THESIS REPORT

Master's Degree

Integrated Approach for Hybrid Shop Layout

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ABSTRACT

Title of Thesis: Integrated Approach for Hybrid Shop Layout

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This thesis presents a comprehensive methodology for the design of a hybrid manufacturing shop layout that comprises both manufacturing cells and individual workcenters. The proposed approach targets the minimization of the material handling effort within the shop and comprises four basic steps: (1) identification of candidate manufacturing cells, (2) evaluation and selection of the cells to be implemented, (3) determination of the intra-cell layout, and (4) determination of the shop layout.

For the first step, an existing cell formation technique has been employed and enhanced to facilitate reduction of part setup times. The resulting manufacturing cells are evaluated with respect to the expected reduction in material handling and the most significant ones are selected for implementation. The layout of each selected cell is determined to minimize the material handling between the cell resources. For this purpose a simulated annealing (SA) algorithm is employed which accounts fully for all physical cell constraints. Once the sizes and shapes of the selected cells are known, the shop layout is determined by a similar algorithm. The resulting hybrid shop consists of the selected cells and the remaining machines. The methodology has been implemented in an integrated software system and has been applied to redesign the shop of a large manufacturer of radar antennas.

Integrated Approach for Hybrid Shop Layout

by

Thomas C. Lu

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DEDICATION

To my parents

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Abbreviation	Meaning
ACPW	Average Common Part Weighting
ALDEP	Automated Layout DEsign Program
AMRF	Automated Manufacturing Research Facility
BEA	Bond Energy Algorithm
CIM	Computer Integrated Manufacturing
CORELAP	COputerized RElationship LAyout Planning
DISCON	DISpersion-CONcentration
ESG	Electronic Systems Group
FLAC	Facility Layout by Analysis of Clusters
FMS	Flexible Manufacturing Systems
GPM	Garcia Proth Method
GT	Group Technology
ICRMA	Identification, Clustering, Refinement, Merging and Allocation
ICTMM	Inter Class Traffic Minimization Method
ISR	Institute for Systems Research
JSC	Jaccard Similarity Coefficient
KBGT	Knowledge Based Group Technology
MAT	Modular Allocation Technique
MIPS	Maryland Industrial PartnerShips
MRP	Manufacturing Resource Planning
MWPS	Maximum Weight Planar Subgraph
NIST	National Institute of Standards and Technology
NP	NonPolynomial
PLANET	Plant Layout Analysis aNd Evaluation Technique

QAP	Quadratic Assignment Problem
ROC	Rank Order Clustering
SA	Simulated Annealing
SHAPE	Selection of materials Handling equipment and Area Placement Evaluation
WIP	Work-In-Process

Chapter 1

Introduction

The layout of the production shop may decisively affect the overall performance of a manufacturing company. A well designed layout results in efficient material handling; smaller move times, queue times, and setup times; lower work-in-process (WIP) inventory; effective management strategies; decreased production cycles and manufacturing costs; and improvements in quality, productivity and on-time delivery [Minis *et al.*, 1990; Vollmann *et al.*, 1992].

Cellular manufacturing is one of the most promising approaches for effective arrangement of the shop resources. In a cellular manufacturing system, each cell comprises several dissimilar machines dedicated to the manufacture of one or more part families which have similar processing characteristics. This arrangement differs drastically from a conventional functional layout (Fig. 1.1), in which machines

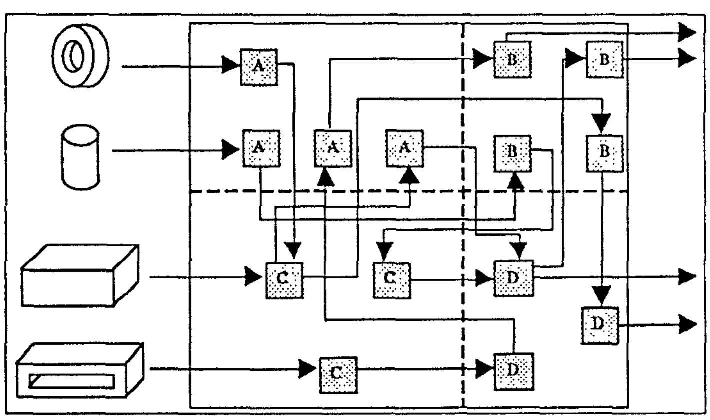

Figure 1.1: Functional arrangement of resources

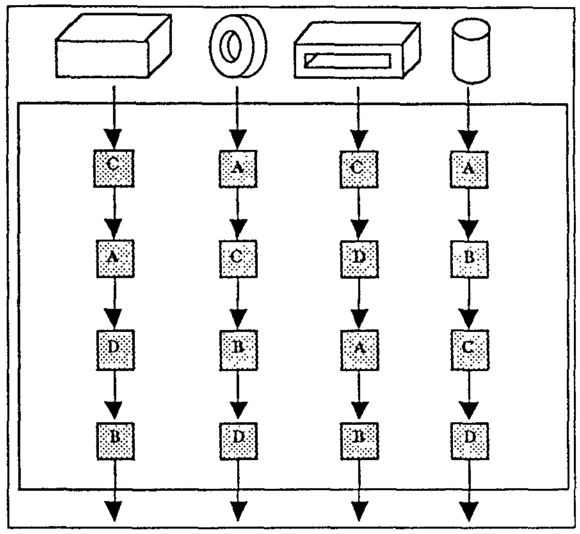

Figure 1.2: Cellular arrangement of resources

performing similar operations are grouped into departments. In this case, frequent inter-departmental part transfers are necessary, placing a severe burden on the material handling system. In addition, the complexity of both production planning and scheduling is high, since the entire set of parts and the entire set of production resources have to be considered in a single decision problem. On the other hand, the ideal cellular arrangement (Fig. 1.2) consists of nearly independent manufacturing cells, each processing one or more part families. This leads to reduced material handling and decouples the shop into small, nearly independent systems drastically reducing the dimensionality of planning and scheduling. In reality, however, the case of perfectly decoupled cells is highly unlikely. In most practical cases a hybrid arrangement (Fig. 1.3), which displays characteristics of both functional and cellular formations, is most appropriate.

Beyond the logical grouping of resources, another important aspect of plant design is the physical placement of these resources on the shop floor which defines the actual flow patterns of parts. Note that in an ideal cellular manufacturing system only the intra-cell layout, or the physical placement of machines within a cell, is important, since each cell

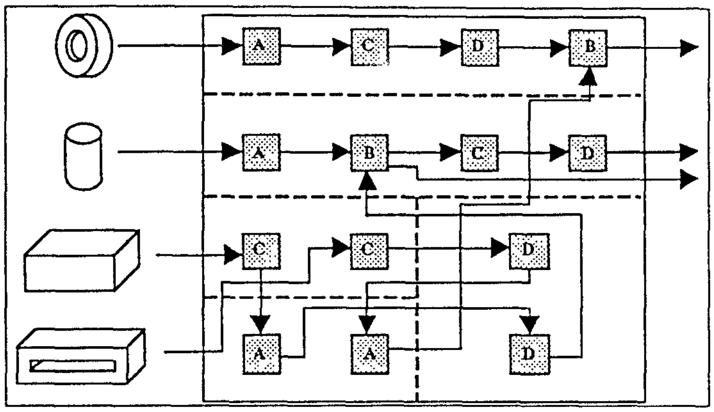

Figure 1.3: Hybrid arrangement of resources

is independent and there is no transfer of parts between cells. However, in a hybrid arrangement both the intra- and inter-cell layout, i.e. the physical placement of machines and cells within the shop floor, are important.

This thesis addresses the problem of designing a hybrid manufacturing facility in a manner that minimizes the material handling within the system. First, parts with similar setup requirements are identified. Next, the disaggregation of the shop into cells is performed such that the traffic of parts between cells is minimized. The cell formation process comprises (1) assignment of parts to setup families, each to be processed by a single cell and (2) logical grouping of machines into cells. Among the proposed cells, only those which lead to significant material handling savings are selected for implementation. The layout of these cells is developed in a manner that minimizes intra-cell material handling. Subsequently, the shop layout is determined targeting an equivalent criterion with respect to inter-cell material handling. Note that throughout the proposed methodology a consistent objective is sought, i.e. minimization of the material handling effort.

Several new issues are addressed in this thesis. (1) In the cell formation procedure a new constraint is introduced to ensure that parts with similarities in setups are assigned to the same cell. This addresses the critical practical need of reducing part setup times. (2) An evaluation scheme is proposed to quantify the material handling savings corresponding to each cell. Thus, only cells with practical significance are selected for implementation. (3) The physical placement of resources within each cell is determined considering the actual machine dimensions. In addition, input and output locations of each cell are determined. (4) A novel layout methodology is developed to design a hybrid shop that comprises a mixture of cells and machines. This layout approach addresses the majority of practical cases, in which a pure cellular arrangement is not feasible.

The thesis is structured as follows. The benefits of cellular manufacturing are discussed in Chapter 2, followed by a detailed survey of the available methods for both the cell formation and layout problems. Chapter 3 presents the formulation and solution of the cell formation problem and proposes a method to evaluate the resulting cells and identify setup part families. Chapter 4 addresses the physical location of the machines within cells and of the cells and machines on the shop floor. Chapter 5 applies the proposed methodology to redesign the shop of a large, discrete parts manufacturer. Finally, Chapter 6 discusses the conclusions of this study and the recommendations for further work.

Chapter 2

Background

A large body of literature focuses on the areas of cell formation and facility layout. Recent literature surveys have examined the most significant methods in these areas and their strengths and weaknesses. This chapter builds upon two such surveys authored by Jajodia [1990] and Ioannou [1993] of the Computer Integrated Manufacturing (CIM) laboratory of the University of Maryland at College Park.

2.1 Cellular Manufacturing

The design of a discrete parts manufacturing shop can be classified into one of two basic types: (1) functional, in which each group of functionally similar machines occupies a dedicated area of the shop floor, or (2) cellular, in which resources are disaggregated into manufacturing cells, each dedicated to the manufacture of one or more part families. Various definitions have been proposed for the concept of cellular manufacturing. Two such definitions are given by Bedworth *et al.*[1] [1991] and Martin[2] [1989].

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1 [Cellular manufacturing is] *the organization of manufacturing machines and people into groups responsible for producing a family of parts.*

2 [A manufacturing cell comprises] *one or more machine tools linked together by common material handling and under the control of a centralized cell controller for the purpose of producing the given requirements of a family of parts.*

Jim Simon, Vice-President of Engineering,
Giddings & Lewis, Fond du Lac, WI.

Manufacturing cells can be further classified into one of two sub-types: (1) a physical cell, in which the resources of the cell are adjacent and located in a dedicated area of the shop floor, or (2) a virtual cell, in which resources are distributed throughout the shop but are dedicated to the manufacture of certain part families.

Some important benefits of cellular manufacturing are listed below [Ham *et al.*, 1985; Bedworth *et al.*, 1991]:

- Reduction in material handling. The confinement of part movement within a cell results in shorter moves and thus reduces material handling.
- Simplification of material flow. Since the operations of a certain part are confined within a cell, the erratic material flow-paths between the departments of a functional shop design are averted.
- Reduction of setup times. Since parts that belong to a part family have similar processing requirements and can be accommodated by standardized tools/fixtures, setup times are significantly reduced. The reduction in setup times also results in lower queue times.
- Simplification of scheduling and production control. Individual cells can be considered as autonomous units within the larger manufacturing facility, and therefore, the scheduling problem can be addressed locally at the cell level. Since only small subsets of the resources and the products are considered at this level, the complexity of scheduling and production control is greatly simplified.
- Improvement of quality. Reduced move, queue, and processing times corresponds to lower through-put times and smaller batch sizes. This leads to shorter feedback times for product defects and faster response towards appropriate corrective actions.
- Increased cell worker motivation. Since cell workers function as a team, jointly operating several machines, performing machine maintenance, and inspecting their

own work, their understanding of the overall manufacturing enterprise increases. This leads to higher levels of motivation and increased worker moral.

Many of these benefits have been quantified in a recent study of companies which have implemented cellular manufacturing [Wemmerlov and Hyer, 1989]. As a direct result of establishing manufacturing cells these companies reported an average of 40 percent reduction in setup times and 21 percent reduction in material handling costs. This led to a 23 percent reduction in through-put times and a 20 percent reduction in WIP inventory.

