 and L3. This is put in the form of trees and is shown in figure 3.10b. The combinations common to both the trees are MH1-L1 i.e. Roller conveyor & Linear single row and MH2-L2 i.e. AGV with tugger & Multirow layout. These are the two feasible combinations of layout and material handling generated based on this new approach. The two sets are taken for further analysis on feasibility and for relative allocation of facilities.

L - Layout MH - Material Handling System

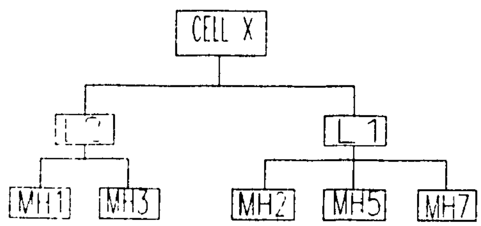


Figure 3.10a Tree 1.

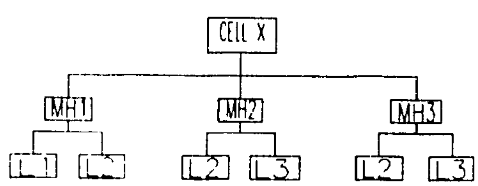


Figure 3.10b Tree 2.

3.2 SIMULATION MODEL

The Cellular Manufacturing System is now divided into independent cells The feasibility of these cells has to be evaluated dynamically, before the cell design can be incorporated into the design of the complete manufacturing system. There are various commercial software available to simulate the manufacturing environment Some of the popular ones are SIMFACTORY, PROMOD, GPSS, SLAM & WITNESS. WITNESS provides the user with greater flexibility in defining the elements of the model, it is easy to use and complex rules and logic can be built for part routing and scheduling It offers flexibility in routing of parts, good animation to visually evaluate the simulation model when running, and generates detailed reports and a trace of events in the simulation occurring every time unit The simulation elements recognized are machines, conveyors, vehicles, buffers, labour and parts with their sub-types The three main stages of developing the model, which is entirely menu driven, are define, display and detail stages. In the define stage all the elements in the system to be modelled are defined. In the display stage a display is set up which may extend to over four screens. The elements are positioned on the screen using a library of icons and colour coded to indicate the status of the machine or element i.e running, waiting, blocked, broken down, or being setup. In the detail stage the input and output rules for work flow, the times of operations, frequency of arrivals, etc. are entered for the element The animation shows the movements of the elements and the state of the simulation being run at any point in time. One of the interesting effects of the way WITNESS is implemented is that it is no longer necessary for the user to complete the model before running it and the user can develop his model a bit at a time, defining each element through all the stages before beginning on a new element. Modelling with WITNESS involves physical elements and logical elements. The input to WITNESS for each cell is described below.

I). Machine data :

- Type of machine

  The types of machine are Production, Assembly, Multiple and Single machines, Depending on the type of machine selected the properties and the input and output rules vary, thus the logic of the simulation is affected by the type of machine selected. In this problem all machines are assumed to be single, that is one part is input processed and output to the system.

- Number of copies of machine available

  If there are multiple copies of the same machine they have to entered together, so that when a part arrives it can select whichever machine is available for processing.

- Processing time of parts

  The processing time for each part to be produced on the machine is entered

- Set up time

  The setup time is an important part of the total production time of the part. In this simulation problem the setup time has been included in the processing time of the parts and hence has not been input separately.

- Breakdown time of machines

  To simulate a manufacturing system close to an actual manufacturing situation, WITNESS provides probabilistic breakdown models for the machines. One of these models can be selected depending on the probability distribution the breakdown time is to follow.

- Input and Output Rules

  The sequence of operations of the parts is built in the simulation by input and output for each element. A machine pulls a part from the buffer and after processing uses the push rule to output to another element

2). Part data :

- Number of parts

  The different parts and their batch sizes are entered under part detail

- Sequence of operation

  The part detail form provides a standard format to input the sequence of operations.

- Part schedule

  The part schedule is input as first arrival time of each part, arrival rate and probabilistic distribution of the arrival times of the parts. The schedule that is generated using the Kusiak's heuristic [13] is incorporated and rules are used to control the flow and loading of the parts on the machines

3) Material handling data :

- Type of material handling system

WITNESS provides two types of MHSs, Conveyors and Vehicles. All other MHSs have to modelled using the two types. For example a robot is defined as a vehicle and its path is defined as a track.

- Speed of handling or movement time

The material handling time is evaluated by defining the speed of the vehicle and the distance between the stations. The starting position and stop times for the MHS are also entered as input data.

- Load and unload time

The loading and unloading of parts from buffers and machines, is sometimes included in the setup time, but WITNESS provides a separate entity to incorporate loading and unloading time of the MHS.

4). Layout of cells and relative allocation of machines

The relative allocation of machines is generated by the CRAFT algorithm. The machines and MHS are laidout in the system according to the layout generated The machine icons are placed in their respective positions and distances between them are entered for the calculation of movement times.

Performance Measures

- Production rate of each part
- Production volume for each part

- Machine utilization

- MHS utilization

Output from the model gives the cell report and the cell trace from which we can calculate the production rate and volume of the parts. The report file provides a listing of utilization of the machines and MHS. A sample of a trace and the reports are shown in the appendix C.

3. 3 KNOWLEDGE BASE RULES

The design procedure requires the application of various algorithms and external programs but at different stages it also requires experience based knowledge. This knowledge would be present in the human expert and based on which he/she would make a decision. The CMS design problem is a multifaceted problem and involves expert knowledge in various areas of the problem. The experience based knowledge can be extracted from the human expert and written in the form of production and expert rules. When a decision is to be made in the problem the respective rule is fired and a solution or alternative solution are suggested Knowledge base rules have been developed for different parts of the design process which are classified as under A few knowledge base rules for material handling system selection, layout structure selection and for forming the "rel" chart were adopted from existing literature. Additional rules are developed for these purposes and new set of rules are developed for joint selection of layout and MHS and for the design of a CMS.

Set 1 rules for material handling system selection

These rules aid in the selection of a MHS for a cell. 11 types of material handling equipment have been considered like, robot, forklift, conveyor etc. and based on user input for the qualifiers and variables, a material handling equipment is selected by firing the respective rule. For example

IF
load is less than 4000lb
AND usage frequency is high
AND surface of floor is smooth
THEN
select a tractor-trailer with electric engine having cushioned tires

Set 2 rules for the type of layout structure selection

The layout structure is dependent on the number of machines in the cell and various other variables and qualifiers. Layout structures of 5 types have been considered. The user choice of variables and qualifiers is matched with the IF premise of the rules and if there is a match, the rule is fired and a layout structure is selected. Based on a different set of user input a different layout structure can be selected for the same cell, this provides alternative layout structures for the cell.

Set 3 rules for the joint selection of layout and MHS

The layout structure selection and the material handling equipment selection are interdependent, that is one cannot be selected without affecting the selection of the other. A new method for the joint selection of layout and MHS is proposed in this research. Knowledge base rules have been developed for this purpose and are listed under this heading in appendix A.

Set 4 rules for determining the activity relationship chart 'REL Chart'

The relative allocation of machines in the cell, or the cell layout is determined using the CRAFT algorithm. The machines are laidout in the layout structure already selected. To incorporate the different layout structures and for cell layout a relationship chart or "REL CHART" is to be formed between the machines in the cell Depending on the amount of material handling between the two machines and user choice, a relationship of A, E, I, O, U is assigned from A for absolutely important to U for unimportant respectively in that order. The rules written to facilitate the formation of "REL CHART" are listed under topic in appendix A.

Set 5 rules for cellular manufacturing system design

The CMS design stage has various problems to solve, like the MHS selection, cellular layout, formation of functional cell and resolving bottleneck machines Knowledge base rules have been developed and a sample is presented in the appendix A

3. 4 QUERY TO USER

The input to the problem is entered as database files and the user is prompted or queried to enter a choice or a selection. This facilitates the incorporation of user choice from among the alternatives available. The variables and the qualifiers are entered by prompting the user, for example "What is the level of automation in the manufacturing system" ? The choices given are HIGH/MEDIUM/LOW and the user selects one of the choices When the design process generates alternatives at various stages, the user is queried again to select from among the alternatives The interactive approach to input the data and the design problem make the expert systems approach easier for the user to implement and the design process more user friendly.

CHAPTER 4

THE INFERENCE ENGINE

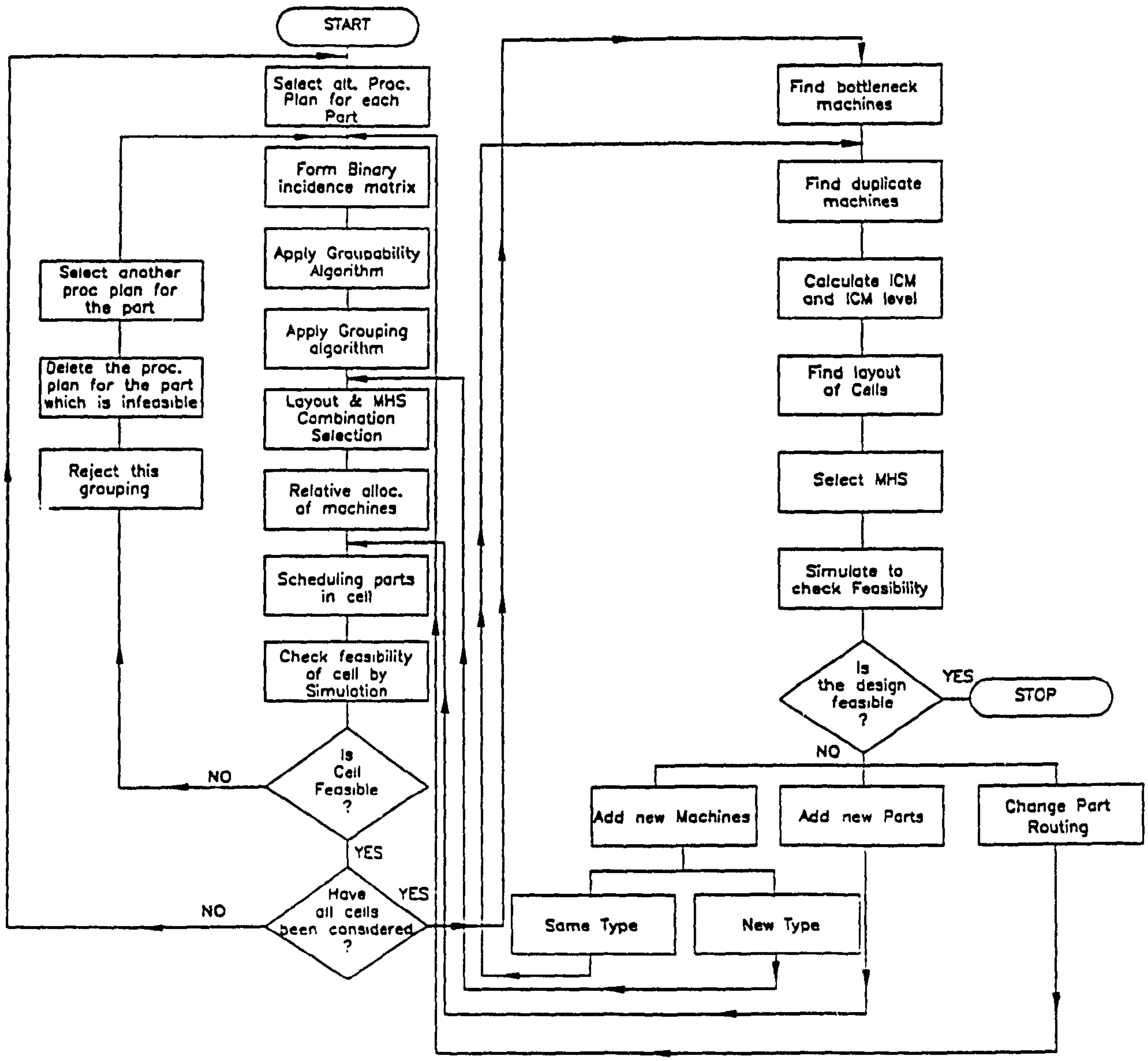
The inference engine contains the logic or the sequence that the design procedure has to follow. It is the central part of the expert system According to the logic coded, it will retrieve the appropriate algorithm from the database and execute it The inference engine also interfaces with the knowledge base, retrieving rules as and when needed during the procedure of the design. The inference engine takes user input and prompts the user whenever required to enter a choice or value interactively. The design methodology can be divided into two main phases, cell design and CMS design The two phases are very different in their approach and are discussed separately in this section

4.1 CELL DESIGN METHODOLOGY

The cell design procedure is built into a heuristic, which forms a part of the logic of the inference engine of the expert system. There are two parts to the problem, the first part is cell design and the second part is feasibility checking of the cell design The following are the steps for cell design :

1. *Process plan selection*

   Each part can be produced using more than one process plan with a small change in cost. The presence of alternative process plans increases the chances of obtaining a block diagonal matrix and helps generate alternative groupings of machines and parts. Generally only 2 or 3 process plans are available by which the part can be produced economically Select the alternative process plans for each part.



Flow Chart of Inference Engine
Figure 4.1

2. *Binary incidence matrix formation*

Place machines along the rows and process plans along the columns As shown in figure below.

	a1	a2	a3	b4	b5
1	1	0	1	1	0
2	0	0	1	1	1
3	1	1	1	0	0
4	0	0	1	0	1

3. *Groupable matrix formation*

The GMF algorithm performs a statistical evaluation of the binary matrix and outputs a matrix with atleast one process plan for each part present in the matrix This matrix has higher expectancy to form a better grouping and have fewer elements outside the diagonal blocks.

4. *Machine-Part Grouping*

The matrix output from the GMF algorithm has one or more process plans for each part. The grouping algorithm of Abdou [1] is applied to the matrix All the process plans for one part might be allocated to one cell or to different cells If the process plans are allocated to the same cell then select the plan with less cost and if the plans are in different cells then check feasibility by simulation by considering one plan at a time and allocate the part to the cell giving higher throughput and utilization levels

5. *Layout and MHS selection*

Each cell in the grouping is considered separately and for each cell, feasible layout and MHSs are selected using knowledge base rules. The algorithm for the joint selection of layout and MHS is used and feasible layout and MHS combinations are formed.

6. *Relative allocation of machines in the cell*

The machines in each cell are laid out using the CRAFT algorithm. Depending on the type of layout selected the procedure varies slightly. For example in order to define a circular layout, all machine have absolute relationship with the robot and a weighted relationship with each other. This assures that the machine are laid out in a circular layout around the robot.

7. *Scheduling of parts in the cell*

The scheduling of parts under cellular manufacturing requires a slightly different approach. The approach selected was developed by Kusiak [13] for the n-part, m-machine problem. The method defines seven rules, based on these rules the parts are scheduled. This method was selected because of the ease of application to the complicated n-part, m-machine scheduling problem and since the method is based on rules, it can be easily incorporated into the expert system.

8. *Feasibility check for each cell in the grouping*

The group technology output of part families and machine cells may or may not be feasible based on the following constraints: plant and cell layout, material handling system, part routing and the production schedule of the parts. The groupings should first be checked for feasibility. The feasibility of each cell is to be evaluated before evaluating the feasibility of the whole grouping. The procedure for the evaluation of cell feasibility involves simulating each cell and dynamically checking the throughput, production rate, utilization of machines and the material handling system. The simulation requires further input from the user concerning the parts and machines. Input the layout, material handling system, part schedule and part route to the simulation program. Use the above criteria to check if the cell is feasible.

9. *Feasibility check for all cells in the grouping*

A grouping is not feasible even if one cell in the grouping fails to satisfy the decision criteria and if one cell is not feasible reject the grouping and select another grouping for the design. If all the cells in a grouping are feasible go to the second phase of the methodology for the design of a CMS.

4.2 CELLULAR MANUFACTURING SYSTEM DESIGN METHODOLOGY

A simple and step by step procedure for the design of the entire system including all the feasible cells generated in the cell design stage and bottleneck machines is presented below.

1. *Find the bottleneck machines*

   These are machines which can be located at off diagonal positions in the grouped part-machine matrix. The machines process parts in two or more cells and hence cannot be allocated to any particular cell.

2. *Find the number of duplicate machines added in the cell design stage*

   In the cell design stage after simulation it was observed that certain parts do not meet the production volume requirements because of high machine utilizations. Another copy of the machine was added to improve the throughput of the parts. The size and area of these machines is compared to the available area in the cell, if the space is sufficient then the machine is allocated to the cell, else it is placed in the functional cell.

3. *Find all the subcontracted parts*

   These are parts which require machining in more than one cell and the parts whose production requirements could not be satisfied within the cell. Evaluate the feasibility of the part by duplicating the machine or adding buffer etc. to the cell. If the part is still not feasible then the part is to be subcontracted, either the whole lot or only the excess production volume required

4. *Calculate the ICM and ICM level*

The number of inter-cellular movements(ICM) performed by transporting parts from cell to cell is calculated. When a part is carried from one cell to another and returned to the cell after its operations, the number of ICM is 2. ICM level is the fraction of ICM between two cells over the total ICM in the system calculated as a percentage.

6. *Find layout of the cells in the system including the functional layout*

The layout of the cells including the functional cell is evaluated by using the CRAFT algorithm. Unlike the layout procedure for the cell, there are no standard layout types for the system and whatever layout the CRAFT algorithm generates is taken as the layout. The procedure was outlined in an earlier section

7. *Select MHS for the system considering the ICM and functional cell*

The MHS is selected using user input, knowledge base rules and MHS table. If the functional cell has only one machine then the cell is laid out by the CRAFT algorithm in such a way that the MHS for the cell might be used for the functional cell as well.

8. *Combine all the cells and simulate to observe the dynamic behaviour of the system*

The cells simulated in the cell design stage are combined in the WITNESS simulation program, so that the ICM can be incorporated and its effect studied dynamically. The input to the simulation are cell MHS, layout and scheduling, cellular layout, MHS for the system and ICM. The simulation is evaluated for feasibility based on the throughput, utilization of machines and MHSs.

CHAPTER 5

CASE STUDIES AND ANALYSIS OF RESULTS

The cell design procedure proposed in this research is applied to two problems selected from literature. The problems were selected based on the extent of data provided in the problem The type of solutions obtained by the approaches will provide a basis to compare our solution with previously published results. The first case study illustrates the application of the groupability algorithm and the generation of alternative solutions. The second case study deals with the design of the CMS. It takes the grouped machine - part matrix and the cell design procedure is applied following which with MHS and layout is generated

5.1 Case Study 1.

The first problem selected is from Kusiak [11]. The initial machine - part matrix is shown in figure 5.1. The problem has 5 parts to be machined on 4 machines. Each part can be produced by more than one process plan, the alternate process plans are listed along the column in the matrix. The objective of the example is to demonstrate the application of the groupability algorithm and the generation of alternative groupings using a different set of process plans.

Part #		1			2		3		4		5	
Process Plan #		1	2	3	4	5	6	7	8	9	10	11
	1			1		1	1		1	1		1
Machine #	2		1	1	1			1				
	3	1			1	1				1	1	
	4	1	1				1	1	1		1	

Figure 5.1

<u>Applying the Groupability algorithm</u>

The matrix as shown in figure 5.1 is input to the groupability algorithm, including part numbers and their process plans.

Step a) Calculate the Groupability index of the matrix in

figure 5.1 including all the process plans for the parts

The Jaccard similarity values are shown in figure 5.2a.

	1	2	3	4
1	-	.11	.22	20
2		-	.125	.22
3			-	.22
4				-

Figure 5.2a

The values for the groupability index σ_{sj} = 0.0467 and X = 0 1825

Step b) Remove the process plans which consist of only one operation, for example plan 11 for part 5. The new similarity values are shown in figure 5.2b

	1	2	3	4
1	-	.125	.25	.22
2		-	.125	.22
3			-	.22
4				-

Figure 5.2b

The values of groupability index are σ_{sj} = 0.0495 and X = 0.1933. It is observed that the value of the groupability index is increased from 0.0467 to 0.0495

Step c) Locate the set of machines with the lowest similarity value. Delete the process plan with processing requirements on both the machines and giving the lowest similarity value Calculate the similarities again, if the value of the groupability index σ_{sj} is between 0.2 and 0.4 then the matrix is groupable, else repeat step c, till the desired value of σ_{sj} is obtained. In this example we see S_j for machines 1-2 is the lowest (0.125), so we delete the process plan 3 with operations on both machines, and calculate the similarity index again. The new similarity matrix is shown in figure 5.2c.

	1	2	3	4
1	-	0	.28	.25
2		-	.143	.28
3			-	.22
4				-

Figure 5.2c

The groupability index values are σ_{sj} = 0.0990 and X = 0.1955. The value of σ_{sj} is much below the limit of 0 2 so we repeat the procedure in step c)

Iteration 2.

We see that the similarity between machines 2 and 3 is the lowest. Delete process plan 4 for part 2 and recalculate the similarity matrix Figure 5.2d shows the revised similarity matrix.

$$
\begin{array}{c|cccc|}
 & 1 & 2 & 3 & 4 \\
\hline
1 & - & 0 & .33 & .25 \\
2 & & - & 0 & .33 \\
3 & & & - & .25 \\
4 & & & & - \\
\end{array}
$$

Figure 5.2d

The groupability index values are σ_{sj} = 0.1405 and X = 0.1933 Proceeding similarly after 3 more iterations, and deleting process plans 1, 6, and 8, we get a matrix which has an acceptable value of the groupability index σ_{sj} The similarity matrix is shown in figure 5.2e

$$
\begin{array}{c|cccc|}
 & 1 & 2 & 3 & 4 \\
\hline
1 & - & 0 & .66 & 0 \\
2 & & - & 0 & .66 \\
3 & & & - & .20 \\
4 & & & & - \\
\end{array}
$$

Figure 5 2e

The groupability index values are σ_{sj} = 0.2961 and X = 0.2533.

The remaining machine - part matrix after the plans are deleted is shown in figure 5 2f To reduce the similarity between machines 3 and 4 we cannot delete process plan 10 as at least one process plan for each part has to be selected. The process plans which had only one operation and were deleted in step b are now used to replace the process plans for those parts. It is useful in decreasing the similarity between machines when all other except one process plan for that part have been deleted. So in our example process plan 10 is replaced with process plan 11. The final matrix is shown in figure 5.3a.

	2	5	7	9	10
1		1		1	
2	1		1		
3		1		1	1
4	1		1		1

Figure 5.2f

	2	5	7	9	11
1		1		1	1
2	1		1		
3		1		1	
4	1		1		

Figure 5.3a

	1	2	3	4
1	-	0	.66	0
2		-	0	1.0
3			-	0
4				-

Figure 5.3b

The groupability index for matrix 21. is σ_{sj} = 0.4034 and X = 0.273

67. This matrix is now grouped and machine cells & part families are generated The final grouped matrix which is also the solution obtained by Kusiak [11] is shown in figure 5.4. Before we can progress with the analysis of the grouped matrix, a lot of information is needed, which is input by the user.

<u>User input to the problem :</u>

Qualifiers :

Shape of space available = rectangular

level of automation = high

level of flexibility = high

layout adaptability = low

weight load of MHS = low

MHS uniform speed = yes

MHS mechanism attached = yes

MHS unmanned = yes

routing flexibility desired = high

safety of machines = high

maintenance of machines = low

part variety = low

part volume = low

Variables :

processing times are given in figure 5.4

production volume required - in figure 5.4

setup time - included in the processing times of parts

type of machines - 4

	2	7	5	9	11
2	.1	.2			
4	2	1			
1			1	.1	.1
3			.2	.3	
Demand	2	3	2	4	2

Figure 5.4

CELL 1

Parts = {1,3}, machines = {2,4}, Schedule · 1-3-1-3...

Layout and MHS selection

From rule 1, set 2 rules

layout selected = Single row layout

From rule 1, set 1 rules

MHS selected = Unit load AGV

Parts	Units/min	Sequence	Max Tp	Production rate = 1/Tp
1	2	2-4	2=12 sec	5 parts/min
3	3	2-4	2=12 sec	5 parts/min

The demand is met hence the cell is feasible

CELL 2

Parts = {2,4,5}; machines = {1,3}, Schedule . 2-4-5-2-4-5 .

Layout and MHS selection .

From rule 1, set 2 rules

Layout selected = Single row layout

From rule 1, set 1 rules

MHS selected = Unit load AGV

Parts	Units/min	Sequence	Max Tp	Production rate = 1/Tp
2	2	1-3	.2	5 parts/min
4	4	3-1	3	3 3 parts/min
5	2	1-3	.1	10 parts/min

The demand for part 4 is not met as only 3 3 parts are produced per minute Once we have concluded that the part cannot be produced in this cell alone, cell 2 is not feasible If one cell in a grouping has been declared not feasible then the whole grouping is rejected as not feasible The process plan which makes this cell infeasible is deleted and an alternative is selected. The alternative matrix is shown in figure 5 5a and the similarity values are shown in figure 5 5b The groupability index is 0 2097, hence the matrix is groupable. By applying the grouping algorithm two cells with intercellular movement are formed. Process plan 8 takes 0 1 minutes on machine 1 and 0 2 minutes on machine 4 and volume requirement is 2 parts/hour Checking the production volume requirement for part 4 produced using process plan 8 we find that the volume requirement is met

$$
\begin{array}{c|ccccc|}
 & 2 & 5 & 7 & 8 & 11 \\
1 & & 1 & & 1 & 1 \\
2 & 1 & & 1 & & \\
3 & & 1 & & & \\
4 & 1 & & 1 & 1 &
\end{array}
$$

Figure 5.5a

$$
\begin{array}{c|cccc|}
 & 1 & 2 & 3 & 4 \\
1 & - & 0 & .50 & .25 \\
2 & & - & 0 & .66 \\
3 & & & - & 0 \\
4 & & & & -
\end{array}
$$

Figure 5 5b

In the first case the grouping was not feasible because cell 1 was feasible, but cell 2 was not feasible since the demand for part 4 was not met in the cell The alternative grouping generated by using another process plan for the part resulted in a grouping which is feasible based on the minimum production volume requirement.

Case study 2.

The cell design procedure proposed in this research is applied to a problem selected from the literature The problem is selected based on the extent of data provided in the problem. This problem will provide a basis to compare our solution with previously published results. The problem is taken from Nagi [17] Figure 5 6 shows the initial matrix with multiple process plans for each part. The final grouping obtained by Nagi [17] is shown in figure 5 7 The grouping results in 5 cells. We take the grouping output by Nagi and apply the cell design methodology. Then in the second stage the CMS design methodology is applied.