It is noted that the benefits of cellular manufacturing may be amplified in production environments in which the batch sizes are large, the variety of products is limited, and the production flows are standardized (Fig. 2.1). On the other hand, a pure cellular manufacturing layout may not be appropriate for batch production and job-shop environments, in which batch sizes become progressively smaller and the product variety increases. In this case similarities in the parts within a part family decrease and most parts have to visit one or more resources outside their cell. For these manufacturing environments a hybrid shop, consisting of manufacturing cells and individual machines, is most appropriate. Hybrid shop design requires the identification of significant manufacturing cells and the layout of the resulting mixture of machines and cells within

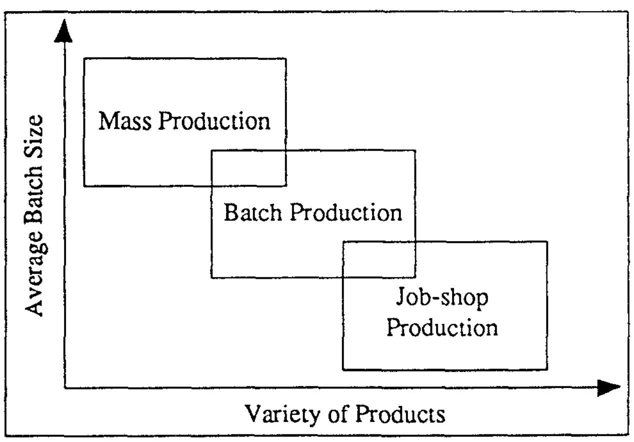

Figure 2.1: Relationship between variety of products and average batch size

the available area of the shop. A methodology that addresses these issues is presented in this thesis. It is based on previous work on cell formation and layout [Jajodia, 1990; Nagi, 1988] and extends these methodologies to address the unique requirements of hybrid facilities.

2.2 Methods for Cell Formation

Extensive research efforts have focused on the problem of aggregating machines into manufacturing cells. The methods described in the literature can be broadly classified into three basic categories: (1) clustering approaches based upon similarity measures, (2) cell and part family synthesis based on the part-machine incidence matrix, and (3) other methods which form cells based upon alternate criteria, such as inter-cell traffic and cost measures.

The clustering approaches utilize similarities between parts and machines to create part families and manufacturing cells. Each of these methods comprise at least two-stages. In the first stage, a similarity criterion is established and calculated. In the second stage, cells and part families are generated with respect to this similarity criterion. The major clustering methods reported in the literature include: (1) The Single Linkage algorithm [McAuley, 1972], which uses the Jaccard Similarity Coefficient (JSC) to define the similarity between each pair of machines in terms of the number of parts which visit both machines and the number of parts which visit each machine. (2) The Knowledge-Based Group Technology (KBGT) system of Kusiak and Wadood [1988], which forms perfect manufacturing cells. Each part family is processed exclusively by a single cell. The parts and machines which cannot be assigned to a family and a cell are assigned to a large general shop. (3) The Average Common Part Weighting (ACPW) metric of Leskowsky *et al.* [1987], which is similar to the Jaccard metric of McAuley [1972]; it defines the similarity between each pair of machines in terms of the average number of parts which visit both machines. (4) The Linear Cell Clustering Algorithm for Group Technology of Wei and Kern [1989], which formulates the cell formation as a p-medium problem and solves it using integer programming. The commonality score determined for each pair of machines is weighted and parts which visit both machines are given the highest weight. The score also considers parts which utilize neither machine and parts which utilize one of the two machines, each with lesser weight, respectively.

The second class of algorithms utilize the part-machine incidence matrix, A, in which each row, i, represents a part and each column, j, represents a machine. The elements of this matrix assume the boolean values, 1 or 0; element, $a_{ij} = 1$, if part i requires machine j during its manufacture and 0 otherwise. Parts and machines are permutated to form diagonal blocks with high densities of 1 elements. Each block corresponds to a part family and its associated manufacturing cell. The grouping approaches employing this matrix include: (1) The method of McCormick *et al.* [1972], which uses the Bond Energy Algorithm (BEA) to maximize the total bond-energy of the incidence matrix. (2) The Rank Order Clustering (ROC) method [King, 1980], which represents each row and column as binary words. Subsequently the rows and columns are ranked according to their binary value. (3) The Direct Clustering algorithm [Chan and Milner, 1982], which forms cells and part families by minimizing the number of 1 elements in the off-diagonal blocks. (4) The Garcia and Proth Method (GPM) [Garcia and Proth, 1985; 1986], which rewards the operations of a part family performed within its cell and penalizes those operations performed outside this cell.

The third class of cell formation algorithms include: (1) The cost-based heuristic of Askin and Subramanian [1987], which creates cells and part families based on WIP, intra-cell material handling, and machine setup and run costs. (2) The five-stage Identification, Clustering, Refinement, Merging and Allocation (ICRMA) heuristic of Tabucanon and

Ojha [1987], which minimizes inter-cell traffic by aggregating machines to cells in the first four stages. In the fifth stage, parts are assigned to cells, creating part families. (3) The two-stage Inter-Class Traffic Minimization Method (ICTMM) of Nagi *et al.* [1990; Harhalakis *et al.*, 1990], which also minimizes the inter-cell traffic. In the first stage, manufacturing cells are formed minimizing the total inter-cell traffic within the shop. The second stage forms part families by assigning each part to the cell containing the most machines required for its production.

The clustering approaches and the incidence matrix methods have several major drawbacks: (1) The machine workload requirements and their available capacities are not considered, and thus, machines may be overloaded, possibly creating infeasible cell formations. (2) Similarities in setups are not considered even though they may result in significant cycle-time benefits. (3) The sequence of operations in a process plan is not considered, although it is critical to material flow considerations. Recently, some clustering methodologies have been proposed [Choobineh, 1988; Tam, 1990] to account for the sequence of operations.

The third class of algorithms are more comprehensive. However, none addresses setup considerations directly. Furthermore, only a few of the methods discussed have considered the case of a shop consisting of functionally identical machines. This type of environment is quite common in a job or batch manufacturing shop, which comprises functional areas. In a cellular arrangement, the functionally identical machines have to be disaggregated into different cells. In addition, the part process plans must be altered to designate a specific member of the group of identical machines on which an operation is to be performed. It is emphasized that part assignment directly influences the material flow within the shop, and therefore, has to be considered carefully.

The approaches which address the case of functionally identical machines include Kusiak and Wadood's [1988] KBGT method, Choobineh's [1988] similarity method, and the work of Co and Araar [1988]. As mentioned above, in KBGT those machines and parts which do not belong to a perfect cell or family are assigned to a large general area. This leads to a sub-optimal solution. Choobineh's method assigns machines to part families until the processing requirements of the family are satisfied since the number of functionally identical machines assigned to each family is not limited, this method is not appropriate for facility redesign in which only a limited number of resources is available. Co and Araar [1988] load the machines of the same functionality with approximately the same work. In their procedure, however, parts with similar process plans may be assigned to different machines utilizing the functional group, creating unnecessary traffic and nullifying the benefits of cellular manufacturing. Jajodia [1990] has proposed a methodology which enhances Nagi's, ICTMM method [Nagi, 1988] to consider functionally identical machines. However, the issue of reducing setups has not been addressed.

The concept of virtual cells has been recently introduced as a generalization of manufacturing cells to overcome the limitations of physical cells. It was first proposed by McLean *et al.* [1982] as part of their work in the Automated Manufacturing Research Facility (AMRF) at the National Institute of Standards and Technology (NIST). The software developed to control this facility allowed machines of different cells to be shared in order to produce part families with common resource requirements. The system control software, supported by a flexible material handling system, allowed for a dynamic reconfiguration of resources on the shop floor. From a practical standpoint, this method requires a novel shop floor control system and the existence of an extremely flexible material handling system. Thus, its implementation is costly and its application is limited.

Hybrid manufacturing arrangements have been discussed by several authors [Ang and Willey, 1984; Flynn and Jacobs, 1987; Gupta and Tompkins, 1982; Irani *et al.*, 1993]. This type of resource arrangement combines the flexibility of a functional solution and the material handling savings of a cellular solution. Irani *et al.* [1993] proposed a procedure for designing hybrid layouts combining graph theory and a clustering approach that uses the part-machine incidence matrix. The uniqueness of this method is that graph theory was used to simultaneously solve the cell formation and layout problems. However, the method proposed by Irani *et al.* does not consider similarities in setups.

2.3 Methods for Facility Layout

Facility layout has been addressed by a rich body of literature. Most of the corresponding methods utilize the Quadratic Assignment Problem (QAP) formulation and seek to minimize the total weighted distance between resources. The weights are defined by adjacency priorities or material flow volumes [Tam, 1992]. This problem has been proven to be NP-complete by Sahni and Gonzalez [1976]. Thus, many of the methods employed are heuristics seeking to obtain near-optimal solutions and may be classified into five basic categories: (1) construction methods, (2) improvement methods, (3) hybrid methods, (4) methods based on graph theory, and (5) methods based on simulated annealing.

Construction methods assign the manufacturing resources to shop locations one at a time. They include: (1) CORELAP [Lee and Moore, 1967], which uses a closeness rating between entities. This rating may be user-specific, reflecting environmental or material flow considerations and is used to assign the resources to the shop. (2) ALDEP [Seehof and Evans, 1967], which utilizes a preference table to indicate the proximity desirability between entities. (3) PLANET [Apple and Deisenroth, 1972], which, in addition to utilizing such a table, accounts fully for the resources that have been already assigned to the shop. Other construction methods include (1) MAT [Edwards *et al.*, 1970], (2) SHAPE [Hassan *et al.*, 1986], and (3) the FMS layout algorithms of Kusiak and Heragu [1988].

The second class of facility layout methods use improvement heuristics. They begin with an initial layout, and alter it iteratively until a satisfactory configuration is obtained. Methods belonging to this class include: (1) CRAFT [Amour and Buffa, 1963; Buffa *et al.*, 1964], which utilizes the steepest descent pairwise interchange procedure. This method is by far the most well known and widely used in practice. (2) The method of Nugent *et al.* [1968], which utilizes a similar procedure to that of CRAFT that is simpler and computationally less costly. (3) The method of Hillier [1963], which uses a move desirability table to prioritize improvements. (4) Hillier and Conner's method [1966], which also utilizes the move desirability table and considers improvements along the four orthogonal directions: up, down, left, or right. (5) The Revised Hillier procedure [Picone and Wilhelm, 1984], which enhanced Hillier's method by allowing 3-way and 4-way exchanges of resources, thus extending the neighborhood over which the search is conducted. (6) The method of O'Brien and Abdel Barr [1980], which is similar to CRAFT, but has an interactive stage during which user input is used to determine the final layout. (7) The method of Golany and Rosenblatt [1989], which creates two lists; the first ranked in ascending order of the cumulative distance of each entity from all other entities; the second ranked in descending order of the material flow volume between each entity and all other entities. The entities are assigned to locations according to the order in which they appear in both lists. A pairwise interchange of entities is performed as a final refinement procedure to improve the solution.

The third class of methods are based on hybrid heuristics, which bear similarities to both the construction and improvement methods. Examples of hybrid heuristics include: (1) DISCON [Drezner, 1980], which represents each entity by a circular disk. The disks are connected through springs, the elasticity constants of which represent the relationship between the corresponding entities. Spring compression repels entities and prevents overlapping. The system of disks and springs is modeled by a set of differential equations. To determine the layout, the system is released from an initial configuration, after which some transient motion occurs and equilibrium is reached. This method was further improved by Drezner [1987]. (2) The FLAC heuristic of Scriabin and Vergin [1985], which utilizes a three-stage procedure. In the first stage entities are located on an unconstrained map minimizing distance and traffic. The second stage assigns entities to a constrained map maintaining the relationships obtained in the previous stage. A final refinement stage uses a pairwise exchange of entities similar to CRAFT.

The fourth class of layout heuristics utilize weighted graphs to represent the relationships between entities. Positive weights represent material flow volume and negative weights represent undesirable flow paths due to environmental or other incompatibilities. The goal is to position nodes with high positive weights to adjacent locations and to disperse nodes with negative weights. Graph-theory based heuristics include: (1) The methods which use a Maximum Weight Planar Subgraph (MWPS) [Carrie *et al.*, 1978; Tam, 1992] identifies maximal relationships between adjacent entities which, if the graph is planar, may be converted into a two-dimensional feasible block layout. (2) The heuristic of Geotschalckx [1992], which uses a hexagonal, maximum weight, planar adjacency graph. (3) The method of Montreuil *et al.* [1987], which uses a b-matching model for adjacency graphs. (4) The method of Montreuil and Ratliff [1989], which uses cut trees to obtain a relationship graph. The graph can then be transformed into a block layout with user intervention.

The drawbacks of the construction, improvement, and hybrid layout methods include: (1) The final solution is very sensitive to the initial conditions. (2) Most methods are greedy, leading to local optima. (3) Most methods utilize equidimensional entities, and therefore, area conflicts may result in the final layout. The graph theory-based methods share many of the same drawbacks. Area constraints are not considered, optimality is not guaranteed, and the transformation of the graph to a feasible layout is accomplished by a second stage which may lead to further sub-optimalities.

The simulated annealing (SA) methods succeed to a great extend in overcoming the sensitivity of the final solution to the initial conditions and typically converge to a near-optimal solution. This is accomplished through a procedure which allows uphill reconfigurations with certain probability. The latter decreases as the algorithm progresses. Several methods have utilized the SA methodology: (1) Jajodia [1990] represents entities by equidimensional square blocks and uses the Manhattan formula to compute the distance between entities. SA is employed to reconfigure the block assignments on the shop grid. (2) The method of Heragu and Alfa [1992] uses the modified penalty algorithm of Heragu and Kusiak [1991] to generate the initial configuration. SA is then used to improve this configuration. (3) Kouvelis *et al.* [1992] provide significantly improved solutions by restricting entities with high material flow to be adjacent. (4) The heuristic of Proth and Souilah [1992], which represents entities as rectangular blocks and considers the entrance and exit locations of machines in computing the distance between entities.

The limitations of Jajodia's method [1990] stem from the fact that equidimensional blocks are used to represent the entities and the Manhattan distance is used to determine their distance. Both these simplifications do not consider the physical constraints of the problem and may lead to infeasible or impractical solutions. The method of Proth and

Souilah [1992] accounts for these constraints and is appropriate for intra-cell design. In the case of shop hybrid design, however, the issue of reassigning parts to the most appropriate machines to further improve the solution is yet to be addressed. This issue is important, when the manufacturing system contains functionally identical machines, or the make parts have more than one alternative production routings. At each new shop configuration, the objective function may be further minimized to more appropriate machines or by using more appropriate production routings. Both the physical constraints and the part reassignment issue are fully addressed in this thesis.

2.4 Scope of Hybrid Design Methodology

An integrated design methodology for hybrid manufacturing shops has been developed. It includes four steps: (1) cell formation, (2) evaluation of cells, (3) determination of intra-cell layout, and (4) determination of inter-cell hybrid layout. In cell formation aspects that are common in practice are addressed including the distribution of functionally identical machines among cells and the preservation of setup families. The second step of the methodology retains only the cells that yield substantial reductions in material handling. The third step determines the layout of these cells to minimize a cumulative measure of traffic and distance, respecting all physical constraints. Finally, the inter-cell layout is determined in the fourth step considering the following issues:

- Dimensions of the shop
- Dimensions of manufacturing resources
- Restrictions to the shop area
- Realistic flow paths

Thus, the integrated methodology for hybrid shop design targets a consistent objective and accounts for most important practical issues. This methodology may be used for the design of planned facilities, or the redesign of existing ones.

Chapter 3

Cell Formation

This chapter discusses the cell formation stage of the proposed methodology. Although this stage is based on the grouping heuristic proposed by Jajodia [1990], two critical enhancements have been introduced: (1) the criterion of assigning parts to machines has been improved and (2) parts with similar setup requirements are assigned to the same machine. Furthermore, a new evaluation scheme is employed to identify cells that result in significant savings in material handling.

3.1 Problem Definition

The cell formation problem is considered in a manufacturing environment that includes multiple workcenters. Each workcenter consists of one or more functionally identical machines, whereby each machine is defined as a unique piece of equipment. The problem consists of forming a set of manufacturing cells, $C = \{c_1, c_2, c_3, \ldots, c_N\}$, such that the inter-cell traffic is minimized. Note that a manufacturing cell consists of dissimilar machines. Thus, functional departments of the shop as well as multi-machine workcenters are disaggregated into cells according to a criterion that targets the minimization of inter-cell material handling. Furthermore, the parts processed by a multi-machine workcenter are assigned to a specific unique machine, which is a member of a cell. This assignment is done in a manner that (1) is consistent with the objective and (2) directs parts with similar setups to the same machines. The latter consideration targets standardization of setups and reduction of setup times.

Certain additional assumptions are employed during the cell formation process:

- The environment is a discrete parts manufacturing facility.
- A unique process plan exists for each product. It specifies the sequence of workcenters required for its production.
- Workcenter capacity is assumed to be sufficient for all operations which require this workcenter. This holds for both the case of single- and multi-machine workcenters.
- Machines belonging to the same workcenter are assumed to be inter-changeable.
- Consecutive operations on the same workcenter are aggregated.
- Workcenters are assigned a moveability status according to Table (3.1).

Only type A, B, and C workcenters are considered in the cell formation stage. Type D workcenters are visited by almost every part and, thus, they cannot be grouped into any particular cell. Such an assignment would result in a large amount of inter-cell traffic. Type E workcenters are the ones not to be considered by the analysis; such workcenters belong to a different shop of the facility or identify a subcontractor. The corresponding operations are also removed from the part routings. Note that types A, B, and C are defined to differentiate workcenters during the layout stage of the problem.

Table 3.1: Moveability status of workcenters

Status	Assumption
A	Workcenter is easily moveable; moving costs are negligible
B	Workcenter is moveable if necessary; moving costs are significant
C	Workcenter is immovable; moving costs are prohibitive
D	Workcenter is not to be merged with other machines
E	Workcenter is be removed from the analysis along with the operations performed by it

The objective function of the cell formation problem is now expressed as:

Minimize:

$$T = \sum_{i=1}^{N}\sum_{j=1}^{i-1}\left(\frac{t_{ij}}{q_i + q_j}\right) \tag{3.1}$$

where T is the cumulative normalized traffic between all cells; N is the number of manufacturing cells; q_i and q_j represent the number of machines in cell c_i and c_j, respectively; and t_{ij} is the traffic between these cells in terms of the number of pallet transfers. It is provided by:

$$t_{ij} = \sum_{h=1}^{M}\left\lceil\frac{d_h}{ps_h}\right\rceil \times x_h(i,j) \tag{3.2}$$

where M is the number of part types; d_h is the demand of part type h; ps_h is the average pallet size for part type h, i.e. the average number of parts which may be moved in one pallet; and $x_h(i,j)$ is the number of times part p_h is transferred between cells c_i and c_j during its manufacture. The traffic value, t_{ij} in Eq. (3.2) is normalized by the number of machines in these cells to favor the union of smaller cells [Nagi *et al.*, 1990].

The minimization of inter-cell traffic is subject to the following constraints:

<u>Limiting Cell Size Constraint</u>

$$q_i \le Q; \; i = 1, 2, \ldots, N \tag{3.3}$$

where q_i is the number of machines in cell c_i and Q is the user-defined maximum number of machines allowed per cell. The limiting cell size depends on several factors, such as volume of work, inter-dependencies between workcenters and machines, labor skills required, and machine size [Ang and Wiley, 1984].

Machine Capacity Constraint

$$\sum_{i=1}^{M}\sum_{j=1}^{NP_i}\left[\left(SUT_i^j\left\lceil\frac{d_i}{bs_i}\right\rceil + RUT_i^j \times d_i\right)\times y(i,j,k)\right] \le \left(\frac{W_k \times NM_k}{PF_k}\right) \tag{3.4}$$

$$\forall k = 1,2,3,\ldots,Z$$

where Z is the number of workcenters, M is the number of part types, NP_i is the number of operations required for the production of part type i, SUT_i^j is the setup time of operation j of part type i, RUT_i^j is the processing time of operation j of part type i, d_i is the demand of part type i, bs_i is the average batch size of part type i, W_k is the available capacity of each machine of workcenter type k, NM_k is the number of functionally identical machines of workcenter type k, PF_k is the performance factor of machines of workcenter type k, and y(i,j,k) is defined as:

$$y(i,j,k) = \begin{cases} 1 & \text{if operation j of part type i is performed by workcenter k} \\ 0 & \text{otherwise} \end{cases} \tag{3.5}$$

Note that RUT_i^j and SUT_i^j are the standard setup and run times, provided in the production routing of part i. The performance factor, PF_k, adjusts these times based on the historical performance of workcenter k. Additionally, note that the demand, d_i, of part i is defined over a user-specified time horizon.

Setup Part Families Constraint

The parts that are processed by each workcenter k (k = 1,..., Z) are grouped into part sets, $R_1{}^k, \ldots, R_{n_k}{}^k$, as follows:

$$R_j^k = \{P_i\text{: } P_i \text{ requires setup j on workcenter k}\} \tag{3.6}$$

Thus, each part set, R_j^k, contains those parts that use a similar setup on workcenter k. All parts in R_j^k should be assigned to the same machine of workcenter k in order to take advantage of the similarity in setups.

$$\mathcal{A}(P_i \in R_j^k) = M_q^k \qquad \forall\, j = 1,\ldots, n_k,\ \forall\, k = 1,\ldots, Z \tag{3.7}$$

where $\mathcal{A}(\bullet)$ denotes the machine to which P_i is assigned and M_q^k is the q-th machine of workcenter k. The definition of the part sets for each workcenter is performed prior to the cell formation procedure and is discussed below.

3.2 Data Pre-processing

Identifying parts with similar setups and grouping them into families is critical in reducing cycle times. This can be accomplished by developing standardized fixtures or jigs to facilitate changeover between the setups of family members on the same machine. However, the family identification process is tedious and labor-intensive.

To assist this process, a simple tool was developed which consists of two steps. In the first step, two ratios, r_{1k} and r_{2k}, are computed for each workcenter k using Eqs. (3.8) and (3.9), respectively.

$$r_{1k} = \left(\frac{su_k}{su_k + ru_k} \right) \tag{3.8}$$

$$r_{2k} = \left(\frac{su_k + ru_k}{cap_k} \right) \tag{3.9}$$

where su_k is the total setup time of machine k over the user-specified time horizon, ru_k is the total run time of machine k over this horizon, and cap_k is the total available capacity of machine k over this horizon. r_{1k} provides the ratio of total setup time over the total workload for machine k, while r_{2k}, quantifies the utilization of machine k. Both values are utilized to identify bottleneck workcenters for which a high percentage of operating time is consumed by setup. For these workcenters, standardization of setups is critical.

For each critical workcenter identified above, the second step of the procedure determines the parts processed by it. These parts are ranked in descending order according to the ratio:

$$s_j = \frac{su_{j_k}}{su_{j_k} + ru_{j_k}} \tag{3.10}$$

where su_{j_k} is the total setup time of part j on workcenter k and ru_{j_k} is the total run time for an average batch size of part j on workcenter k. The parts at the top of this list consume significant capacity of the bottleneck workcenter in setup. Therefore, their process plans should be analyzed to determine whether they can be grouped into a setup part family.

It is noted that the data pre-processing presented here may be used to identify candidate workcenters and parts for setup standardization. However, the actual generation of part families remains a manual task. Algorithmic methods that may aid this process are based on part clustering techniques, such as GT coding, which are beyond the scope of this study.

3.3 Approach

An iterative heuristic procedure, which reduces the maximum normalized inter-cell traffic at each iteration, has been employed to solve the cell formation problem. The basic steps of this heuristic are similar to the ones in the Inter-Class Traffic Minimization Method

(ICTMM) proposed by Nagi [1988; Harhalakis *et al.*, 1990] and enhanced by Jajodia [1990]. However, further enhancements were necessary to address the setup part family constraint. In addition, the criterion for assigning parts to machines is different from Jajodia's method.

Inputs

The following input information is necessary for the cell formation heuristic:

- The set of workcenters (workcenter number, description, number of functionally identical machines, performance factor, moveability status, and capacity).
- The set of parts (demand, average pallet size, average batch size, and part description).
- The production routings, or process plans, of all parts. Each routing identifies the sequence of workcenters visited by the part. For each operation, the setup time per batch and the run time per part are given.
- The maximum number of machines allowed per cell.
- For each workcenter k, the sets of parts, $P_1^k,\ldots,P_{n_k}^k$, which have similar setups (see §3.2).