Rq vol	Part #	Ref #	Machines																			
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2 0	1	1						3			2			1								
2 0	1	2							3		2			1								
2 0	2	3	3					1						2								
2 0	2	4	3						1					2								
2 0	3	5	1						4		2			3								
2 0	3	6	1						4		2			3								
2 0	4	7	1					3						2								
2 0	4	8	1						3					2								
2 0	5	9	2								i			3							4	
2 0	5	10	2								1			3						4		
2 0	5	11	2								1			3								4
2 0	6	12		3			2	1														
2 0	6	13		3			2		1													
2 0	7	14					1		4									2			3	
2 0	7	15					1		4									2		3		
2 0	7	16					1		4									2				3
2 0	7	17					1	4										2			3	
2 0	7	18					1	4										2		3		
2 0	7	19					1	4										2				3
2 0	8	20		3					2									1				
2 0	8	21		3				2										1				
1 0	9	22		2					4									1			3	
1 0	9	23		2				4										1			3	
1 0	9	24		2					4									1		3		
1 0	9	25		2				4										1		3		
1 0	9	26		2					4									1				3
1 0	9	27		2				4										1				3
3 0	10	28		1			3	4										2				
3 0	10	29		1			3		4									2				
3 0	11	30			2					1			3							4		
3 0	11	31			2					1			3								4	
3 0	11	32			2					1			3									4
3 0	12	33			1					2										3		
3 0	12	34			1					2											3	
3 0	12	35			1					2												3
4 0	13	36			3					2			1							4		
4 0	13	37			3					2			1								4	
4 0	13	38			3					2			1									4
2 0	14	39										1				3			4	2		
2 0	14	40										1				3			4		2	
2 0	14	41										1				3			4			2
2 0	15	42										3							2	1		
2 0	15	43										3							2		1	
2 0	15	44										3							2			1
2 0	16	45										2				3				1		
2 0	16	46										2				3					1	
2 0	16	47										2				3						1
2 0	17	48										3				2			1			
3 0	18	49				2									1		3					
3 0	19	50				1									2		3					
3 0	20	51				2											1					

Figure 5 6 Input matrix for the Case Study

	01	07	09	12	02	05	06	16	20	03	08	11	18	04	13	15	10	14	17	19
2		3	2	1																
4	3	1		2																
6	1	4	2	3																
8	1	3		2																
9	2		1	3																4
12					3	2	1													
19						1	4	2	3											
21					3		2	1												
27					2		4	1	3											
28					1	3	4	2												
30										2	1	3	4							
33										1	2		3							
36										3	2	1	4							
49														2	1	3				
50														1	2	3				
51														2		1				
40																	1	3	4	2
43																	3		2	1
46																	2	3		1
48																	3	2	1	

Figure 5.7 Grouped matrix obtained by Nagi [17]

User input to the problem

Qualifiers

Shape of space available = Rectangular

Level of automation = High

Level of flexibility = High

Layout adaptability = Low

Weight load of MHS = Low

Uniform speed of MHS = Yes

Mechanism attached to MHS = Yes

Unmanned MHS = Yes

Part variety = Low

Part volume = Low

Part routing flexibility desired = High

Safety of machines = High

Maintenance of machines = Low

Variables

Processing times - given in problem

Production volume/rate required - given in figure 5 6

Part Schedule - listed under each cell

Setup time - included in processing times

Type of machines - 20

Additional Qualifiers for cells

Number of machines - very low

Layout Adaptability - high

Layout flexibility - low

Evaluation of the Layout, MHS and the combination of layout and MHS for each cell

The first step is the selection of layout and MHS independently using knowledge base rules Then the selection of layout and MHS combinations for each cell The new method for the joint selection of layout and MHS is applied and feasible combinations of layout and MHS are selected The layout and MHS combinations selected for each cell are given below.

CELL 1

Parts in cell = 5 [2,4,6,8,9], Machines in cell = 4 [1,7,9,12]

Matching the factors with user requirements for layout we see that no layout matches perfectly, but we can find an approximate match in which most factors match user requirements. According to rule 1, set 2 rules we select a feasible layout - Linear single row. The layout table gives - Cluster layout

The Material handling systems feasible are - Gantry Robot 9/10 and Robot 7/10

CELL 2

Parts in cell = 5 [12,19,21,27,28], Machines in cell = 4 [2,5,6,16,20]

The type of layout selected - Linear single row and Cluster layout

Material Handling system - Gantry Robot and Robot

CELL 3

Parts in cell = 3 [30,33,36], Machines in cell = 4 [3,8,11,18]

The type of layout selected by applying the rules is Linear Single Row, and from the table of layout factors and criteria layout is Circular.

The material Handling Systems feasible from the table are - Robot and Gantry Robot.

CELL 4

Parts in cell = 3 [49,50,51]; Machines in cell = 3 [4,13,15]

Layouts feasible are - Linear Single Row and Circular

Material Handling Systems feasible - Robot and Gantry Robot

CELL 5

Parts = 4 [40,43,46,48], Machines = 4 [10,14,17,19]

Layouts feasible are - Linear Single Row and Circular

Material Handling System feasible - Robot and Gantry Robot

To generate the feasible combinations of layout and material handling system for each cell, we use the new method suggested in this research. Using the knowledge base rules we simultaneously find the feasible layouts for the MHSs selected and also find the MHSs feasible for the layouts selected. Applying the method the combinations found feasible for this example are .

Cell 1. - Cluster Layout + Gantry Robot

Cell 2. - Cluster Layout + Gantry Robot

Cell 3. - Circular Layout + Robot

Cell 4 - Circular Layout + Robot

Cell 5. - Circular Layout + Robot

Calculate the minimum production rate for each part

After evaluating the layout and MHS combinations for each cell we calculate the minimum production rate that can be achieved for each part in the cell before the actual throughput and production rate are evaluated by simulation. The maximum processing time for each part on any machine is taken as the processing time for the part and production rate is calculated. The production rate calculated for each part and cell is shown in table below

CELL 1

Parts	Units/min	Sequence	Max Tp	Production rate = 1/Tp
2	2	12-9-7	2 min	5 parts/min
4	2	7-12-1	.1 min	10 parts/min
6	2	1-9-7	.2 min	5 parts/min
8	2	1-12-7	.2 min	5 parts/min
9	2	9-1-12-7	2 min	5 parts/min

Tp is the processing time of parts in minutes.

CELL 2

Parts	Units/min	Sequence	Max Tp	Prodn rate = 1/Tp
12	2	6-5-2	2	5 parts/min
19	2	5-16-20-6	.2	5 parts/min
21	2	16-6-2	.1	10 parts/min
27	1	16-2-20-6	.4	2.5 parts/min
28	3	2-16-5-6	.1	10 parts/min

CELL 3

Parts	Units/min	Sequence	Max Tp	Prodn. rate = 1/Tp
30	3	8-3-11-18	.1	10 parts/min
33	3	3-8-18	.1	10 parts/min
36	4	11-8-3-18	.2	5 parts/min

CELL 4

Parts	Units/min	Sequence	Max Tp	Prodn. rate = 1/Tp
49	3	13-4-15	.1	10 parts/min
50	3	4-13-15	.2	5 parts/min
51	3	15-4	1	10 parts/min

CELL 5

Parts	Units/min	Sequence	Max Tp	Prodn. rate = 1/Tp
40	2	10-19-14-17	.2	5 parts/min
43	2	19-17-10	2	5 parts/min
46	2	19-10-14	.2	5 parts/min
48	2	17-14-10	.2	5 parts/min

Relative allocation of machine in the cell

The relative allocation of the machines in the cells is determined by using the CRAFT algorithm. The relative allocation is important as it affects the material handling time and thus the throughput and utilization of machines.

Scheduling parts in the cell

The Kusiak [13] scheduling algorithm is applied to the parts in all the cells The method was illustrated by an example in the framework of the expert system The final schedules are given below.

CELL 1

Machines are 1,7,9,12

1 : 7[6]-11[8]-15[9]-6[4]

7 : 4[4]-13[8]-3[2]-10[6]

9 : 14[9]-8[6]-2[2]

12 : 1[2]-5[4]-12[8]-9[6]-16[9]

CELL 2

Machines are 2,5,6,16,20

2 · 15[28]-12[27]-3[12]-10[21]

5 . 4[19]-2[12]-17[28]

6 : 1[12]-9[21]-7[19]-18[28]-14[27]

16 : 11[27]-5[19]-8[21]-16[28]

20 : 6[19]-13[27]

CELL 3

Machines are 3,8,11,18

3 : 5[33]-2[30]-10[36]

8 : 1[30]-6[33]-9[36]

11 : 8[36]-3[30]

18 7[33]-4[30]-11[36]

CELL 4

Machines are 4,13,15

4 · 4[50]-2[49]-8[51]

13 · 1[49]-5[50]

15 . 7[51]-3[49]-6[50]

CELL 5

Machine are 10,14,17,19

10 : 1[40]-9[4(]-7[43]-13[48]

14 . 12[48]-3[40]·10[46]

17 . 11[48]-6[43]-4[40]

19 : 5[43]-8[46]-2[40]

Feasibility check for cells by simulation

The cells are simulated separately using the WITNESS simulation software The following are input to the simulation :

- Number and type of machines
- Number of parts, part routing and processing time for parts on individual machines
- Relative allocation of machines in each cell
- Layout type and the MHS selected
- Schedule of parts

The output from the simulation is obtained in the form of a report which is printed at the end of every simulation run. The simulation for each cell was run for 500 minutes and a warmup of 100 minutes. A sample of the report is shown in appendix C. The production rate and throughput are calculated by studying the trace file of the simulation Trace is the listing of events in the simulation every minute for the entire run time of the simulation. A sample trace file is shown in appendix C.

Cellular Manufacturing System Design Stage

The example problem that was considered in the cell design stage is input to the CMS design stage. The output from the cell design stage are·

- feasible Machine cells and part families
- feasible MHS and layout for the cell
- Duplicate and bottleneck machines
- Utilization of machines and throughput of the parts

Further the following observations are made :

a) Part # 28/part E in cell 2 and part #36/part C in cell 3 are not feasible because of production volume requirements.

b) Machine 19 performs one operation on part 9 in cell 1 and 3 operations in cell 5

c) Machine 1 in cell 1 has a duplicate to share the excess load

The excess production volume requirement for parts 28 and 36 has to be subcontracted as it was not possible to meet the volume requirement even when machines were duplicated. The additional machine 1 in cell 1 is placed within the cell itself as the machine has all operations in cell1. In our study it is assumed that sufficient floor space is available in the cell to accommodate the additional machine Since there is one bottleneck machine and ICM is low the machine is put in a separate functional cell The number of ICM is 2 between cells 1 & 5 and the functional cell The layout of the system is evaluated using the CRAFT algorithm. The final layout obtained is shown below in figure 5.8 The system is now simulated once again including all the cells and the functional cell. The simulation of the system shows the movement of parts between the cells and the functional cell and we can calculate the final throughput of the parts and utilization of the machines.

The output from the simulation is a report file and a trace file. The report gives the utilization of machines and the material handling system The throughput or production rate is calculated from the trace of the simulation. The output from the simulation is summarised in the table 5.7 :

Table 5.7 Summary of simulation output

CELL 1.

ELEMENT Machine	UTILN1 %	UTILN2 %	PART	V.REQD. Part/Hr	V.PROD1 Part/Hr	V.PROD 2Part/
1(2)	86.96	187 09	A	2	0.64	1.80
2	28.50	74.94	B	2	0.64	1.80
3	33 00	75.68	C	2	0.64	1.80
4	24 00	75.01	D	2	0.64	1.80
GANTRY	37 60	100.00	E	2	0.64	1.80

CELL 2.

ELEMENT Machine	UTILN1 %	UTILN2 %	PARTS	V.REQD. Part/Hr	V.PROD.1 Part/Hr	V.PROD2 Part/Hr
1	36 97	86.57	A	2	0.92	2.00
2	36.18	76 50	B	2	0.92	2.00
3	36 18	83 58	C	2	0.92	2.00
4	36.18	84.80	D	1	0.92	2.00
5	41.23	100.0	E	3	0.92	2.00
GANTRY	66.46	90.26				

CELL 3.

ELEMENT Machine	UTILN1 %	UTILN2 %	PARTS	V.REQD. Part/Hr	V.PROD1 Part/Hr	V.PROD2 Part/Hr
1	55.50	86.41	A	3	2.05	2.86
2	55.50	86.00	B	3	2 05	2.86
3	45.72	71.25	C	4	2.05	2.86
4	52.50	86.47				
ROBOT	64.84	100.0				

CELL 4.

ELEMENT Machine	UTILN1 %	UTILN2 %	PART	V.REQD. Part/Hr	V.PROD1 Part/Hr	V.PROD2 Part/Hr
1	46.50	85.50	A	3	1.64	2.87
2	57.45	85.50	B	3	1 64	2 87
3	56.88	85.85	C	3	1 64	2 87
ROBOT	59.67	97.15				

CELL 5.

ELEMENT Machine	UTILN1 %	UTILN2 %	PART	V.REQD. Part/Hr	V.PROD1 Part/Hr	V.PROD2 Part/Hr
1	54 86	78 97	A	2	1.90	1.98
2	41.37	62.52	B	2	1.90	1.98
3	42.29	59 30	C	2	1.90	1.98
4	42 20	60 22	D	2	1.90	1.98
ROBOT	66 51	100 0				

UTILN1 Percentage utilization of the machines and Material Handling System

UTILN2 Percentage utilization when input buffers are added to individual machines

V REQD · Production rate required in parts/hour

V PROD1 : The production volume in parts/hour

V.PROD2 : The production volume when input buffers are added to the machines

In cell 1 machine 1 has duplicate machines to cater to the excess load on that machine only. In cell 2 the speed of the Robot has been increased to adjust to the under utilization of the machines. Input buffers have been added to all the machines individually to simulate a pallet which can be loaded while the machine is processing another part. All input buffers have a maximum capacity of 3 parts.

The simulation has shown that all the cells generated by Nagi [17] are feasible after considering the layout of machines, MHS and Schedule of parts. The utilization of the machines and the MHS is satisfactory and the production rate required is met for most of the parts. The parts which do not meet the production rate requirement are part-E in cell 2 and part-C in cell 3, these parts are to be subcontracted since their volume requirement cannot be met even after the excessively loaded machines were duplicated

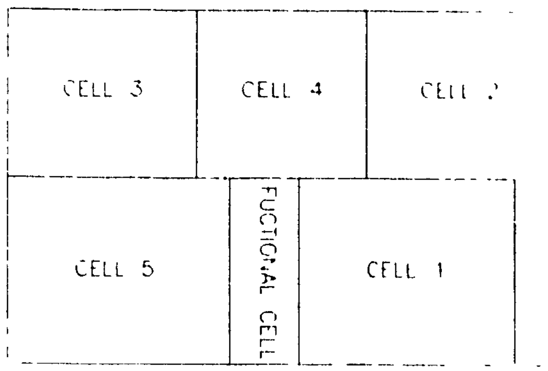


Figure 5.8 Final Layout of Cells

CHAPTER 6

CONCLUSIONS

In this study a complete approach to the design of a cellular manufacturing system was presented. A new algorithm called the groupable matrix formation (GMF) algorithm was presented. Alternate process plans for parts are placed along the columns and machines form the rows of the matrix. After performing a statistical study of the matrix, a groupable matrix is generated by deleting process plans which render the matrix infeasible The algorithm was applied to an example from literature and very good results were obtained.

This research is the first to consider the complete design problem of the cellular manufacturing system (CMS), earlier approaches limited themselves to the formation of machine cells and part families. Two major steps were identified in the design process namely, cell design and CMS design. Both steps are multifaceted problems involving material handling system (MHS) selection, layout of machines and cells and the movement of parts. The complexity of the problem and the use of experience based knowledge lead to the use of an expert system. The framework of an expert system was presented, which included a database, a knowledge base consisting of production and expert rules, and an inference engine which provides the procedure and logic for the CMS design. A new procedure for the joint selection of layout and MHS for cells was developed. It considers the interdependent nature of the selection of layout and MHS. The design procedure was applied to a problem selected from literature. A feasible combination of layout and MHS was developed for each cell and a CMS design was generated. The design for each cell was evaluated by simulation and the feasible cells were input to CMS design stage. The CMS design, which included all the cells and inter-cellular movement was evaluated by simulation and a feasible CMS design was generated

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APPENDIX A

KNOWLEDGE BASE RULES

The knowledge base consists of production and expert rules for the following aspects of the cellular manufacturing system design procedure :

set 1 . Rules for material handling system selection.

set 2 : Rules for the type of layout selection.

set 3 Rules for the joint selection of layout and MHS.

set 4 : Rules for determining the activity relationship chart 'REL Chart'.

set 5 : Rules for CMS design

Set 1 rules

<u>Rules for the selection of Material Handling system for a cell</u>

1 IF
loading an unloading of parts is unmanned
and percentage handling is high or medium
and required speed is either uniform or variable
and a mechanism can be attached
THEN
unit-load AGV - probability = 9/10

2 IF
loading/unloading of parts is unmanned
and a mechanism cannot be attached
and weight load is high or medium
and required speed is either uniform or variable
THEN
AGV-tugger with trailers - probability = 9/10
and unit load AGV - probability = 9/10

ELSE
towline - probability = 9/10

3 IF

loading/unloading of parts is manned
and required speed is uniform
THEN
tractor trailer - probability = 9/10
and monorail conveyor - probability = 9/10
and chain conveyor - probability = 7/10
and roller conveyor - probability = 7/10
ELSE
fork lift tractors - probability = 9/10
and power and free conveyor - probability = 9/10
and monorail conveyor - probability = 9/10
and chain conveyor - probability = 9/10

4. IF
loading and unloading of parts is manned
and weight load is high
THEN
monorail conveyor - probability = 9/10
and power and free conveyor - probability = 9/10
ELSE
fork lift tractors - probability = 9/10

5. IF
level of automation is high
and expansion flexibility is high
and buffer storage of central
THEN
unit load AGV - probability = 9/10
ELSE
towline - probability = 9/10
and AGV tugger with trailers - probability = 9/10

6. IF
load is less than 4000lb
AND usage frequency is high
AND surface of floor is smooth
THEN
select a tractor-trailer with electric engine having cushioned tires

7 IF
loading/unloading of parts is manual
AND a mechanism cannot be attached
AND weight load is high or medium

AND the required speed is either uniform or variable
THEN
AGV tugger - probability=9/10
AND unit-load AGV - probability=9/10

Set 2 rules

Rules for layout selection

1 IF
number of parts in the system is < 5
and production rate is > 10 (pcs/hr)
THEN
single row layout

2 IF
number of parts in the system is > 5
and production rate is > 30 (pcs/hr)
THEN
circular layout

3 IF
number of parts in the system is < 16
and production rate is < 10 (pcs/hr)
THEN
linear single row - 9/10
multirow layout - 7/10

4. IF
number of parts in the system is > 16
and production rate is < 2 (pcs/hr)
THEN
cluster layout - 9/10
multirow layout - 9/10

5 IF
[NMACH] =< 5
and [FL] > 1.2 * [MXRCH]
and [FW] > 1.2 * [MXRCH]
THEN
circular layout - 9/10

ELSE

linear single row - 9/10

Set 3 rules

Rules for joint selection of layout and MHS

1. IF

layout type is linear single row

and level of automation is low

THEN

the feasible MHSs are mono-rail conveyor, roller conveyor, chain conveyor and power conveyor

2 IF

layout is linear single row

and level of automation is high

THEN

feasible MHSs are AGV tugger and unit load AGV

3. IF

layout type is circular

THEN

MHS is a Robot

4 IF

layout type is linear double row

and level of automation is low

and flexibility is low

THEN

the feasible MHSs are conveyors

5. IF

layout type is linear double row

and level of automation is high

and flexibility is high

THEN

feasible MHS is AGV with trailer or unit load AGV

6 IF

layout type is multirow
and level of automation is low
THEN
feasible MHS is towline or fork lift truck or tractor trailer

7. IF

layout type is multirow
and level of automation is high
THEN
feasible MHSs are AGV+trailer or unit load AGV

8 IF

type of layout is cluster layout
and level of automation is high
THEN
MHS is gantry robot

9 IF

MHS is fork lift truck or tractor trailer
and level of flexibility is high
and level of automation is low
THEN
layout type is multirow or double row or cluster layout

10 IF

Gantry robot is the MHS
and level of flexibility is high
and level of automation is high
THEN
cluster layout

Set 4 rules

Rules for the forming of "activity relationship chart"

1 IF

closeness of two machines is due to : sequence of work
or closeness of two machines is due to : share the equipment
or closeness of two machines is due to : share personnel
THEN
relationship between machines is A - probability=9/10

2. IF

closeness of two machines is due to : noise
or closeness of two machines is due to : vibration
or closeness of two machines is due to : odours

THEN

relationship between machines is X - probability=9/10

3. IF

process is joining
or process is painting
or process is heat treatment

THEN

relationship between machines is E - probability=9/10

4. IF

user's importance of relationship between two machines is absolutely important

THEN

relationship between machines is A - probability=10/10

5. IF

user's importance of relationship between two machines is especially important

THEN

relationship between machines is E - probability=9/10
and relationship between machines is I - probability=7/10

6 IF

user's importance of relationship between machines is
: important

THEN

relationship between two machines is I - probability=9/10
and relationship between two machines is E - probability=7/10
and relationship between two machines is O - probability=7/10

7. IF

user's importance of relationship between machines is
: ordinarily important

THEN

relationship between two machines is O - probability=9/10
and relationship between two machines is I - probability=7/10
and relationship between two machines is E - probability=3/10

8. IF

user's importance of relationship between machines is
: unimportant

THEN

relationship between two machines is U - probability=9/10
relationship between two machines is O - probability=7/10
relationship between two machines is I - probability=3/10

9 IF

fraction of parts processed by any two machines is high

THEN

the relationship between machines is A - probability=9/10

10 IF

number of trips between machines is high

THEN

relationship between machines is - A probability=9/10

Set 5 rules

Rules for Cellular Manufacturing System Design

1. IF

Number of bottleneck machines is >= 1
AND icm level is > 30 %
AND icm reduction when machines are assigned to cell is <20%

THEN

A functional cell should be formed

2. IF

Machine has been duplicated to meet volume requirements
AND Area available in the cell is sufficient

THEN

Place the machine in the same cell

ELSEIF

Machine has been duplicated to meet volume requirements
AND Area available in the cell is not sufficient

THEN

Place the machine in the functional cell

3 IF

The machine is bottleneck
AND Processes parts in more than two cells

THEN
    The machine should be placed in a functional cell

4 IF
    The machine is bottleneck
AND ICM reduction is < 20%
AND Cost of machine is low
THEN
    Duplicate the machine

5. IF
    The ICM between two cells is high
AND ICM with all other cells is very low
THEN
    Use a dedicated MHS between the two cells

6. IF
    The level of automation in the plant is low
AND ICM between the cells is low
THEN
    Select Forklift as the MHS
ELSEIF
    The level of automation is low
AND ICM between the cells is high
THEN
    Select conveyor as the MHS