The principal steps of the method are summarized in the flow-chart shown in Fig. (3.1) and are described below.

Step 1

Initially one machine of each workcenter type is placed in each cell. Thus, at the beginning of the algorithm the number of cells is the same as the number of workcenters.

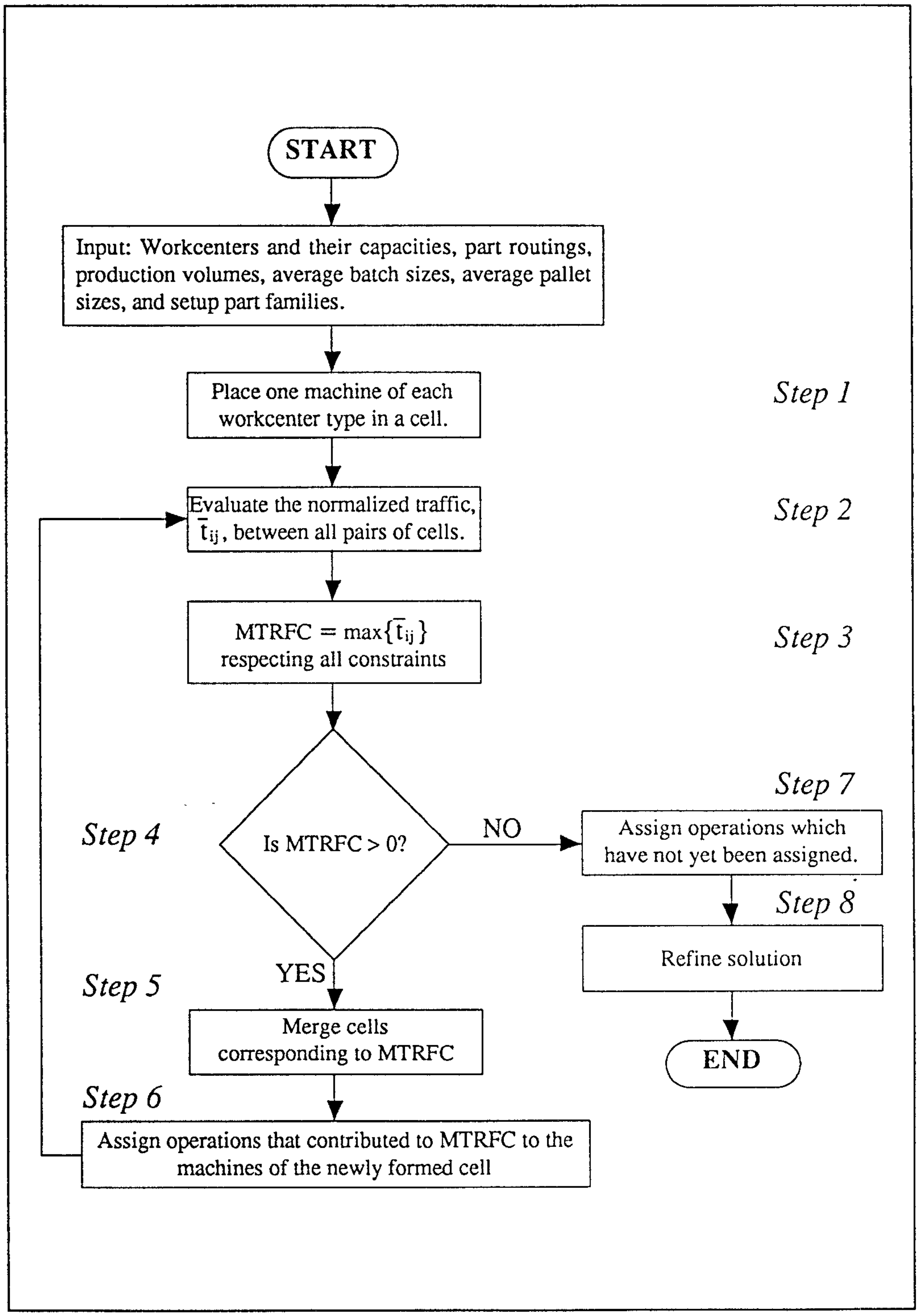

Figure 3.1: Flow-chart of the cell formation method

Step 2

The normalized inter-cell traffic, $\bar{t}_{ij}$, is calculated between all pairs of cells, c_i and c_j:

$$\bar{t}_{ij} = \frac{t_{ij}}{q_i + q_j} = \frac{\sum_{u=1}^{N_{ci}} \sum_{v=1}^{N_{cj}} t_{uv}}{q_j + q_j} \tag{3.11}$$

where q_i and q_j are the number of machines in cell c_i and c_j, respectively; t_{uv} is the traffic between a pair of machines (u, v) with $u \in c_i$ and $v \in c_j$; and N_{ci} and N_{cj} are the number of machines in cells c_i and c_j, respectively. To evaluate t_{uv} three distinct cases are considered: (1) a pair consists of two unique machines, (2) a pair consists of a unique machine and a member of a multi-machine workcenter, and (3) a pair consists of machines belonging to different multi-machine workcenters. The procedures employed to determine the value of $\bar{t}_{ij}$ for each case are outlined below.

Case I: Normalized traffic between two unique machines, M_u and M_v.
This is the simplest case, since it is not necessary to consider machine capacity or setup constraints. The traffic value, t_{uv}, is computed by Eq. (3.2).

Case II: Normalized traffic between a unique machine, M_u, and a functionally identical machine, G_v^P, of workcenter G^P.
This traffic t_{uv} is computed in a manner that respects both the capacity and the part setup constraints. To compute t_{uv}, the list of all parts that visit M_u and G^P in sequence is compiled. Parts are selected from this list and assigned to machine, G_v^P, to maximize t_{uv} while respecting the above constraints. For this purpose, the part list is ranked according to an appropriate criterion. In Jajodia [1990] the average processing time per part was employed; however, this criterion does not consider the remaining available capacity of machines, nor is it consistent with the objective of minimizing traffic. The following criterion is employed in this study:

$$f_h^{uv} = \frac{c_h^{uv}}{b_h^{uv}} \tag{3.12}$$

where c_h^{uv} is defined by Eq. (3.13) and is the traffic contributed by the movement of part h between M_u and G_v^P. The variable b_h^{uv} is defined by Eq. (3.14) and is the processing time required by this part on G_v^P.

$$c_h^{uv} = \left\lceil \frac{d_{i_h}}{ps_{i_h}} \right\rceil \times e_h^{uv} \tag{3.13}$$

where d_{i_h} is the demand of part i_h, ps_{i_h} is the average pallet size of part i_h, and e_h^{uv} is the number of times part h is transfered between M_u and G_v^P during its manufacture.

$$b_h^{uv} = \left(\left\lceil \frac{d_{i_h}}{bs_{i_h}} \right\rceil \times SUT_{i_h}^{j} + d_{i_h} \times RUT_{i_h}^{j} \right) \times PF_{G(h,j)} \tag{3.14}$$

where the variables are the same as those defined for Eq. (3.4). Note that the subscript G(h,j) designates to the workcenter required for operation j of part type h. Parts with high f_h^{uv} values contribute considerable traffic between M_u and G_v^P, while consuming a small percentage of capacity of G_v^P. If such parts are assigned to G_v^P and the two machines are merged to a single cell, then a large number of inter-cell moves will be saved. Thus, this criterion is consistent with the objective of the problem.

If the part under consideration is a member of a setup part family, the entire part family must be considered in the normalized traffic value. Eq. (3.12) is still valid in this case, but the method by which the processing time b_h^{uv} and the traffic c_h^{uv} are computed accounts for the entire setup part family . The appropriate equations are given below. Note that in this case the subscript h identifies a family of parts with similar setups on workcenter G_v^P.

$$c_h^{uv} = \sum_{i_h=1}^{U(h)} \left[\frac{d_{i_h}}{ps_{i_h}} \right] \tag{3.15}$$

$$b_h^{uv} = \sum_{i_h=1}^{U(h)} \left[\left(\left[\frac{d_{i_h}}{bs_{i_h}} \right] \times SUT_{i_h}^{j} \times SUF(h) + d_{i_h} \times RUT_{i_h}^{j} \right) \times PF_{G(i_h,j)} \right] \tag{3.16}$$

where U(h) is the number of parts in the setup part family, i_h is the i-th member of the setup part family h, and j is the operation j of part i_h. The remainder of the variables, except for SUF(h), are the same as those defined in Eq. (3.7). The variable SUF(h) ($0 < SUF(h) \leq 1$) is a reduction factor for the setup time of the part family; it reflects the savings in setup time resulting from standardization. Note that only the members of the family with the proper sequence between M_u and G^p are considered when computing the traffic, c_h^{uv}, in Eq. (3.15). However, since the entire part family must be assigned to a machine as a single unit, the cumulative processing time of all parts of the family are considered when computing b_h^{uv} from Eq. (3.16).

All parts/families in the above list are then ranked in descending order of the normalized traffic value of Eq. (3.12). Note that a setup part family cannot appear more than once in the list. However, a part may appear more than once if its process plan includes the corresponding sequence of operations more than once. The traffic between M_u and G_v^p is calculated by starting at the top of the list and considering the parts in decreasing order of f_h^{uv} until the capacity of G_v^p is exhausted. Thus, if the two members under consideration are merged into one cell in *Step 5* of the algorithm, the maximum possible traffic between the two cells will be eliminated within the existing capacity and setup family constraints. In the case that the entire production volume of the last part or setup part family cannot be processed by G_v^p due to the capacity constraint, the special procedure found in Jajodia [1990] is utilized.

Case III: The traffic between two machines, G_u^p and G_v^q, which belong to different multi-machine workcenters G^p and G^q.

In this case, t_{uv} is determined by considering a single representative from each of the two functionally identical machines and their respective capacities. The parts that contain the sequence of operations (G^p, G^q) or (G^q, G^p) are identified and assigned a traffic value as given by Eq. (3.12). The traffic, b_h^{uv}, is defined by Eq. (3.14) for parts not belonging to a setup part family and by Eq. (3.16) for members of such a family. For the processing times c_h^{uv}, Eqs. (3.13) and (3.15) are utilized, respectively. The manner in which the parts are then assigned to Gu^p and Gv^q, and the calculation of t_{uv}, is similar to the procedure of Case II discussed above.

Step 3

The pair of cells that corresponds to the maximum normalized traffic is identified. Its two members are to be merged under the conditions of *Step 5* and *Step 6.*

Step 4

If the maximum normalized traffic value is greater than zero, continue merging cells through *Steps 5* and *6* until (1) the traffic between all pairs of cells becomes zero or (2) it is impossible to further merge any cells without violating the cell size constraint. If either (1) or (2) are met, continue to *Steps 7* and *8*, which refine the solution obtained.

Step 5

The two cells are merged if the size of the newly formed cell does not violate the cell size constraint. If one of the cells contains a member of a multi-machine workcenter, then, after the two cells are merged, a new cell must be created to contain the next machine of this workcenter group (if there are any remaining).

Step 6

The routings of those parts which were used to determine the $\bar{t}_{uv}$ values in *Step 2* are modified as necessary to reflect the specific member(s) of the multi-machine workcenter group(s) that belong(s) to the newly formed cell. Thus, these parts now have unique production routings. At the end of this step, the total inter-cell traffic is reduced by the traffic value between the two cells being merged. It is emphasized that this is the maximum possible traffic that could have been reduced by merging any pair of cells at this iteration.

Step 7

Some operations which are performed on multi-machine workcenters may remain unassigned at the end of the iterative procedure. Since the assignment of these operations is a combinatorial problem, a simple heuristic is employed as follows: A list of all parts that contain such operations is created. Each part in this list includes the cell assignment of the machines corresponding to the previous and next operations in the part routing. Since the objective is to minimize the number of inter-cell moves, the list is ranked in descending order of the number of potential moves to be saved. From this list, the heuristic selects those parts which have the potential to reduce the greatest amount of inter-cell traffic and assigns them to the machines in the appropriate cells, without violating their capacity constraints.

Operations which, when assigned, reduce two inter-cell moves, would be considered initially followed by operations which reduce one inter-cell move. Lastly, the operations which yield no reductions in inter-cell moves are assigned randomly to the required functionally identical machines. This final assignment is performed considering the capacity constraints of workcenters in addition to the setup part family constraint.

Step 8

A refinement step is performed after all operations have been assigned. Since the cell formation heuristic is a greedy algorithm, i.e. once machines have been merged together into a cell they cannot be removed from this cell, a refinement operation is performed to determine if the movement of a machine from one cell to another will further reduce traffic. This is performed by selecting one machine at a time and assigning it to all other cells iteratively, respecting cell size constraints. The machine is assigned to the cell that results in the maximum reduction of inter-cell traffic.

Outputs

The following information is obtained from the application of the cell formation algorithm to a manufacturing system:

- The list of manufacturing cells identifying the machines belonging to each cell.
- One or more routings for each part which identify specific machines to be utilized during production.
- The production volume corresponding to each alternate part routing.

In addition to the above mentioned information, several performance measures, originally proposed by Nagi *et al.* [1990], are computed to estimate the effectiveness of the cell formation method. For the present work, the most relevant of these measures is the GT Efficiency, which is defined as:

$$\text{GT Efficiency} = \left(1 - \frac{T_f}{T_i}\right) \times 100\% \tag{3.17}$$

where T_i is the initial inter-resource traffic and T_f is the final inter-cell traffic. This measure reflects the percentage of savings in material handling that resulted from the cell formation.

3.4 Cell Evaluation

The cell formation methodology described in the previous section disaggregates a discrete parts manufacturing facility into manufacturing cells. Prior to implementing these cells, two evaluation tests are performed. First, the benefits resulting from the development of each cell are determined. Secondly, the robustness of the cellular arrangement with respect to changes in the product mix is assessed.

In order to evaluate the benefits of a proposed cell, the savings in inter-cell part traffic resulting from its implementation are evaluated. Note that a typical manufacturing facility is functionally arranged. The cell formation methodology creates new cells by aggregating machines from several functional areas. In order to evaluate the shop traffic without the cell under consideration, only the part transfers between functional areas and/or existing cells are considered. After including the candidate cell, this traffic is computed again, neglecting the intra-cell part transfers. The resulting two values are compared. Thus, the cells which contribute to significant reductions in inter-cell traffic can be identified and considered further for implementation. Note that this procedure is applicable only to the rearrangement of existing shops. An example of the evaluation procedure is given in the following section.

Given the most promising cells from the previous step, the robustness of the proposed cellular solution is assessed. It is noted that a change in production mix may significantly

Table 3.2: Robustness analysis of cellular arrangements

Demand	Cellular Arrangements		
	A_1	A_2	A_3
D_1	40%	25%	48%
D_2	30%	55%	44%
D_3	10%	17%	52%

affect the performance of the cellular arrangement. In order to assess the impact of such changes, a matrix, such as the one in Table (3.2), is employed.

Several demand streams, D_1, D_2, and D_3, are utilized in this analysis, each representing an appropriate time-horizon. For demand, D_i, the cellular formation, A_i, is determined by applying the cell formation heuristic. The GT Efficiency of A_i under demand D_i is the ii element of the robustness matrix. For example, in Table (3.2), the GT Efficiency of arrangement A_2, which was determined by considering demand D_2, is 55%. In addition, the GT Efficiencies of all A_i under all demands $D_j \neq D_i$ are determined. For example, the GT Efficiency of A_2 for demand D_3 is 17%.

The most robust arrangement may be directly selected by examining the entries of this matrix. For example, if robustness is a primary consideration, A_3 will be selected from Table (3.2) as the most robust arrangement. In most production facilities, effectiveness of a cellular arrangement will not change significantly unless new product lines are created or old ones are eliminated.

3.5 Example

This section illustrates the application of the cell formation method to a small example. Consider a manufacturing facility consisting of 30 part types and 16 workcenters. Workcenters #15 and #16 consist of functionally identical machines and include 5 and 2 machines, respectively. The part and workcenter data are shown in Table (3.3). Each row of this table contains specific part information along with the sequence of operations required for the part manufacture. Column 1 of the matrix provides the part number; column 2, the demand of this part over the user-specified time horizon; column 3, the average batch size; and column 4, the average pallet size. Each subsequent column represents a workcenter of the manufacturing system. Element a_{ij} is equal to the number in the operation of the routing of part i that uses workcenter j. The element a_{ij} is equal to zero (blank) if workcenter j is not used for the manufacture of part i. Table (3.5) provides the setup part families. Note that a part may belong to more than one part families (§3.2). Table (3.6) indicates the initial configuration of the functional shop. Table (3.4) indicates the production routings of each part along with the corresponding operation setup and run times. The capacity of the machines of each workcenter is set to 8.0 units over the user-specified time horizon, and the maximum number of machines allowed per cell is set to 6.

Table 3.3: Part and workcenter data for example shop

PART INFORMATION				WC 1	WC 2	WC 3	WC 4	WC 5	WC 6	WC 7	WC 8	WC 9	WC 10	WC 11	WC 12	WC 13	WC 14	WC 15	WC 16
Part Number	Part Demand	Batch Size	Pallet Size																
PT1	1	1	1		1		2							4				3	5
PT2	12	3	1	1				2										4	3
PT3	2	1	1			5			4			3					2	1	
PT4	1	1	1			4			5			1					3	2	
PT5	6	2	1	4				1			3							2	
PT6	1	1	1	1				4			2							3	
PT7	2	2	1							3					1			2	4
PT8	1	1	1		2		3							5				1	4
PT9	3	2	1	2				3			4							1	
PT10	8	4	1	5		4			2		1							3,6	
PT11	2	1	1		4		1							2					3
PT12	2	1	1							4					2			1	3
PT13	3	3	1							2					3			4	1
PT14	3	1	1										1			2			
PT15	1	1	1		3		4							1				2	5
PT16	5	4	1			1			2			5					4	3	
PT17	2	1	1										2			1			
PT18	3	3	1	4				2			3							1	
PT19	1	1	1							2								3	1
PT20	2	1	1			1						3					2	4	
PT21	1	1	1			4			3			2					1	5	
PT22	6	2	1	3				1			4							2	
PT23	1	1	1		4		2							1				3	5
PT24	2	2	1		5		2							3				4	1
PT25	1	2	1							1					3			2	4
PT26	4	2	1							2					1				3
PT27	1	3	1					1			2							3	
PT28	4	3	1							2					4			1	3
PT29	3	1	1										1			2			
PT30	1	2	1	4				3			1							2	

Table 3.4: Part routings for example shop

Part Type	Routing Sequence: $WC^{\text{setup time}}_{\text{run time}}$					
PT1	$WC2^{0.10}_{0.20}$	$WC4^{0.10}_{0.20}$	$WC15^{0.40}_{0.42}$	$WC16^{0.20}_{0.40}$		
PT2	$WC1^{0.20}_{0.15}$	$WC5^{0.30}_{0.20}$	$WC16^{0.20}_{0.10}$	$WC15^{0.20}_{0.15}$		
PT3	$WC15^{0.32}_{0.45}$	$WC14^{0.10}_{0.40}$	$WC9^{0.25}_{0.40}$	$WC6^{0.20}_{0.30}$	$WC3^{0.20}_{0.20}$	
PT4	$WC9^{0.25}_{0.20}$	$WC15^{0.40}_{0.51}$	$WC14^{0.10}_{0.20}$	$WC3^{0.10}_{0.30}$	$WC6^{0.20}_{0.10}$	
PT5	$WC5^{0.20}_{0.50}$	$WC15^{0.10}_{0.30}$	$WC8^{0.30}_{0.10}$	$WC1^{0.50}_{0.40}$		
PT6	$WC1^{0.30}_{0.20}$	$WC8^{0.10}_{0.10}$	$WC15^{0.16}_{0.25}$	$WC5^{0.60}_{0.10}$		
PT7	$WC12^{0.20}_{0.70}$	$WC15^{0.30}_{0.31}$	$WC7^{0.23}_{0.30}$	$WC16^{0.20}_{0.25}$		
PT8	$WC15^{0.60}_{0.11}$	$WC2^{0.30}_{0.90}$	$WC4^{0.34}_{0.40}$	$WC16^{0.30}_{0.30}$	$WC11^{0.50}_{0.10}$	
PT9	$WC15^{0.09}_{0.30}$	$WC1^{0.30}_{0.10}$	$WC5^{0.30}_{0.20}$	$WC8^{0.20}_{0.20}$		
PT10	$WC8^{0.20}_{0.40}$	$WC6^{0.50}_{0.20}$	$WC15^{0.09}_{0.10}$	$WC3^{0.21}_{0.10}$	$WC1^{0.30}_{0.15}$	$WC15^{0.50}_{0.10}$
PT11	$WC4^{0.20}_{0.18}$	$WC11^{0.50}_{0.20}$	$WC16^{0.10}_{0.25}$	$WC2^{0.50}_{0.30}$		
PT12	$WC15^{0.40}_{0.20}$	$WC12^{0.30}_{0.10}$	$WC16^{0.23}_{0.30}$	$WC7^{0.10}_{0.10}$		
PT13	$WC16^{0.20}_{0.20}$	$WC7^{0.20}_{0.10}$	$WC12^{0.10}_{0.10}$	$WC15^{0.50}_{0.12}$		
PT14	$WC10^{0.30}_{0.25}$	$WC13^{0.20}_{0.20}$				
PT15	$WC11^{0.20}_{0.20}$	$WC15^{0.78}_{0.25}$	$WC2^{0.30}_{0.20}$	$WC4^{0.30}_{0.20}$	$WC16^{0.18}_{0.30}$	
PT16	$WC3^{0.30}_{0.10}$	$WC6^{0.50}_{0.10}$	$WC15^{0.30}_{0.15}$	$WC14^{0.50}_{0.20}$	$WC9^{0.20}_{0.10}$	
PT17	$WC13^{0.30}_{0.20}$	$WC10^{0.20}_{0.20}$				
PT18	$WC15^{0.12}_{0.50}$	$WC5^{0.30}_{0.20}$	$WC8^{0.10}_{0.10}$	$WC1^{0.30}_{0.20}$		
PT19	$WC16^{0.10}_{0.10}$	$WC7^{0.40}_{0.10}$	$WC15^{0.20}_{0.40}$			
PT20	$WC3^{0.50}_{0.30}$	$WC14^{0.20}_{0.10}$	$WC9^{0.10}_{0.10}$	$WC15^{0.60}_{0.38}$		
PT21	$WC14^{0.20}_{0.20}$	$WC9^{0.30}_{0.20}$	$WC6^{0.20}_{0.30}$	$WC3^{1.00}_{0.20}$	$WC15^{0.80}_{0.55}$	
PT22	$WC5^{0.20}_{0.30}$	$WC15^{0.30}_{0.20}$	$WC1^{0.60}_{0.30}$	$WC8^{0.50}_{0.20}$		
PT23	$WC11^{0.10}_{0.10}$	$WC4^{0.10}_{0.05}$	$WC15^{0.62}_{0.35}$	$WC2^{0.10}_{0.20}$	$WC16^{0.40}_{0.20}$	
PT24	$WC16^{0.10}_{0.40}$	$WC4^{0.20}_{0.30}$	$WC11^{0.60}_{0.30}$	$WC15^{0.49}_{0.40}$	$WC2^{0.40}_{0.10}$	
PT25	$WC7^{0.70}_{0.30}$	$WC15^{0.10}_{0.16}$	$WC12^{0.90}_{0.30}$	$WC16^{0.20}_{0.15}$		
PT26	$WC12^{0.50}_{0.20}$	$WC7^{0.40}_{0.08}$	$WC16^{0.20}_{0.20}$			
PT27	$WC5^{0.20}_{0.30}$	$WC8^{0.60}_{0.30}$	$WC15^{0.26}_{0.10}$			
PT28	$WC15^{0.10}_{0.11}$	$WC7^{0.10}_{01.0}$	$WC16^{0.30}_{0.20}$	$WC12^{0.10}_{0.06}$		
PT29	$WC10^{0.40}_{0.20}$	$WC13^{0.60}_{0.10}$				
PT30	$WC8^{0.20}_{0.10}$	$WC15^{0.40}_{0.22}$	$WC5^{0.30}_{0.20}$	$WC1^{0.10}_{0.10}$		