7. IF
    The level of automation is high
AND ICM level is high
THEN
    Select AGV as the MHS

Appendix B.

```
#include <stdio h>
#include <math h>
#include <ctype.h>

#define TRUE    1
#define FALSE   0
#define MAXROW  64
#define MAXGROUPS 32

/* function proto */
int *get_col();
float   get_variance(),


int   *marked_col; /* cols that have only one 1 */
int   *marked_col2; /* columns that have the least coefficient */
int   g_ngroup = 0;  /* number of column groups */
int   g_nrow, g_ncol;
typedef struct tag_row_coeff
{
  int row1, row2,
  float coeff;
  int   flag;
} row_coeff;

int        **col_group=NULL; /* a ptr to arrays of col groups */
int        rc_index = 0; /* global index for rc */
row_coeff  rc[MAXROW],

float   coeff_val[512];

main (argc, argv)
int  argc;
char **argv;
{
  FILE *fp= NULL;
  int  nrows, ncols;
  int  ngroup, ncol_per_group;
  int i, j;

  int   **matrix;
```

```
if ((fp = fopen(argv[1], "r")) == NULL)
  {
    printf("Unable to open %s\n", argv[1]),
    exit(1);
  }

/* read the # of rows & cols */
fscanf(fp, " %d", &nrows);
fscanf(fp, " %d", &ncols);

/* allocate the matrix and read in the values */
matrix = (int **)malloc(sizeof(int) * nrows);

for (i = 0; i < nrows; i++)
  matrix[i] = (int*) malloc(sizeof(int) * ncols);

/* read in the values */
read_input(fp, matrix, nrows, ncols);
g_nrow = nrows;
g_ncol = ncols;  /* set globaol rows and cols */
print_mat(matrix, nrows, ncols);

/* read the column group information */
fscanf(fp, " %d", &ngroup);  /* total number of groups */
col_group = (int **)malloc(sizeof(int) * ngroup);
for (i = 0; i < ngroup; i++)
  {
    col_group[i] = (int *)malloc(sizeof(int) * ncols);
    for (j = 0; j < ncols; j++)
      col_group[i][j] = -1;
  }
/* read and store the values */
/* format: <#col in group>  <columns in group> */
for (i = 0; i < ngroup; i++)
  {
    fscanf(fp, " %d", &ncol_per_group);
    for (j = 0; j < ncol_per_group; j++)
      fscanf(fp, " %d", &col_group[i][j]);
  }
printf("Printing the column groups:\n");
for (i = 0; i < ngroup; i++)
  {
    printf("Group %d: ", i);
    for (j = 0; col_group[i][j] >= 0; j++)
```

```
      printf("%d ", col_group[i][j]);
    printf("\n"),
  }
g_ngroup = ngroup, /* set global # of groups for convenience */
printf("----------------------------------------\n");
/* get the column indices of those that have one elt */
marked_col = (int *) malloc(sizeof(int) * ncols);
marked_col2 = (int *) malloc(sizeof(int) * ncols);

for (i = 0, i < ncols; i++)
  marked_col[i] = -1;
for (i = 0; i < ncols; i++)
  marked_col2[i] = -1;

/* initialise the rc array; if flag is true skip that index */
for (i = 0; i < MAXROW; i++)
  {
    rc[i].row1 = rc[i].row2 = -1;
    rc[i].coeff = -1.0;
    rc[i].flag = FALSE,
  }

reset_rc();  /* allocate the row coeff */

for (i = 0; i < ncols; i++)
  {
    int *col;
    col = get_col(matrix, i, nrows, ncols);

    if (has_one_elt(col, ncols))
      marked_col[i] =  i;
  }

/* at this point we have marked all the columns that have one elt */

printf("printing the marked col indices\n");
for (i = 0; i < ncols; i++)
printf("%d ", marked_col[i]);
printf("\n");

/* scan the rows */
do_scanning(matrix, nrows, ncols);
/*  scan_row(matrix, nrows, ncols); */
```

```
  exit(0);
}

int read_input(fp, m, r, c)
FILE *fp;
int **m;
int r, c;
{

  int i, j;

  for (i = 0; i < r, i++)
    for (j = 0; j <c; j++)
      fscanf(fp, " %d", &m[i][j]),

  return(0); /* not used */

}

print_mat(m, r, c)
int **m;
int r, c;
{
  int i, j;

  for (i = 0; i < r; i++)
    {
      for (j = 0; j < c; j++)
        printf("%d ", m[i][j]);

      printf("\n");
    } /* endfor (i = 0; ... */
}


/* get_col: get the column corresponding to the index */
int*   get_col(m, col_index, nrows, ncols)
int **m;
int col_index, nrows, ncols;
{
  int i;
  int *p;

  p = (int *)malloc(sizeof(int) * ncols);
```

```
  for (i = 0, i < nrows; i++)
    p[i] = m[i][col_index];

/*printf("Column:");
for (i = 0; i < ncols; i++)
  printf("%d ", p[i]);
printf("\n");
*/
  return(p);

}

/* has_one_elt: return TRUE if the column has only one element */
int    has_one_elt(p, ncols)
int *p,
int ncols;
{
  int i;
  int n_nonzero = 0;

  for (i = 0; i < ncols; i++)
    if (p[i])
      n_nonzero++;

  if (n_nonzero > 1)
    return(FALSE);

  return(TRUE);
}


/* scan_row: scan each pair to get the coeff for each pair */
int      scan_row(mat, r, c)
int **mat;
int r, c;
{
  int i, j;
  float min = 10000.00;
  int  min_row1, min_row2;
  float   sd  = -1.0; /* standard deviation */
  float   variance = -1.0;
  float   mean = -1.0, sum = 0.0;
  int     n_terms = 0,
  int     k = 0;
```

```
for (i = 0; i < r; i++)
  for (j = i+1; j < r, j++)
    {
      float n, m, coeff,


      n = (float)get_equal_entry_no(mat, i, j, c),
         /* # of entries in row i and  j that has a 1 */
      m = (float)get_unequal_entry_no(mat, i, j, c);

      if (n == 0.0)
        continue;

      /* no of entries in i & j that differ(ie)only one has a 1*/
      coeff = n/m,

      coeff_val[k++] = coeff;  /* store it for std devn */

      if (coeff <= min)
        {
          min = coeff;
          min_row1 = i;
          min_row2 = j;
        }

      /* to get mean and sd */
      sum = sum + coeff;
      n_terms++;

      printf("%d %d coeff  %f\n", i, j, coeff);
      rc[rc_index] row1 = min_row1,
      rc[rc_index].row2 = min_row2;
      rc[rc_index].coeff = coeff;
    }  /* endfor */

printf("Minimum: %f <%d %d>\n", min, min_row1, min_row2),

printf("Mean:  %f\n", (float)sum/(float)n_terms);
mean = (float)sum/(float)n_terms;

variance = get_variance(mean, n_terms),

sd = sqrt(variance);
```

```
  printf("Variance = %f\n", variance);
  printf("Std deviation = %f\n", sd);

  if (query_user(sd) == 'Y')
    return(1);
  else if (mark_approp_col(mat, min_row1, min_row2, c))
    /* all columns under a group are about to be marked */
    {

    }

  return(0);

}  /* scan_row  end */


int query_user(sd)
float sd;
{
  char buf[80];
  int i = 0,
  printf("\nStandard Deviation is: %f\n", sd);
  printf("Is this OK (Y/N)?\n");

  gets(buf);

  while (buf[i] && isspace(buf[i])) i++; /* skip white space */

  if (buf[i] == 'y' || buf[i] == 'Y')
    return('Y');
  else
    return('N');

}
/* get_variance: get the std deviation */
float       get_variance(avg, nterm)
float avg;
int nterm;
{

  float sum = 0.0;
  float diff = 0.0;
  int i = 0;
```

```
printf("nterm : %d mean  %f\n", nterm, avg),
  for (; i < nterm, i++)
    {
      diff = coeff_val[i] - avg,
      sum = sum + diff * diff;
    }


  return((float)sum/(float)(nterm-1)),

} /* get_variance  end */

int  get_equal_entry_no(m, row1, row2, ncol)
int **m;
int row1, row2, ncol;
{
  int *p = m[row1], *q = m[row2],
  int count = 0;
  int i,

  for (i = 0; i < ncol, i++)
    {
      if (marked_col[i] >= 0)
         continue;       /* ignore the marked columns */
      if (marked_col2[i] >= 0)
         continue;

      if ((p[i] == q[i]) && p[i])
         count++;
    }

/*printf("DEBUG >> # of equal entries: %d\n", count); */
  return(count);
}  /* get_equal_entry_no  end */


int  get_unequal_entry_no(m, row1, row2, ncol)
int **m;
int row1, row2, ncol;
{
  int *p = m[row1], *q = m[row2],
  int count = 0;
  int i;
```

```
  for (i = 0, i < ncol; i++)
    {
      if (marked_col[i] >= 0)
        continue;         /* ignore the marked columns */
      if (marked_col2[i] >= 0)
        continue;
      if (p[i] || q[i])
        count++;
    }  /* endfor */

/*printf("DEBUG >> # of unequal entries: %d\n", count);*/
  return(count);
}


/* reset_rc: reset thae array of coeeff */
int reset_rc()
{
  int i = 0,

  for (, i < MAXROW; i++)
    {
      rc[i].row1 = rc[i].row2 = -1;
      rc[i].coeff = -1.0,
    }
  return(0);
}


/* mark_approp_col. mark the column in which both elts are 1 in the
two rows passed */
int    mark_approp_col(m, r1, r2, ncol)
int **m;
int r1, r2;
int ncol;
{
  int i, first = 1;
  int *p = m[r1], *q = m[r2],
  int n,
  for (i = 0; i < ncol, i++)
    {
      if (marked_col[i] >= 0)
        {
          marked_col2[i] = marked_col[i];
```

```
            continue;
          }
        else if (marked_col2[i] >= 0)
          continue;
        else if (p[i] && q[i])
          {
            if (first)
              {
                if (!allcol_undergrp_marked(i))
                  marked_col2[i] = i;
                else
                  {
                    printf("All columns in group containing %d are ", i);
                    printf("about to be marked (not marked so)\n"),
                    printf("Trying to mark a new column...\n");
                    if ((n = mark_new_col(r1, r2, i, m)) < 0)
                      /* no more col markable*/
                      {
                        printf("Cannot mark any more columns in rows  "),
                        printf("%d %d\n", r1, r2),
                        exit(0);
                      }
                    else
                      {
                        printf("from marke_new_col  n = %d\n", n),
                        marked_col2[n] = n;
                      }
                    /*return(1);*/  /* code to indicate above condition */
                  }
                /*break; 29 Nov 92 */
                first=0;
              }
          }
      }
    printf("printing the marked col2 indices\n");
    for (i = 0; i < ncol; i++)
      printf("%d ", marked_col2[i]);
    printf("\n");

    return(0);

} /* mark_approp_col  end */
```

```
/* all_marked  true if all columns are marked (i e.) all entries
in marked_col2 are +ve */
int  all_marked(ncol)
int ncol,
{
  int i = 0,

  for (; i < ncol; i++)
    if (marked_col2[i] < 0)
      return(0),

  return(1);
}

/* do_scanning: keep on getting coeff and check it until we reach end or
all columns marked */
int        do_scanning(mat, nr, nc)
int **mat, nr, nc,
{

  for (;,)
    {
      if (scan_row(mat, nr, nc))
         break,
      if (all_marked(nc))
         {
           printf("All columns deleted\n");
           return(0),
         }
    }
}  /* do_scanning  end */


/* allcol_undergrp_markrd(col)  get the group to which col belongs and check if
every column in this group except (col) is in marked_col2; if so return TRUE
else return FALSE */
int      allcol_undergrp_marked(col)
int col;
{
  int    i,j, ngrp = -1,

  /* get the group */
  for (i = 0, i < g_ngroup; i++)
    {
```

```
    for (j = 0; col_group[i][j] >= 0; j++)
      {
        if (col_group[i][j] == col)
          {
            ngrp = i;
            continue;
          }
        else if (!is_marked(col_group[i][j]))
          break;  /* at least one more col not marked */
      }
    if (ngrp == -1) /* group not yet found */
      continue;
    if (col_group[i][j] < 0)
      return(TRUE);
    else
      return(FALSE),
   }

  return(FALSE),
}  /* allcol_undergrp_marked  end */


/* is_marked(col): true if col is in marked_col2 */
int        is_marked(col)
int   col;
{
  int i = 0;
  for (, i < g_ncol; i++)
    if (col == marked_col2[i])
      return(TRUE);

  return(FALSE);
}


/* get_new_min(r1, r2, min): find the r1, r2 and coeff entry in rc
   (after skipping all those that have flag set). Set that
entries flag (can no longer be used). Return the new minimum value */
int       get_new_min(r1, r2, min)
int  r1, r2;
float  min;
{
  float   small = 100.00;
  int i ;
```

```
  for ( i = 0; i < rc_index, i++)
    {
      if (rc[i].flag)
        continue;
      if (rc[i].row1 == r1 && rc[i] row2 == r2 &&
          rc[i] coeff == min)
        ;
    }
} /* get_new_min  end ; not used */


/* mark_new_col(r1,r2, col) - col is the last left over col of a group;
hence try to find a new column under r1 and r2. If not return -1 */
int     mark_new_col(r1, r2, col, m)
int   r1, r2, col;
int **m,
{
  int     i;
  int     *p = m[r1], *q = m[r2];
  for (i = 0; i < g_ncol; i++)
    {
      if (marked_col2[i] >= 0)
        continue; /* skip; already marked */
      if (p[i] && q[i])
        {
          if (i == col)
            continue,
        }
      else  if (allcol_undergrp_marked(i))
        continue,
      else
        return(i);
    }

  return(-1);
}  /* mark_new_col  end */
```

Appendix C

A sample trace file from Witness

ROBOT output to T00
0.00 : A(s) arriving
A output to ENTER
0.00 : Vehicle ROBOT, currently DEMANDED, reaching end of track
A input to T00 from ENTER
0.00 : Vehicle has completed loading period on track T00
ROBOT output from T00 to T01
0.10 : Vehicle ROBOT, currently LOADED, moving along track
0.20 : Vehicle ROBOT, currently LOADED, moving along track
0.30 : Vehicle ROBOT, currently LOADED, moving along track
0.40 : Vehicle ROBOT, currently LOADED, moving along track
0.50 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T01 to T11
0.50 : Vehicle ROBOT, currently LOADED, reaching end of track
0.50 : Vehicle has completed unloading period on track T11
A output from T11 to MC2
ROBOT output from T11 to T10
0.58 · Vehicle ROBOT, currently DEMANDED, moving along track
0.66 : Vehicle ROBOT, currently DEMANDED, moving along track
0.74 : Vehicle ROBOT, currently DEMANDED, moving along track
0.82 : Vehicle ROBOT, currently DEMANDED, moving along track
0.90 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T10 to T00
0.90 : Vehicle ROBOT, currently DEMANDED, reaching end of track
1.00 : B(s) arriving
B output to ENTER
B input to T00 from ENTER
1.00 : Vehicle has completed loading period on track T00
ROBOT output from T00 to T01
1.10 : Vehicle ROBOT, currently LOADED, moving along track
1.20 : Vehicle ROBOT, currently LOADED, moving along track
1.30 : Vehicle ROBOT, currently LOADED, moving along track
1.40 : Vehicle ROBOT, currently LOADED, moving along track
1.50 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T01 to T11
1.50 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T11 to T12
1.55 : Vehicle ROBOT, currently LOADED, moving along track
1.60 : Vehicle ROBOT, currently LOADED, moving along track
1.65 : Vehicle ROBOT, currently LOADED, moving along track

1.70 . Vehicle ROBOT, currently LOADED, moving along track
1 75 . Vehicle ROBOT, currently LOADED, moving along track
1.80 : Vehicle ROBOT, currently LOADED, moving along track
1 85 : Vehicle ROBOT, currently LOADED, moving along track
1.90 · Vehicle ROBOT, currently LOADED, moving along track
1.95 . Vehicle ROBOT, currently LOADED, moving along track
2 00 : C(s) arriving
C output to ENTER
2.00 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T12 to T22
2 05 Vehicle ROBOT, currently LOADED, reaching end of track
2 05 . Vehicle has completed unloading period on track T22
B output from T22 to MC1
ROBOT output from T22 to T21
2 09 Vehicle ROBOT, currently DEMANDED, moving along track
2 13 Vehicle ROBOT, currently DEMANDED, moving along track
2.17 Vehicle ROBOT, currently DEMANDED, moving along track
2 21 . Vehicle ROBOT, currently DEMANDED, moving along track
2 25 Vehicle ROBOT, currently DEMANDED, moving along track
2 29 Vehicle ROBOT, currently DEMANDED, moving along track
2 33 · Vehicle ROBOT, currently DEMANDED, moving along track
2 37 Vehicle ROBOT, currently DEMANDED, moving along track
2 41 Vehicle ROBOT, currently DEMANDED, moving along track
2.45 . Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T21 to T11
2 45 Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T11 to T10
2 53 Vehicle ROBOT, currently DEMANDED, moving along track
2 61 Vehicle ROBOT, currently DEMANDED, moving along track
2 69 . Vehicle ROBOT, currently DEMANDED, moving along track
2 77 Vehicle ROBOT, currently DEMANDED, moving along track
2 85 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T10 to T00
2 85 Vehicle ROBOT, currently DEMANDED, reaching end of track
C input to T00 from ENTER
2 85 . Vehicle has completed loading period on track T00
ROBOT output from T00 to T01
2 95 Vehicle ROBOT, currently LOADED, moving along track
3 00 TIME UPDATED
3 05 · Vehicle ROBOT, currently LOADED, moving along track
3 15 Vehicle ROBOT, currently LOADED, moving along track
3 25 Vehicle ROBOT, currently LOADED, moving along track
3 35 Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T01 to T11