Table 3.5: Setup part families for example shop

Part Family	Workcenter Required	Parts of Family (Operation of Part)
Family #1	WC15	PT1(3), PT2(4), PT3(1), PT4(2), PT5(2), PT7(2), PT8(1), PT9(1), PT10(3), PT12(1), PT13(4), PT15(2), PT16(3)
Family #2	WC15	PT25(2), PT27(3), PT28(1), PT30(2)
Family #3	WC16	PT19(1), PT23(5), PT24(1), PT25(4)
Family #4	WC16	PT1(5), PT2(3), PT7(4)
Family #5	WC16	PT8(4), PT13(1), PT15(5)

Table 3.6: Initial departmental configuration of shop

Department Number	Machines in Department							
Department #1	WC1	WC2	WC3	WC15(1)	WC15(2)	WC15(3)	WC15(4)	WC15(5)
Department #2	WC4	WC5	WC6	WC12	WC13	WC14	WC16(1)	WC16(2)
Department #3	WC8	WC9	WC10	WC11				
Department #4	WC7							

Table 3.7: Incidence matrix for example shop

PART INFORMATION																								
Part Number	Part Demand	Batch Size	Pallet Size	WC1	WC5	WC8	WC15 #1	WC3	WC6	WC2	WC15 #2	WC4	WC11	WC7	WC16 #1	WC12	WC16 #2	WC15 #4	WC9	WC14	WC15 #3	WC10	WC13	WC15 #5
PT2	12	3	1	1	2										3			4						
PT5	6	2	1	4	1	3																		2
PT6	1	1	1	1	4	2	3																	
PT9	3	2	1	2	3	4																		1
PT10	8	4	1	5		1	6	4	2															3
PT18	3	3	1	4	2	3																		1
PT21	1	1	1				5	4	3										2	1				
PT22	6	2	1	3	1	4	2																	
PT27	1	3	1		1	2	3																	
PT30	1	2	1	4	3	1	2																	
PT1	1	1	1							1	3	2	4		5									
PT8	1	1	1							2	1	3	5		4									
PT11	2	1	1							4		1	2				3							
PT15	1	1	1							3	2	4	1		5									
PT23	1	1	1							4	3	2	1		5									
PT24	2	2	1							5	4	2	3		1									
PT7	2	2	1											3	4	1		2						
PT12	2	1	1											4		2	3	1						
PT13	3	3	1											2	1	3		4						
PT19	1	1	1											2	1			3						
PT25	1	2	1				2							1	4	3								
PT26	4	2	1											2		1	3							
PT28	2	3	1				1							2	3	4								
PT28	2	3	1				1							2		4	3							
PT3	2	1	1					5	4										3	2	1			
PT4	1	1	1					4	5										1	3	2			
PT16	5	4	1					1	2										5	4	3			
PT20	2	1	1					1											3	2	4			
PT14	3	1	1																			1	2	
PT17	2	1	1																			2	1	
PT19	3	1	1																			1	2	

The results of the cell formation method are shown in Tables (3.7) and (3.8). Table (3.7) is the part-machine incidence matrix which was obtained from the cell formation process. Notice that the functionally identical machines are assigned to different manufacturing cells. From this table it can be observed that the total number of parts is now 31, since the production volume of part PT28 has been assigned to two different routings due to capacity constraints. Table (3.8) displays cell statistics and the machines which comprise each cell. Figure (3.3) is an explanation of the statistical information provided in the table and is used to help the user decide which cells are the potentially significant ones.

Table 3.8: Manufacturing cells

```
Number of Routings:          31
Number of Workcenters:       16
Limiting Cell Size:           6
Global Efficiency:        80.95%
Group Efficiency:         80.00%
G.T. Efficiency:          71.97%

Cell # 1:(10:32.26%)
     1 A  1    8  80.00%    14.40 WC1             WORKCENTER_1
     2 A  1    8  80.00%    13.40 WC5             WORKCENTER_5
     3 A  1    8  80.00%    10.60 WC8             WORKCENTER_8
     4 A  5    6  60.00%     7.54 WC15(1)         WORKCENTER_15
     5 A  1    2  20.00%     6.32 WC3             WORKCENTER_3
     6 A  1    2  20.00%     5.90 WC6             WORKCENTER_6
Cell # 2:(6:19.35%)
     1 A  1    6 100.00%     4.50 WC2             WORKCENTER_2
     2 A  5    5  83.33%     4.82 WC15(2)         WORKCENTER_15
     3 A  1    6 100.00%     3.25 WC4             WORKCENTER_4
     4 A  1    6 100.00%     4.10 WC11            WORKCENTER_11
Cell # 3:(8:25.81%)
     1 A  1    8 100.00%     4.95 WC7             WORKCENTER_7
     2 A  2    5  62.50%     7.93 WC16(1)         WORKCENTER_16
     3 A  1    7  87.50%     6.24 WC12            WORKCENTER_12
     4 A  2    3  37.50%     3.66 WC16(2)         WORKCENTER_16
     5 A  5    4  50.00%     6.18 WC15(4)         WORKCENTER_15
Cell # 4:(4:12.90%)
     1 A  1    4 100.00%     3.55 WC9             WORKCENTER_9
     2 A  1    4 100.00%     4.30 WC14            WORKCENTER_14
     3 A  5    4 100.00%     5.76 WC15(3)         WORKCENTER_15
Cell # 5:(3:9.68%)
     1 A  1    3 100.00%     4.25 WC10            WORKCENTER_10
     2 A  1    3 100.00%     4.30 WC13            WORKCENTER_13
Cell # 6:(0:0.00%)
     1 A  5    0     NaN%    5.78 WC15(5)         WORKCENTER_15
```

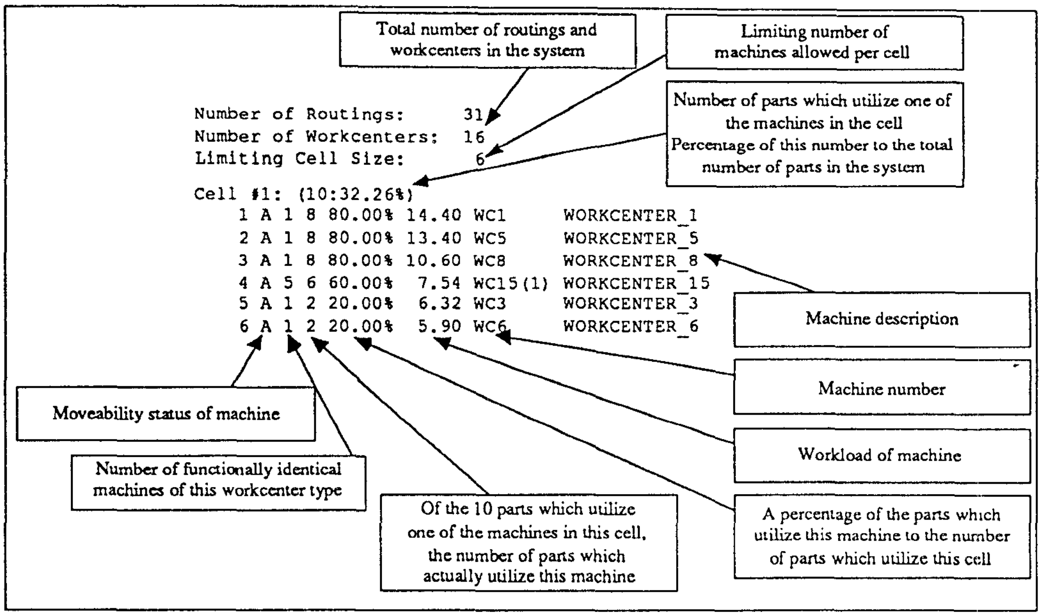

Figure 3.2: Explanation of cell statistics for Table 3.8

The G.T. Efficiency of 71.97% given in Table (3.8) represents the reduction of inter-cell traffic from a purely functional layout to a cellular one. However, this solution may be feasible only for non-existing manufacturing facilities. For pre-existing facilities, the rearrangement of the entire shop may be too costly. In this case, the tool presented in section 3.4 was used to determine the effectiveness of creating two of the suggested cells.

For the shop in Table (3.7), the number of inter-department moves and the total number of moves can be determined from the part production volumes and the process plans of Table (3.3) and (3.6), respectively. The corresponding values are:

Table 3.9: Summary of shop traffic for the initial shop arrangement

Total Number of Inter-department Moves	202	76.52%
Total Number of Intra-department Moves	62	23.48%
Total Number of Moves	264	100.00%

The following table shows that the creation of the two new cells, cell #1 and cell #3 greatly reduces the number of inter-cell moves.

Table 3.10: Summary of shop traffic for the proposed arrangement

Total Number of Inter-Cell Moves	117	44.32%
Total Number of Intra-Cell Moves	147	55.68%
Total Number of Moves	264	100.00%

Thus, after changing the existing layout to the suggested one, 85 inter-cell moves would be eliminated. This corresponds to a 42.08% reduction in inter-resource traffic. Note that the robustness analysis was not performed for this example. However an example of this analysis is given in §5.4.

Chapter 4

Hybrid Facility Layout

This chapter addresses the facility layout problem for a hybrid shop consisting of both manufacturing cells and independent machines. Two major issues are addressed: (1) intra-cell layout, i.e. the placement of the machines within a cell and (2) inter-resource layout; i.e. the placement of the manufacturing resources (cells and independent machines) in the available area of the facility. Both problems are similar and can be addressed using the same formulation. A simulated annealing (SA)-based algorithm is developed and utilized to obtain a near-optimal solution for the layout problem, which is NP-complete[1]. The general problem is defined below along with the solution approach. The latter is first applied to the intra-cell case. Subsequently, the algorithm is enhanced appropriately to address the inter-resource case.

4.1 Problem Definition

The layout problem entails the physical placement of machines within a cell, as well as the physical placement of the cells and independent machines on the shop floor. The general framework, upon which the approach for both problems is based, is shown in Fig. (4.1). A square grid is imposed on the area available for the placement of the resources.

[1] The computational time needed for the exact solution of an NP-complete problem increases exponentially with N. N is the number of nodes in the graph representation of the problem [Press *et al.*, 1990].

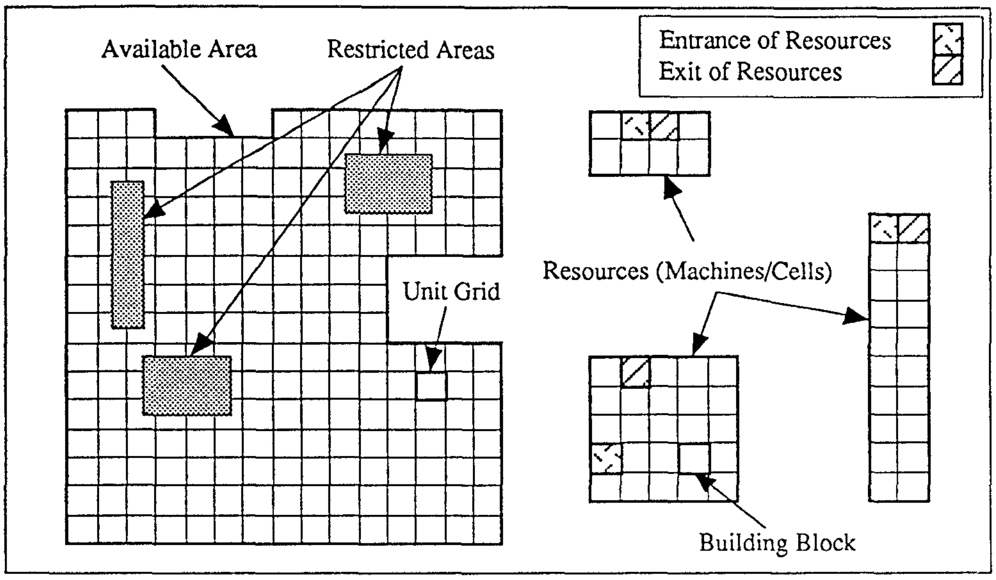

Figure 4.1: Framework of the layout problem

The latter may occupy one or more nodes of the grid depending on the resource size. Restricted areas are excluded from this grid as shown in Fig. (4.1), i.e. no nodes are assigned to these areas. The following assumptions are used:

- The available shop area is pre-defined and is adequate to fit all cells and machines.
- The resources of the production system are enclosed by rectangular work envelopes.
- Restrictions on the shop floor are enclosed by rectangular envelopes.
- Distances, d_{ij}, between resources are Euclidean and are computed form the exit of resource i to the entrance of resource j.

Given this framework, the objective of the layout problem is stated as follows:

Minimize

$$E = \sum_{i=1}^{M} \sum_{j=1}^{(i-1)} \left(t_{ij} \times d_{ij} \right) \tag{4.1}$$

where E is the total distance resulting from part transfers between resources within the specified time horizon, M is the number of resources, t_{ij} is the traffic between resources i and j expressed in the number of pallet transfers, and d_{ij} is the shortest feasible distance between resources i and j. This distance is computed from the exit of resource i to the entrance of resource j in a manner that avoids passing through resources and shop floor restrictions.

The problem is subject to the following constraints:

<u>Area Overlap Constraint</u>

This set of constraints ensures that one and only one resource block (see Fig. 4.1) is assigned to each node, Eq. (4.2), and that each resource block is assigned to a grid node, Eq. (4.3).

$$\sum_{i=1}^{M}\sum_{p=1}^{N_i} K_{pq}^{i} \leq 1 \qquad q = 1,\ldots,S \tag{4.2}$$

$$\sum_{q=1}^{S} K_{pq}^{i} = 1 \qquad i = 1,\ldots,M;\ p = 1,\ldots,N_i \tag{4.3}$$

$$K_{pq}^{i} \in \{0,1\} \tag{4.4}$$

where

$$K_{pq}^{i} = \begin{cases} 1 & \text{if block p of resource i is assigned to location q} \\ 0 & \text{otherwise} \end{cases} \tag{4.5}$$

In Eqs. (4.2) through (4.5), S is the number of nodes of the grid, M is the number of resources, and N_i is the number of building blocks required to satisfy the area requirements of i.

As previously noted, the layout problem is NP-complete, and thus a heuristic method has been developed to find a near-optimal solution in a reasonable amount of time. The method employs simulated annealing (SA) in order to avoid local optima and to provide several alternate solutions from the same initial configuration. Some background on SA and the shortest path algorithm employed to determine d_{ij} ($i,j = 1,\ldots,M$; $i \neq j$) is given below. These methods are combined in §4.3 to develop the approach for the layout problem.

4.2 Background

Simulated Annealing

Simulated annealing (SA) is a heuristic method that searches for a near-optimal solution to a combinatorial optimization problem. SA is an extension of downhill descent methods that typically converge to local optima. However, the SA solution can escape from such local optima by probablistically accepting uphill moves. The relative probability of accepting an uphill move decreases as the algorithm progresses.

SA method is analogous to the cooling and annealing process of metals. At high temperatures, metals are in a free molten state. If the metal is cooled slowly, the atoms of the metal slowly lose mobility and form an orderly, purely crystalline state, which is the state of minimum energy for the system. However, quickly cooling a metal results in a polycrystalline state of higher energy. The latter is analogous to the progression of most downhill descent methods.

Metropolis *et al.* [1953] first developed an algorithm, called the Metropolis algorithm, similar to SA. It searches for the optimum solution E^* (minimum energy) by interactively modifying the system configuration. In SA, the system will change from a configuration with energy E_1 to a configuration E_2 with the probability, p, given by Eq. (4.6).

$$p = \begin{cases} \exp\left[-(E_2 - E_1)/kT\right] & \text{if } E_2 > E_1 \\ 1 & \text{if } E_2 \leq E_1 \end{cases} \tag{4.6}$$

where k is a constant which relates temperature to energy (Boltzmann's constant) and T is the temperature of the system. If, $E_2 \leq E_1$, the change is always accepted. Otherwise, there is a non-zero probability of accepting the uphill solution. Four elements are essential to the Metropolis algorithm as described by Press *et al.* [1990].

- Description of possible system configurations.
- Generator of random changes in a system configuration.
- An objective function E (analogous to energy) the minimization of which is the goal of the procedure.
- A control parameter T (analogous to temperature) and an annealing schedule which dictates how T is decreased, i.e. after how many random configuration changes is each downward step in T taken and how large is that step. The initial value of T and the determination of the annealing schedule may require physical insight and/or trial-and-error experiments.

The Shortest Path Algorithm

For every candidate system configuration, the shortest path, d_{ij}, between all pairs of resources i and j ($\forall$i, j = 1,...,M; i $\neq$ j) is evaluated. The d_{ij} values are then used to compute the objective function of Eq. (4.1) for this configuration. Much research has already been performed on the shortest path problem, which can be formulated as follows: Given a weighted, directed graph, $G = (\mathcal{V}, \mathcal{E}, w)$, where $\mathcal{V}$ is the set of vertices (exit and entrance of resources), $\mathcal{E}$ is the set of edges (grid edges), and w is the set of weights of edges (distance between two adjacent nodes), compute the shortest path between two nodes (d_{ij}).

Dijkstra's algorithm as described by Cormen *et al.* [1992] has been utilized to solve the shortest path problem in this study. This algorithm computes the minimum distance from node *i*, the starting node, to all other nodes in the graph. Each node, *j* (j = 1,...,S; j $\neq$ i), is associated with two variables, d and π. At the end of the algorithm these variables become: (1) d equal the shortest distance from the starting node i to j and (2) π equals the shortest flow path from i to j. The latter is used to compute the actual flow path from i to j. The basic steps of Dijkstra's algorithm are given by the following pseudo-code [Cormen *et al.*, 1992] and are explained below:

```
DIJKSTRA(G,w,i)
INITIALIZE-SINGLE-SOURCE(G,i)
S = Ø
Q = V[G]
while Q ≠ Ø
    do u = EXTRACT-MIN(Q)
        S = S ∪ {u}
        for each vertex j ∈ Adj[u]
            do RELAX(u,j,w)
```

The algorithm utilizes two linked lists, S and Q. The former is initially NIL while the latter initially contains all the nodes of the solution grid. Additionally, the variable d of all nodes is set to infinity and the variable π of all nodes is NIL, except for the distance from i to itself which is 0, or $d[i] = 0$. At each iteration, a node, u, is removed from S and placed into Q. Thus, Q is the list of nodes which have been examined. This node is the one with the lowest value of d in Q and is found from the subroutine EXTRACT-MIN. EXTRACT-MIN searches all of the nodes in list Q and returns the node, u, with the lowest $d[k]$ value (k = 1,...,P; P is the number of nodes in Q). Each node, j, which is reachable from u is then relaxed in the subroutine RELAX, as follows:

$$d[j]=\begin{cases} d[j] & \text{if } d[j] < d[u]+w(u,j) \\ d[u]+w(u,j) & \text{if } d[j] > d[u]+w(u,j) \end{cases} \tag{4.7}$$

where $w(u,j)$ is the pre-defined distance from node u to node j. When Q becomes NIL, all nodes have been examined and the minimum distances, d_{ij}, from node i to all other nodes ($j \neq i$) have been determined and are stored in the variable d of each node j. The flow path of the shortest distance from the starting node, i, to each node j may be found in the variable $\pi[j]$.

4.3 Approach

The SA-based layout method minimizes the objective function of Eq. (4.1). The shortest distance, d_{ij}, between all pairs of resources is determined at each iteration of the method through repeated applications of Dijkstra's algorithm. The following input information is necessary for the layout method:

- The set of resources. For each resource the following data are provided: the size of its rectangular envelope, its moveability status, and the location of its exit and entrance. Fig. (4.2) shows the conventions used to define this information. For the example in Fig. (4.2), the location of the resource entrance is given by (3, x_2), where 3 is the side of the resource and x_2 is the distance of the entrance from the origin of side 3.
- The set of area restrictions, defined by location and rectangular size.
- The geometry of the area that is available for the placement of resources. Note that the dimensions of the shop, the resources, and the restricted areas should be given in the same units.

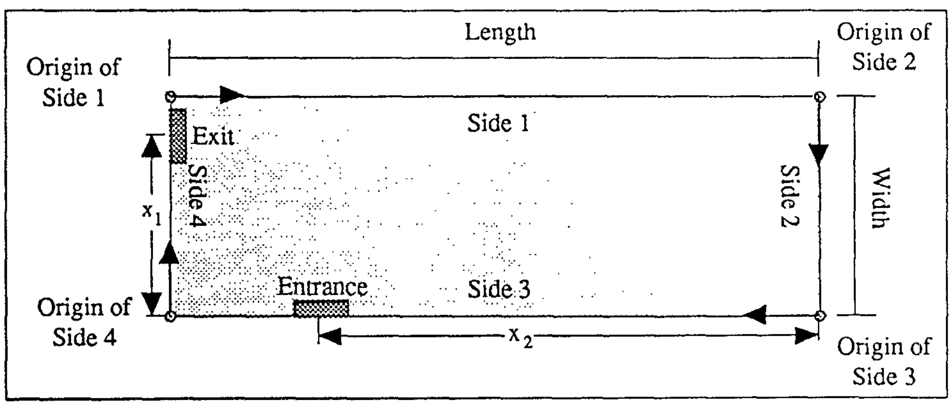

Figure 4.2: Definition of resource length, width, and location of its entrance and exit

- The input parameters required for the SA algorithm.
- The minimum width of material handling corridors.
- The set of parts (demand, average pallet size, average batch size, and part description).
- The production routings, or process plans, for all parts. Each routing identifies the sequence of machines visited by the part and includes operation number, setup time, and run time.

As mentioned above, the shop area available for the placement of resources, excluding the restrictions, is covered by a square grid. The resolution of this grid is defined such that the basic system entities, i.e., resource, material handling corridors, as well as the details of the shop area can be described adequately. It is also noted that in order to accommodate for material handling corridors between resources, both length and width of each resource are incremented by the corridor width.

In addition to the definition of a system configuration, the three remaining basic elements of the Metropolis algorithm are given below:

Generation of System Configurations

Given an initial configuration, new system configurations are generated by applying the following operations:

Swap: Exchanges two entities

Translate: Moves an entity one unit from its original position along one of four orthogonal directions: up, down, left, or right

Rotate: Rotates an entity by 0°, 90°, 180°, or 270°

A random number generator is utilized at each iteration to select the type of operation to be performed: swap, translate, or rotate. Since SA is most effective when small configuration changes are performed, the probability of choosing between these operations is not uniform. **Swap** alters the energy of the system the most, and thus, it has the lowest probability of being selected (0.2). The other two remaining operations, **translate** and **rotate** have a smaller impact on the system's "energy", and thus are selected with probability of 0.4 each.

Objective Function, E (Analogous to Energy)

The objective function to be minimized has been defined by Eq. (4.1).

Control Parameter, T (Analogous to Temperature)

The control parameter, T, is specified by the user. A high value of T will result in an initial random search of the configuration space, followed by a more systematic search as T assumes lower values. A good initial value for T is given by the maximum possible change in the objective function [Aarts and van Laarhoven, 1989]. This will result in initially accepting some random changes; soon however, solutions of lower energy will be primarily accepted. The change of temperature is dictated by the annealing schedule, which is also specified by the user. This is a constant by which the temperature is reduced at each temperature iteration. Since the temperature reduces exponentially with the annealing schedule, its value drops quickly. An annealing schedule value of 0.9 allows for moderate changes in the objective function under which SA works best [Aarts and van Laarhoven, 1989]. The Metropolis criterion is selected to govern the acceptance or rejection of configuration changes as described in §4.2.

The major steps of the SA-based method are summarized in the flow-chart shown in Fig. (4.3) and are described below.

Step 1

Place all entities upon the solution grid of the shop area. There are two types of entities which should be placed on the grid: (1) manufacturing resources and (2) restrictions.

Since restrictions are areas on which no resources may be placed, such as load bearing walls, the grid is redefined not to include the nodes corresponding to the restrictions. Resources of moveability type C are first placed onto the grid at user specified locations. These entities are immovable throughout the layout analysis. The remainder of the resources are placed randomly onto the available area.

Step 2

Define the SA annealing parameters listed in Table (4.1). The counters ntemp, nsucc, and niter are employed to control the algorithm and are explained below.

Table 4.1: Simulated annealing parameters

Variable	Definition
T	Initial temperature
TFTR	Annealing schedule factor (0.0-1.0)
NITER	Total number of temperature changes
NTEMP	Total number of iterations at each temperature
NSUCC	Number of successes at each temperature before continuing to the next temperature

Step 3

Compute the objective function, E_1, of the initial layout configuration from Eq. (4.1). The distance, d_{ij}, between all pairs of entities is computed using Dijkstra's algorithm which also determines the shortest path between these entities. This path may not pass through other entities and restrictions. It starts at the exit node of entity i and finishes at the entrance node of entity j. The pallet traffic, t_{ij}, is computed from the material handling traffic between entity i and j.