3 35 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T11 to T12
3.40 Vehicle ROBOT, currently LOADED, moving along track
3.45 . Vehicle ROBOT, currently LOADED, moving along track
3.50 : Vehicle ROBOT, currently LOADED, moving along track
3.55 : Vehicle ROBOT, currently LOADED, moving along track
3.60 : Vehicle ROBOT, currently LOADED, moving along track
3.65 : Vehicle ROBOT, currently LOADED, moving along track
3.70 : Vehicle ROBOT, currently LOADED, moving along track
3.75 : Vehicle ROBOT, currently LOADED, moving along track
3.80 : Vehicle ROBOT, currently LOADED, moving along track
3 85 Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T12 to T22
3 90 Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T22 to T23
3.93 : Vehicle ROBOT, currently LOADED, moving along track
3.97 : Vehicle ROBOT, currently LOADED, moving along track
4.00 . TIME UPDATED
4 00 . Vehicle ROBOT, currently LOADED, moving along track
4 03 : Vehicle ROBOT, currently LOADED, moving along track
4 07 : Vehicle ROBOT, currently LOADED, moving along track
4 10 . Vehicle ROBOT, currently LOADED, moving along track
4 13 · Vehicle ROBOT, currently LOADED, moving along track
4 17 : Vehicle ROBOT, currently LOADED, moving along track
4.20 : Vehicle ROBOT, currently LOADED, moving along track
4.23 . Vehicle ROBOT, currently LOADED, moving along track
4 27 : Vehicle ROBOT, currently LOADED, moving along track
4.30 · Vehicle ROBOT, currently LOADED, moving along track
4 33 : Vehicle ROBOT, currently LOADED, moving along track
4 37 · Vehicle ROBOT, currently LOADED, moving along track
4.40 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T23 to T33
4 40 : Vehicle ROBOT, currently LOADED, reaching end of track
4.40 : Vehicle has completed unloading period on track T33
C output from T33 to MC3
ROBOT output from T33 to T32
4.43 : Vehicle ROBOT, currently DEMANDED, moving along track
4.45 . Vehicle ROBOT, currently DEMANDED, moving along track
4.48 : Vehicle ROBOT, currently DEMANDED, moving along track
4.51 : Vehicle ROBOT, currently DEMANDED, moving along track
4 53 : Vehicle ROBOT, currently DEMANDED, moving along track
4 56 : Vehicle ROBOT, currently DEMANDED, moving along track
4.59 : Vehicle ROBOT, currently DEMANDED, moving along track
4.61 : Vehicle ROBOT, currently DEMANDED, moving along track

4 64 . Vehicle ROBOT, currently DEMANDED, moving along track
4 67 : Vehicle ROBOT, currently DEMANDED, moving along track
4 69 : Vehicle ROBOT, currently DEMANDED, moving along track
4 72 : Vehicle ROBOT, currently DEMANDED, moving along track
4.75 : Vehicle ROBOT, currently DEMANDED, moving along track
4 77 Vehicle ROBOT, currently DEMANDED, moving along track
4.80 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T32 to T22
4.84 . Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T22 to T21
4.88 . Vehicle ROBOT, currently DEMANDED, moving along track
4.92 : Vehicle ROBOT, currently DEMANDED, moving along track
4 96 : Vehicle ROBOT, currently DEMANDED, moving along track
5.00 : A(s) arriving
A output to ENTER
5 00 Vehicle ROBOT, currently DEMANDED, moving along track
5.04 : Vehicle ROBOT, currently DEMANDED, moving along track
5 08 Vehicle ROBOT, currently DEMANDED, moving along track
5.12 . Vehicle ROBOT, currently DEMANDED, moving along track
5 16 . Vehicle ROBOT, currently DEMANDED, moving along track
5 20 · Vehicle ROBOT, currently DEMANDED, moving along track
5 24 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T21 to T11
5.24 . Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T11 to T10
5 32 : Vehicle ROBOT, currently DEMANDED, moving along track
5 40 · Vehicle ROBOT, currently DEMANDED, moving along track
5 48 : Vehicle ROBOT, currently DEMANDED, moving along track
5 56 : Vehicle ROBOT, currently DEMANDED, moving along track
5 64 · Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T10 to T00
5 64 . Vehicle ROBOT, currently DEMANDED, reaching end of track
A input to T00 from ENTER
5.64 Vehicle has completed loading period on track T00
ROBOT output from T00 to T01
5.74 . Vehicle ROBOT, currently LOADED, moving along track
5 84 Vehicle ROBOT, currently LOADED, moving along track
5 94 : Vehicle ROBOT, currently LOADED, moving along track
6 00 : B(s) arriving
B output to ENTER
6 04 Vehicle ROBOT, currently LOADED, moving along track
6 14 · Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T01 to T11
6 14 Vehicle ROBOT, currently LOADED, reaching end of track

6.14 : Vehicle has completed unloading period on track T11
6.50 : Machine MC2 attempting to leave state BUSY
A output from T11 to MC2
A input to T11 from MC2
6.50 : Vehicle has completed loading period on track T11
ROBOT output from T11 to T12
6.55 : Vehicle ROBOT, currently LOADED, moving along track
6.60 : Vehicle ROBOT, currently LOADED, moving along track
6.65 : Vehicle ROBOT, currently LOADED, moving along track
6.70 : Vehicle ROBOT, currently LOADED, moving along track
6.75 : Vehicle ROBOT, currently LOADED, moving along track
6.80 : Vehicle ROBOT, currently LOADED, moving along track
6 85 : Vehicle ROBOT, currently LOADED, moving along track
6.90 : Vehicle ROBOT, currently LOADED, moving along track
6.95 : Vehicle ROBOT, currently LOADED, moving along track
7 00 : C(s) arriving
C output to ENTER
7.00 · Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T12 to T22
7.05 : Vehicle ROBOT, currently LOADED, reaching end of track
7.05 : Vehicle has completed unloading period on track T22
8.00 : TIME UPDATED
8.05 : Machine MC1 attempting to leave state BUSY
A output from T22 to MC1
B input to T22 from MC1
8 05 : Vehicle has completed loading period on track T22
ROBOT output from T22 to T21
8.10 : Vehicle ROBOT, currently LOADED, moving along track
8.15 : Vehicle ROBOT, currently LOADED, moving along track
8 20 : Vehicle ROBOT, currently LOADED, moving along track
8.25 : Vehicle ROBOT, currently LOADED, moving along track
8.30 : Vehicle ROBOT, currently LOADED, moving along track
8.35 : Vehicle ROBOT, currently LOADED, moving along track
8.40 : Vehicle ROBOT, currently LOADED, moving along track
8.45 : Vehicle ROBOT, currently LOADED, moving along track
8.50 : Vehicle ROBOT, currently LOADED, moving along track
8.55 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T21 to T11
8.55 : Vehicle ROBOT, currently LOADED, reaching end of track
8.55 : Vehicle has completed unloading period on track T11
9.00 : TIME UPDATED
10.00 : A(s) arriving
A output to ENTER
11.00 : B(s) arriving

B output to ENTER
12.00 : C(s) arriving
C output to ENTER
12 50 : Machine MC2 attempting to leave state BUSY
B output from T11 to MC2
A input to T11 from MC2
12.50 : Vehicle has completed loading period on track T11
ROBOT output from T11 to T12
12.55 · Vehicle ROBOT, currently LOADED, moving along track
12.60 . Vehicle ROBOT, currently LOADED, moving along track
12.65 : Vehicle ROBOT, currently LOADED, moving along track
12.70 . Vehicle ROBOT, currently LOADED, moving along track
12 75 · Vehicle ROBOT, currently LOADED, moving along track
12.80 : Vehicle ROBOT, currently LOADED, moving along track
12.85 · Vehicle ROBOT, currently LOADED, moving along track
12 90 . Vehicle ROBOT, currently LOADED, moving along track
12.95 : Vehicle ROBOT, currently LOADED, moving along track
13.00 · TIME UPDATED
13.00 Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T12 to T22
13.05 : Vehicle ROBOT, currently LOADED, reaching end of track
13 05 : Vehicle has completed unloading period on track T22
14.00 : TIME UPDATED
14.05 · Machine MC1 attempting to leave state BUSY
A output from T22 to MC1
A input to T22 from MC1
14.05 · Vehicle has completed loading period on track T22
ROBOT output from T22 to T23
14 08 : Vehicle ROBOT, currently LOADED, moving along track
14.12 : Vehicle ROBOT, currently LOADED, moving along track
14.15 · Vehicle ROBOT, currently LOADED, moving along track
14 18 · Vehicle ROBOT, currently LOADED, moving along track
14.22 Vehicle ROBOT, currently LOADED, moving along track
14.25 . Vehicle ROBOT, currently LOADED, moving along track
14.28 . Vehicle ROBOT, currently LOADED, moving along track
14.32 · Vehicle ROBOT, currently LOADED, moving along track
14 35 · Vehicle ROBOT, currently LOADED, moving along track
14 38 Vehicle ROBOT, currently LOADED, moving along track
14 42 : Vehicle ROBOT, currently LOADED, moving along track
14.45 . Vehicle ROBOT, currently LOADED, moving along track
14.48 : Vehicle ROBOT, currently LOADED, moving along track
14 52 . Vehicle ROBOT, currently LOADED, moving along track
14.55 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T23 to T33

14.55 · Vehicle ROBOT, currently LOADED, reaching end of track
14.55 : Vehicle has completed unloading period on track T33
15.00 : A(s) arriving
A output to ENTER
16.00 : B(s) arriving
B output to ENTER
16.40 : Machine MC3 attempting to leave state BUSY
A output from T33 to MC3
C input to T33 from MC3
16.40 : Vehicle has completed loading period on track T33
ROBOT output from T33 to T32
16.43 : Vehicle ROBOT, currently LOADED, moving along track
16.47 : Vehicle ROBOT, currently LOADED, moving along track
16.50 : Vehicle ROBOT, currently LOADED, moving along track
16.53 : Vehicle ROBOT, currently LOADED, moving along track
16.57 · Vehicle ROBOT, currently LOADED, moving along track
16.60 : Vehicle ROBOT, currently LOADED, moving along track
16.63 . Vehicle ROBOT, currently LOADED, moving along track
16.67 : Vehicle ROBOT, currently LOADED, moving along track
16.70 : Vehicle ROBOT, currently LOADED, moving along track
16.73 : Vehicle ROBOT, currently LOADED, moving along track
16.77 : Vehicle ROBOT, currently LOADED, moving along track
16.80 : Vehicle ROBOT, currently LOADED, moving along track
16.83 . Vehicle ROBOT, currently LOADED, moving along track
16 87 . Vehicle ROBOT, currently LOADED, moving along track
16.90 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T32 to T22
16.95 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T22 to T21
17.00 : C(s) arriving
C output to ENTER
17.00 : Vehicle ROBOT, currently LOADED, moving along track
17.05 : Vehicle ROBOT, currently LOADED, moving along track
17.10 : Vehicle ROBOT, currently LOADED, moving along track
17.15 : Vehicle ROBOT, currently LOADED, moving along track
17.20 : Vehicle ROBOT, currently LOADED, moving along track
17.25 : Vehicle ROBOT, currently LOADED, moving along track
17.30 · Vehicle ROBOT, currently LOADED, moving along track
17.35 : Vehicle ROBOT, currently LOADED, moving along track
17.40 · Vehicle ROBOT, currently LOADED, moving along track
17.45 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T21 to T11
17.45 : Vehicle ROBOT, currently LOADED, reaching end of track
17.45 : Vehicle has completed unloading period on track T11

18.00 . TIME UPDATED
18.50 : Machine MC2 attempting to leave state BUSY
C output from T11 to MC2
B input to T11 from MC2
18 50 : Vehicle has completed loading period on track T11
ROBOT output from T11 to T12
18.55 : Vehicle ROBOT, currently LOADED, moving along track
18 60 : Vehicle ROBOT, currently LOADED, moving along track
18.65 . Vehicle ROBOT, currently LOADED, moving along track
18.70 : Vehicle ROBOT, currently LOADED, moving along track
18.75 : Vehicle ROBOT, currently LOADED, moving along track
18 80 : Vehicle ROBOT, currently LOADED, moving along track
18 85 · Vehicle ROBOT, currently LOADED, moving along track
18 90 : Vehicle ROBOT, currently LOADED, moving along track
18 95 · Vehicle ROBOT, currently LOADED, moving along track
19.00 TIME UPDATED
19 00 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T12 to T22
19 05 · Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T22 to T23
19.08 Vehicle ROBOT, currently LOADED, moving along track
19 12 Vehicle ROBOT, currently LOADED, moving along track
19 15 . Vehicle ROBOT, currently LOADED, moving along track
19.18 . Vehicle ROBOT, currently LOADED, moving along track
19.22 . Vehicle ROBOT, currently LOADED, moving along track
19 25 : Vehicle ROBOT, currently LOADED, moving along track
19 28 : Vehicle ROBOT, currently LOADED, moving along track
19.32 . Vehicle ROBOT, currently LOADED, moving along track
19.35 . Vehicle ROBOT, currently LOADED, moving along track
19 38 . Vehicle ROBOT, currently LOADED, moving along track
19 40 . Machine MC3 attempting to leave state BUSY
19.42 . Vehicle ROBOT, currently LOADED, moving along track
19.45 Vehicle ROBOT, currently LOADED, moving along track
19.48 . Vehicle ROBOT, currently LOADED, moving along track
19 52 : Vehicle ROBOT, currently LOADED, moving along track
19.55 Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T23 to T33
19 55 · Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T33 to T34
19 60 · Vehicle ROBOT, currently LOADED, moving along track
19.65 Vehicle ROBOT, currently LOADED, moving along track
19.70 : Vehicle ROBOT, currently LOADED, moving along track
19 75 . Vehicle ROBOT, currently LOADED, moving along track
19 80 . Vehicle ROBOT, currently LOADED, moving along track

19.85 : Vehicle ROBOT, currently LOADED, moving along track
19.90 : Vehicle ROBOT, currently LOADED, moving along track
19.95 : Vehicle ROBOT, currently LOADED, moving along track
20.00 : A(s) arriving
A output to ENTER
20.00 : Vehicle ROBOT, currently LOADED, moving along track
20.05 : Machine MC1 attempting to leave state BUSY
20.05 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T34 to T44
20.10 : Vehicle ROBOT, currently LOADED, reaching end of track
20.10 : Vehicle has completed unloading period on track T44
B output from T44 to MC4
ROBOT output from T44 to T43
20.14 : Vehicle ROBOT, currently DEMANDED, moving along track
20.18 : Vehicle ROBOT, currently DEMANDED, moving along track
20.22 Vehicle ROBOT, currently DEMANDED, moving along track
20.26 : Vehicle ROBOT, currently DEMANDED, moving along track
20.30 . Vehicle ROBOT, currently DEMANDED, moving along track
20.34 : Vehicle ROBOT, currently DEMANDED, moving along track
20.38 : Vehicle ROBOT, currently DEMANDED, moving along track
20.42 : Vehicle ROBOT, currently DEMANDED, moving along track
20.46 : Vehicle ROBOT, currently DEMANDED, moving along track
20.50 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T43 to T33
20.50 · Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T33 to T32
20.53 . Vehicle ROBOT, currently DEMANDED, moving along track
20.55 · Vehicle ROBOT, currently DEMANDED, moving along track
20.58 : Vehicle ROBOT, currently DEMANDED, moving along track
20.61 : Vehicle ROBOT, currently DEMANDED, moving along track
20.63 : Vehicle ROBOT, currently DEMANDED, moving along track
20.66 : Vehicle ROBOT, currently DEMANDED, moving along track
20.69 . Vehicle ROBOT, currently DEMANDED, moving along track
20.71 : Vehicle ROBOT, currently DEMANDED, moving along track
20.74 : Vehicle ROBOT, currently DEMANDED, moving along track
20.77 : Vehicle ROBOT, currently DEMANDED, moving along track
20.79 : Vehicle ROBOT, currently DEMANDED, moving along track
20.82 : Vehicle ROBOT, currently DEMANDED, moving along track
20.85 : Vehicle ROBOT, currently DEMANDED, moving along track
20.87 : Vehicle ROBOT, currently DEMANDED, moving along track
20.90 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T32 to T22
20.94 : Vehicle ROBOT, currently DEMANDED, reaching end of track
A input to T22 from MC1

20.94 : Vehicle has completed loading period on track T22
ROBOT output from T22 to T23
20 97 : Vehicle ROBOT, currently LOADED, moving along track
21.00 : B(s) arriving
B output to ENTER
21 01 : Vehicle ROBOT, currently LOADED, moving along track
21 04 : Vehicle ROBOT, currently LOADED, moving along track
21.07 : Vehicle ROBOT, currently LOADED, moving along track
21 11 : Vehicle ROBOT, currently LOADED, moving along track
21 14 . Vehicle ROBOT, currently LOADED, moving along track
21.17 : Vehicle ROBOT, currently LOADED, moving along track
21.21 : Vehicle ROBOT, currently LOADED, moving along track
21 24 : Vehicle ROBOT, currently LOADED, moving along track
21.27 Vehicle ROBOT, currently LOADED, moving along track
21 31 · Vehicle ROBOT, currently LOADED, moving along track
21.34 Vehicle ROBOT, currently LOADED, moving along track
21.37 Vehicle ROBOT, currently LOADED, moving along track
21 41 Vehicle ROBOT, currently LOADED, moving along track
21.44 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T23 to T33
21 44 · Vehicle ROBOT, currently LOADED, reaching end of track
21 44 Vehicle has completed unloading period on track T33
A output from T33 to MC3
A input to T33 from MC3
21 44 Vehicle has completed loading period on track T33
ROBOT output from T33 to T34
21 49 . Vehicle ROBOT, currently LOADED, moving along track
21 54 · Vehicle ROBOT, currently LOADED, moving along track
21 59 . Vehicle ROBOT, currently LOADED, moving along track
21 64 Vehicle ROBOT, currently LOADED, moving along track
21 69 · Vehicle ROBOT, currently LOADED, moving along track
21 74 Vehicle ROBOT, currently LOADED, moving along track
21.79 . Vehicle ROBOT, currently LOADED, moving along track
21 84 · Vehicle ROBOT, currently LOADED, moving along track
21.89 . Vehicle ROBOT, currently LOADED, moving along track
21.94 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T34 to T44
21 99 Vehicle ROBOT, currently LOADED, reaching end of track
21.99 Vehicle has completed unloading period on track T44
22 00 · C(s) arriving
C output to ENTER
23 00 TIME UPDATED
24 00 TIME UPDATED
24 44 Machine MC3 attempting to leave state BUSY

24.50 . Machine MC2 attempting to leave state BUSY
25.00 A(s) arriving
A output to ENTER
26.00 : B(s) arriving
B output to ENTER
26 10 : Machine MC4 attempting to leave state BUSY
A output from T44 to MC4
B input to T44 from MC4
26 10 : Vehicle has completed loading period on track T44
ROBOT output from T44 to T45
26.20 : Vehicle ROBOT, currently LOADED, moving along track
26.30 . Vehicle ROBOT, currently LOADED, moving along track
26 40 : Vehicle ROBOT, currently LOADED, moving along track
26 50 · Vehicle ROBOT, currently LOADED, moving along track
26.60 : Vehicle ROBOT, currently LOADED, reaching end of track
26 60 : Vehicle has completed unloading period on track T45
B output from T45 to EXIT
ROBOT output from T45 to T54
26.68 Vehicle ROBOT, currently DEMANDED, moving along track
26.76 : Vehicle ROBOT, currently DEMANDED, moving along track
26.84 : Vehicle ROBOT, currently DEMANDED, moving along track
26 92 . Vehicle ROBOT, currently DEMANDED, moving along track
27.00 . C(s) arriving
C output to ENTER
27.00 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T54 to T44
27.04 . Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T44 to T43
27.08 . Vehicle ROBOT, currently DEMANDED, moving along track
27 12 . Vehicle ROBOT, currently DEMANDED, moving along track
27 16 : Vehicle ROBOT, currently DEMANDED, moving along track
27.20 : Vehicle ROBOT, currently DEMANDED, moving along track
27 24 . Vehicle ROBOT, currently DEMANDED, moving along track
27.28 · Vehicle ROBOT, currently DEMANDED, moving along track
27 32 · Vehicle ROBOT, currently DEMANDED, moving along track
27.36 Vehicle ROBOT, currently DEMANDED, moving along track
27 40 : Vehicle ROBOT, currently DEMANDED, moving along track
27.44 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T43 to T33
27 44 · Vehicle ROBOT, currently DEMANDED, reaching end of track
A input to T33 from MC3
27 44 . Vehicle has completed loading period on track T33
ROBOT output from T33 to T34
27.49 : Vehicle ROBOT, currently LOADED, moving along track

27.54 : Vehicle ROBOT, currently LOADED, moving along track
27.59 : Vehicle ROBOT, currently LOADED, moving along track
27.64 : Vehicle ROBOT, currently LOADED, moving along track
27.69 : Vehicle ROBOT, currently LOADED, moving along track
27.74 : Vehicle ROBOT, currently LOADED, moving along track
27.79 : Vehicle ROBOT, currently LOADED, moving along track
27.84 : Vehicle ROBOT, currently LOADED, moving along track
27.89 : Vehicle ROBOT, currently LOADED, moving along track
27.94 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T34 to T44
27.99 : Vehicle ROBOT, currently LOADED, reaching end of track
27.99 : Vehicle has completed unloading period on track T44
28.00 : TIME UPDATED
29.00 : TIME UPDATED
30.00 : A(s) arriving
A output to ENTER
31.00 : B(s) arriving
B output to ENTER
32.00 : C(s) arriving
C output to ENTER
32.10 : Machine MC4 attempting to leave state BUSY
A output from T44 to MC4
A input to T44 from MC4
32.10 : Vehicle has completed loading period on track T44
ROBOT output from T44 to T45
32.20 : Vehicle ROBOT, currently LOADED, moving along track
32.30 : Vehicle ROBOT, currently LOADED, moving along track
32.40 : Vehicle ROBOT, currently LOADED, moving along track
32.50 : Vehicle ROBOT, currently LOADED, moving along track
32.60 : Vehicle ROBOT, currently LOADED, reaching end of track
32.60 : Vehicle has completed unloading period on track T45
A output from T45 to EXIT
ROBOT output from T45 to T54
32.68 : Vehicle ROBOT, currently DEMANDED, moving along track
32.76 : Vehicle ROBOT, currently DEMANDED, moving along track
32.84 : Vehicle ROBOT, currently DEMANDED, moving along track
32.92 : Vehicle ROBOT, currently DEMANDED, moving along track
33.00 : TIME UPDATED
33.00 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T54 to T44
33.04 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T44 to T43
33.08 : Vehicle ROBOT, currently DEMANDED, moving along track
33.12 : Vehicle ROBOT, currently DEMANDED, moving along track

33.16 : Vehicle ROBOT, currently DEMANDED, moving along track
33 20 : Vehicle ROBOT, currently DEMANDED, moving along track
33.24 : Vehicle ROBOT, currently DEMANDED, moving along track
33.28 : Vehicle ROBOT, currently DEMANDED, moving along track
33.32 : Vehicle ROBOT, currently DEMANDED, moving along track
33.36 : Vehicle ROBOT, currently DEMANDED, moving along track
33.40 : Vehicle ROBOT, currently DEMANDED, moving along track
33.44 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T43 to T33
33.44 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T33 to T32
33.47 : Vehicle ROBOT, currently DEMANDED, moving along track
33.49 : Vehicle ROBOT, currently DEMANDED, moving along track
33.52 : Vehicle ROBOT, currently DEMANDED, moving along track
33.55 : Vehicle ROBOT, currently DEMANDED, moving along track
33 57 : Vehicle ROBOT, currently DEMANDED, moving along track
33.60 : Vehicle ROBOT, currently DEMANDED, moving along track
33 63 : Vehicle ROBOT, currently DEMANDED, moving along track
33 65 : Vehicle ROBOT, currently DEMANDED, moving along track
33 68 · Vehicle ROBOT, currently DEMANDED, moving along track
33 71 · Vehicle ROBOT, currently DEMANDED, moving along track
33 73 : Vehicle ROBOT, currently DEMANDED, moving along track
33.76 : Vehicle ROBOT, currently DEMANDED, moving along track
33 79 : Vehicle ROBOT, currently DEMANDED, moving along track
33 81 : Vehicle ROBOT, currently DEMANDED, moving along track
33.84 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T32 to T22
33.88 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T22 to T21
33 92 · Vehicle ROBOT, currently DEMANDED, moving along track
33.96 : Vehicle ROBOT, currently DEMANDED, moving along track
34 00 : TIME UPDATED
34.00 : Vehicle ROBOT, currently DEMANDED, moving along track
34.04 : Vehicle ROBOT, currently DEMANDED, moving along track
34.08 : Vehicle ROBOT, currently DEMANDED, moving along track
34.12 . Vehicle ROBOT, currently DEMANDED, moving along track
34.16 : Vehicle ROBOT, currently DEMANDED, moving along track
34 20 : Vehicle ROBOT, currently DEMANDED, moving along track
34.24 : Vehicle ROBOT, currently DEMANDED, moving along track
34.28 Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T21 to T11
34.28 · Vehicle ROBOT, currently DEMANDED, reaching end of track
C input to T11 from MC2
34.28 : Vehicle has completed loading period on track T11

ROBOT output from T11 to T12
34 33 : Vehicle ROBOT, currently LOADED, moving along track
34.38 · Vehicle ROBOT, currently LOADED, moving along track
34 43 . Vehicle ROBOT, currently LOADED, moving along track
34 48 · Vehicle ROBOT, currently LOADED, moving along track
34 53 : Vehicle ROBOT, currently LOADED, moving along track
34 58 Vehicle ROBOT, currently LOADED, moving along track
34 63 : Vehicle ROBOT, currently LOADED, moving along track
34.68 . Vehicle ROBOT, currently LOADED, moving along track
34.73 : Vehicle ROBOT, currently LOADED, moving along track
34.78 · Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T12 to T22
34 83 . Vehicle ROBOT, currently LOADED, reaching end of track
34 83 . Vehicle has completed unloading period on track T22
C output from T22 to MC1
ROBOT output from T22 to T21
34 87 : Vehicle ROBOT, currently DEMANDED, moving along track
34.91 : Vehicle ROBOT, currently DEMANDED, moving along track
34.95 . Vehicle ROBOT, currently DEMANDED, moving along track
34.99 Vehicle ROBOT, currently DEMANDED, moving along track
35 00 : A(s) arriving
A output to ENTER
35 03 . Vehicle ROBOT, currently DEMANDED, moving along track
35.07 . Vehicle ROBOT, currently DEMANDED, moving along track
35 11 Vehicle ROBOT, currently DEMANDED, moving along track
35.15 . Vehicle ROBOT, currently DEMANDED, moving along track
35 19 Vehicle ROBOT, currently DEMANDED, moving along track
35.23 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T21 to T11
35 23 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T11 to T10
35 31 · Vehicle ROBOT, currently DEMANDED, moving along track
35 39 : Vehicle ROBOT, currently DEMANDED, moving along track
35 47 : Vehicle ROBOT, currently DEMANDED, moving along track
35.55 · Vehicle ROBOT, currently DEMANDED, moving along track
35.63 . Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T10 to T00
35.63 . Vehicle ROBOT, currently DEMANDED, reaching end of track
B input to T00 from ENTER
35 63 : Vehicle has completed loading period on track T00
ROBOT output from T00 to T01
35.73 . Vehicle ROBOT, currently LOADED, moving along track
35.83 : Vehicle ROBOT, currently LOADED, moving along track
35 93 : Vehicle ROBOT, currently LOADED, moving along track

36.00 : B(s) arriving
B output to ENTER
36.03 : Vehicle ROBOT, currently LOADED, moving along track
36.13 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T01 to T11
36.13 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T11 to T12
36.18 : Vehicle ROBOT, currently LOADED, moving along track
36.23 : Vehicle ROBOT, currently LOADED, moving along track
36.28 : Vehicle ROBOT, currently LOADED, moving along track
36.33 : Vehicle ROBOT, currently LOADED, moving along track
36.38 : Vehicle ROBOT, currently LOADED, moving along track
36.43 : Vehicle ROBOT, currently LOADED, moving along track
36.48 : Vehicle ROBOT, currently LOADED, moving along track
36.53 : Vehicle ROBOT, currently LOADED, moving along track
36.58 : Vehicle ROBOT, currently LOADED, moving along track
36.63 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T12 to T22
36.68 : Vehicle ROBOT, currently LOADED, reaching end of track
36.68 : Vehicle has completed unloading period on track T22
37.00 : C(s) arriving
C output to ENTER
38.00 : TIME UPDATED
38.10 : Machine MC4 attempting to leave state BUSY
39.00 : TIME UPDATED
40.00 : A(s) arriving
A output to ENTER
40.83 : Machine MC1 attempting to leave state BUSY
B output from T22 to MC1
C input to T22 from MC1
40.83 : Vehicle has completed loading period on track T22
ROBOT output from T22 to T23
40.86 : Vehicle ROBOT, currently LOADED, moving along track
40.90 : Vehicle ROBOT, currently LOADED, moving along track
40.93 : Vehicle ROBOT, currently LOADED, moving along track
40.96 : Vehicle ROBOT, currently LOADED, moving along track
41.00 : Vehicle ROBOT, currently LOADED, moving along track
41.00 : B(s) arriving
B output to ENTER
41.03 : Vehicle ROBOT, currently LOADED, moving along track
41.06 : Vehicle ROBOT, currently LOADED, moving along track
41.10 : Vehicle ROBOT, currently LOADED, moving along track
41.13 : Vehicle ROBOT, currently LOADED, moving along track
41.16 : Vehicle ROBOT, currently LOADED, moving along track

41.20 : Vehicle ROBOT, currently LOADED, moving along track
41.23 : Vehicle ROBOT, currently LOADED, moving along track
41.26 : Vehicle ROBOT, currently LOADED, moving along track
41.30 : Vehicle ROBOT, currently LOADED, moving along track
41.33 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T23 to T33
41.33 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T33 to T34
41.38 : Vehicle ROBOT, currently LOADED, moving along track
41.43 : Vehicle ROBOT, currently LOADED, moving along track
41.48 : Vehicle ROBOT, currently LOADED, moving along track
41.53 : Vehicle ROBOT, currently LOADED, moving along track
41.58 : Vehicle ROBOT, currently LOADED, moving along track
41.63 : Vehicle ROBOT, currently LOADED, moving along track
41.68 : Vehicle ROBOT, currently LOADED, moving along track
41.73 : Vehicle ROBOT, currently LOADED, moving along track
41.78 : Vehicle ROBOT, currently LOADED, moving along track
41.83 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T34 to T44
41.88 : Vehicle ROBOT, currently LOADED, reaching end of track
41.88 : Vehicle has completed unloading period on track T44
C output from T44 to MC4
A input to T44 from MC4
41.88 : Vehicle has completed loading period on track T44
ROBOT output from T44 to T45
41.98 : Vehicle ROBOT, currently LOADED, moving along track
42.00 : C(s) arriving
C output to ENTER
42.08 : Vehicle ROBOT, currently LOADED, moving along track
42.18 : Vehicle ROBOT, currently LOADED, moving along track
42.28 : Vehicle ROBOT, currently LOADED, moving along track
42.38 : Vehicle ROBOT, currently LOADED, reaching end of track
42.38 : Vehicle has completed unloading period on track T45
A output from T45 to EXIT
ROBOT output from T45 to T54
42.46 : Vehicle ROBOT, currently DEMANDED, moving along track
42.54 : Vehicle ROBOT, currently DEMANDED, moving along track
42.62 : Vehicle ROBOT, currently DEMANDED, moving along track
42.70 : Vehicle ROBOT, currently DEMANDED, moving along track
42.78 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T54 to T44
42.82 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T44 to T43
42.86 : Vehicle ROBOT, currently DEMANDED, moving along track

42.90 : Vehicle ROBOT, currently DEMANDED, moving along track
42.94 : Vehicle ROBOT, currently DEMANDED, moving along track
42 98 : Vehicle ROBOT, currently DEMANDED, moving along track
43.00 : TIME UPDATED
43.02 : Vehicle ROBOT, currently DEMANDED, moving along track
43.06 : Vehicle ROBOT, currently DEMANDED, moving along track
43.10 : Vehicle ROBOT, currently DEMANDED, moving along track
43.14 : Vehicle ROBOT, currently DEMANDED, moving along track
43.18 : Vehicle ROBOT, currently DEMANDED, moving along track
43.22 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T43 to T33
43.22 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T33 to T32
43.25 : Vehicle ROBOT, currently DEMANDED, moving along track
43.27 . Vehicle ROBOT, currently DEMANDED, moving along track
43 30 : Vehicle ROBOT, currently DEMANDED, moving along track
43.33 . Vehicle ROBOT, currently DEMANDED, moving along track
43.35 . Vehicle ROBOT, currently DEMANDED, moving along track
43 38 : Vehicle ROBOT, currently DEMANDED, moving along track
43.41 : Vehicle ROBOT, currently DEMANDED, moving along track
43 43 · Vehicle ROBOT, currently DEMANDED, moving along track
43 46 . Vehicle ROBOT, currently DEMANDED, moving along track
43 49 : Vehicle ROBOT, currently DEMANDED, moving along track
43 51 : Vehicle ROBOT, currently DEMANDED, moving along track
43.54 : Vehicle ROBOT, currently DEMANDED, moving along track
43.57 : Vehicle ROBOT, currently DEMANDED, moving along track
43.59 : Vehicle ROBOT, currently DEMANDED, moving along track
43 62 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T32 to T22
43.66 . Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T22 to T21
43 70 : Vehicle ROBOT, currently DEMANDED, moving along track
43.74 : Vehicle ROBOT, currently DEMANDED, moving along track
43.78 : Vehicle ROBOT, currently DEMANDED, moving along track
43.82 · Vehicle ROBOT, currently DEMANDED, moving along track
43.86 : Vehicle ROBOT, currently DEMANDED, moving along track
43.90 : Vehicle ROBOT, currently DEMANDED, moving along track
43 94 : Vehicle ROBOT, currently DEMANDED, moving along track
43.98 : Vehicle ROBOT, currently DEMANDED, moving along track
44 00 . TIME UPDATED
44 02 : Vehicle ROBOT, currently DEMANDED, moving along track
44.06 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T21 to T11
44.06 : Vehicle ROBOT, currently DEMANDED, reaching end of track

ROBOT output from T11 to T10
44.14 : Vehicle ROBOT, currently DEMANDED, moving along track
44.22 : Vehicle ROBOT, currently DEMANDED, moving along track
44.30 : Vehicle ROBOT, currently DEMANDED, moving along track
44.38 : Vehicle ROBOT, currently DEMANDED, moving along track
44.46 : Vehicle ROBOT, currently DEMANDED, reaching end of track
ROBOT output from T10 to T00
44.46 : Vehicle ROBOT, currently DEMANDED, reaching end of track
C input to T00 from ENTER
44.46 : Vehicle has completed loading period on track T00
ROBOT output from T00 to T01
44.56 : Vehicle ROBOT, currently LOADED, moving along track
44.66 : Vehicle ROBOT, currently LOADED, moving along track
44.76 : Vehicle ROBOT, currently LOADED, moving along track
44.86 : Vehicle ROBOT, currently LOADED, moving along track
44.96 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T01 to T11
44.96 : Vehicle ROBOT, currently LOADED, reaching end of track
ROBOT output from T11 to T12
45.00 : A(s) arriving
A output to ENTER

Appendix D

Report file from Witness

```
cell1x   Report                  Time:  607.58
===============                  =============

PART STATISTICS                          REPORTED BY TOTAL SIMULATION TIME
          Number  Number  Number   Number    Number              Av.    Av.
 Name     Entered Shipped Scrapped Assembled Rejected  W.I.P  W.I.P   Time
 ------------------------------------------------------------------------
 a             25       0        0         0        0     25  12.66 307.58
 b             25       2        0         0        0     23  11.60 281.86
 c             25       0        0         0        0     25  12.66 307.58
 d             25       0        0         0        0     25  12.66 307.57
 e             25       0        0         0        0     25  12.66 307.58

BUFFER STATISTICS                        REPORTED BY TOTAL SIMULATION TIME
               Total  Total                        Average   Av. after Delay
 Name             in    out Now in    Max   Min   Size   Time     No.   Time
 ------------------------------------------------------------------------
 ENTER           125     45     80     80     0  38.98 189.45
 EXIT             29      0     29     29     0  15.05 315.[illegible]3

MACHINE STATISTICS                       REPORTED BY TOTAL SIMULATION TIME
              Number
 Name        of Ops.  %Idle  %Cycle          %Stopped           %Waiting
 -------------------------------------------------------------------------
 mc1              35  12.93  Busy : 87.07    Blocked :  0.00  Setup    :  0.00
                                             Setup   :  0.00  Cycle    :  0.00
                                             Down    :  0.00  Repair   :  0.00
                                                              Off-Shift :  0.00
 mc2              27  73.34  Busy : 26.66    Blocked :  0.00  Setup    :  0.00
                                             Setup   :  0.00  Cycle    :  0.00
                                             Down    :  0.00  Repair   :  0.00
                                                              Off-Shift :  0.00
```

```
mc3          33  67.41  Busy : 32.59  Blocked :  0.00  Setup    :  0.00
                                      Setup   :  0.00  Cycle    :  0.00
                                      Down    :  0.00  Repair   :  0.00
                                                       Off-Shift :  0.00
mc4          23  77.29  Busy : 22.71  Blocked :  0.00  Setup    :  0.00
                                      Setup   :  0.00  Cycle    :  0.00
                                      Down    :  0.00  Repair   :  0.00
                                                       Off-Shift :  0.00
```

TRACK STATISTICS REPORTED BY TOTAL SIMULATION TIME

Name	No on	%Empty	%Busy	%Block
t12	67	94.65	5.35	0.00
t23	68	94.68	5.32	0.00
t34	77	93.89	6.11	0.00
t01	45	98.89	1.11	0.00
t45	29	99.28	0.72	0.00
T00	45	99.70	0.30	0.00
T10	44	99.13	0.87	0.00
T21	66	95.36	4.64	0.00
T32	67	95.21	4.79	0.00
T43	77	94.40	5.60	0.00
T54	29	99.43	0.57	0.00
T11	111	71.29	0.83	27.87
T22	134	87.09	0.00	12.91
T33	144	89.99	1.09	8.92
T44	106	86.98	0.80	12.22

VEHICLE STATISTICS REPORTED BY TOTAL SIMULATION TIME

Name	Distance	Loads	%Idle	%Demand	%Xfer	%Loaded	%Stop	%Block
gantry	5059.00	151	0.00	14.17	61.91	23.91	0.00	0.00
							Off-Shift :	0.00

REPORTED BY TOTAL SIMULATION TIME

VARIABLE STATISTICS

Name	Indices	<--------------- Value(s) ----------------->
cytime	No reporting	
vstop		0