Step 4

A random number generator is utilized to select the type of configuration change: swap, translate, or rotate. The probability of a swap is 0.20 while the probabilities of translate or rotate are 0.40 each.

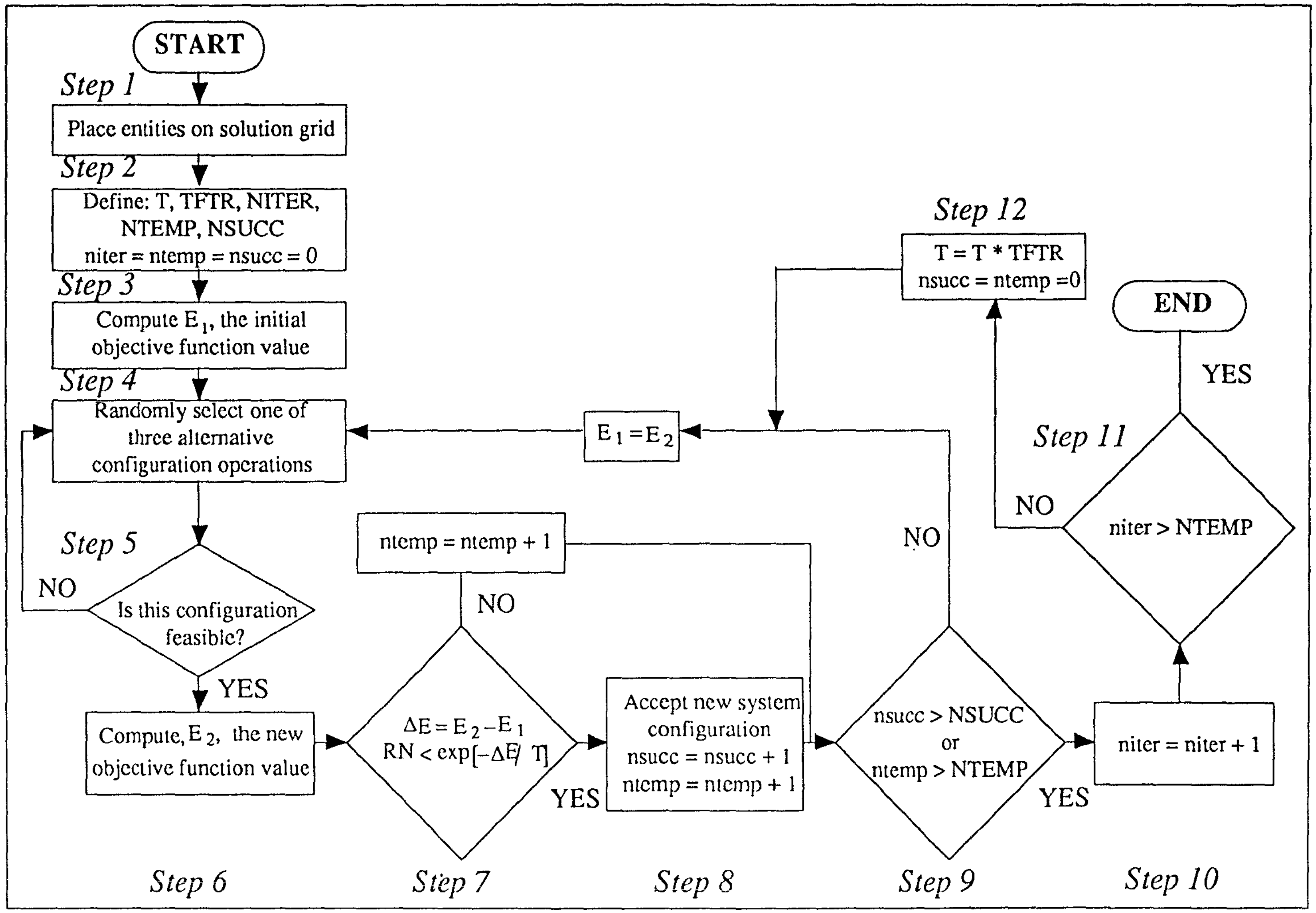

Figure 4.3: Flow-chart for the SA-based layout method

Step 5

If the solution does not satisfy the area overlap constraint (§4.1), continue with a new system configuration, *Step 4*, otherwise continue to *Step 6*.

Step 6

For the new system configuration, compute the new objective function value, E_2, as per *Step 3*.

Step 7

$\Delta E = E_2 - E_1$, is evaluated as the change in the total material handling distance between the current and previous configurations. In order to determine whether the new configuration is acceptable, a random number, RN ($RN \in [0,1]$) is selected and compared to $\exp[-\Delta E/T]$. Improved configurations result in $\Delta E < 0$ and are always accepted, since $\exp[-\Delta E/T] > 1$. Configurations of energy E_2 greater than E_1 result in $\Delta E > 0$ and are accepted if $RN > \exp[-\Delta E/T]$. The probability of acceptance is progressively lower as the temperature decreases. If the solution is not accepted, then increment the counter ntemp (number of iterations at a temperature) and continue to *Step 9*; otherwise continue to the next step.

Step 8

If the solution is accepted, then set $E_1 = E_2$ and increment the counters ntemp (number of iterations at a temperature) and nsucc (number of successes at a temperature).

Step 9

If the number of iterations at a temperature exceeds the maximum number of iterations at a temperature (ntemp $\geq$ NTEMP) or the number of successes at a temperature exceeds the maximum number of successes at a temperature (nsucc $\geq$ NSUCC) then continue to the next temperature, otherwise continue to the next system configuration in *Step 4*.

Step 10

Increment the number of temperature iterations (niter) and begin a set of NTEMP iterations at the new temperature.

Step 11

If the number of temperature iterations exceeds the maximum number of temperature iterations (niter ≥ NITER) then halt the execution of the program, otherwise continue to *Step 12*.

Step 12

The temperature is reduced by the temperature reduction factor, TFTR. This provides a lower probability at which an uphill solution is accepted. *Steps 4* through *12* are repeated until the predefined number of temperature steps is completed.

The following output information is obtained from the application of the layout algorithm to a manufacturing system:

- Optimal or near-optimal layout of the facility.
- The flow paths between all pairs of entities for the optimal solution.
- Final objective function value, which quantifies the total traffic times distance within the shop.

Note that the superiority of SA-based algorithms to facility layout methods has been shown conclusively by Jajodia *et al.* [1992]. In their work a large set of classical layout problems were solved by several methods, in addition to SA. In all cases, SA performed better than all other methods. The present method is the most advanced version to date of SA-based algorithms, since it considers (1) the size of resources, (2) restricted areas, and (3) realistic material handling paths that cannot pass through resources and restrictions.

4.3.1 Intra-cell Layout

The general algorithm presented above is utilized as is for the intra-cell layout problem. This algorithm is executed for each significant cell identified by the cell evaluation stage (§3.4). The following assumptions are used:

- The resources considered are the machines belonging to the cell under consideration. They are represented by their rectangular envelopes. The exit and entrance of each machine is given as shown in Fig. (4.2).
- The distances between machines are Euclidean and are computed from the exit of the output machine to the entrance of the input machine.
- The entrance and exit of the cell are defined as unit square "resources" from which the parts enter and leave the cell. The location of these "resources" within the available area is to be determined by the procedure.
- The part routings are modified such that the entrance "resource" is inserted prior to the first operation in the routing as well as each operation that follows one performed outside the cell. The "exit" resource is inserted prior to each operation performed outside the cell and is also at the end of the routing.

Since the cell entrance and exit must be accessible from the outside environment, the following constraint is added: Acceptable configurations are only those which allow access from the edge of the grid to the entrance and exit of the cell along one of the four orthogonal directions.

The inputs of the intra-cell layout problem are:

- The set of machines (machine number, description, size, and location of its exit and entrance).
- The input parameters required for the SA algorithm.

- The minimum size of corridors. This value is used to artificially increase the size of each machine and allow for material transfer corridors between machines (see previous section).
- The set of parts which are processed by at least one of the machines within the cell, along with the corresponding demand values and pallet sizes.
- The production routings, or process plans, of these parts. Each routing identifies the sequence of machines visited by the part.

The size and shape of the cell may or may not be given as input. In the latter case, the initial area is unrestricted and the final configuration defines the cell boundaries.

The objective function, E, is the product of the intra-cell traffic times the appropriate intra-cell distance. The engine described in the previous section is utilized to solve the problem and provides the following outputs:

- The optimal or near-optimal intra-cell layout.
- The size and shape of the cell, if not given as input.
- The location of the cell's entrance and exit.
- The flow paths between each pair of machines.
- The final value of the objective function.

4.3.2 Shop Layout

The shop layout problem is also solved using the same SA-based algorithm described earlier in this chapter. The following assumptions are used:

- The resources considered include the significant manufacturing cells identified during the cell evaluation stage as well as the remainder of the machines in the shop. All resources are represented by their rectangular envelopes. The exit and entrance of each resource are given as shown by Fig. (4.2). Note that the dimensions of the cell envelopes are defined from the intra-cell analysis described in §4.3.1.

- The distances between resources are Euclidean, computed from the exit of the output resource to the entrance of the input resource.

The inputs of the shop layout problem are:

- The set of independent machines (machine number, description, moveability status, size, location of the exit and entrance, and performance factor).
- The set of cells (cell name, cell description, moveability status, size, location of the exit and entrance, and performance factor).
- The capacity of the independent machines and the remaining capacity of the members of multi-machine workcenters assigned to cells.
- The minimum size of corridors. This value artificially increases the size of the resources as discussed above.
- The set of parts (demand, average pallet size, average batch size, and part description).
- The production routings, or process plans, of the parts in the system. Each routing identifies the sequence of machines visited by the part and the setup and run times for each operation.
- The size of the shop floor.
- The restrictions of the shop floor.

The inter-cell layout algorithm considers two additional critical issues that have not been addressed by the general algorithm presented earlier in this chapter.

<u>Re-assignment of parts to independent machines</u>

This issue arises from the fact that more than one functionally identical machines may be included among independent machines to be placed on the shop floor. For every new system configuration involving the movement of member, G_i^j, of a multi-machine workcenter, G^j, the assignment of all operations which utilize such a machine should be re-examined for the following reason. Consider a part which visits G_i^j for a particular operation in its routing. Also consider that the preceding and succeeding operations to G_i^j in the part's routing are performed in resources R_u and R_v, respectively. Since the relative distances $d(R_u, G_i^j)$ and $d(G_i^j, R_v)$ have been changed, the assignment of this part to another member of the G_i workcenter may be more appropriate with respect to inter-resource distance.

Note that reassignment of operations already assigned to machines that are members of cells is not considered because the traffic formed from these assignments define the cell. However, the remaining available capacity of these machines is available for the reassignment of parts. Thus, this reassignment examines operations assigned to multi-machine workcenters in two areas: (1) operations assigned to independent machines and (2) operations assigned to machines which are members of a cell and are not the original operations assigned to the cell, whose traffic defines the cell. For each iteration of the algorithm, which involves the movement of such a machine G_i^j, the following heuristic procedure is employed for operation reassignment.

A set is generated to include all operations assigned to all independent machines of workcenter G_i. For such operations all possible sequences, $R_u G_i^j R_v$ are determined, where as before R_u and R_v are the predecessor and successor operations (which are fixed), and G_i^j may be any of the available members of G_i. Furthermore, for each such sequence the distance, $d(R_u G_i^j)$ and $d(G_i^j R_v)$, is evaluated. The list of all sequences for all operations is ranked in ascending order of these distance values. Starting from the top of the list the sequences with the lower distance values are selected and the operations are assigned to the appropriate workcenter. This is repeated until all of the operations have been assigned. Note that as soon as an operation sequence is assigned, all of its copies are removed from the list. Additionally, note that some operations may not be assigned to the most appropriate machine due to capacity considerations. In this case, the next sequence in the list is used. Thus, in this manner the part assignment is performed consistently with the objective of the algorithm and respects all problem constraints.

Swap between Cells and Machines

Since the size of a cell is usually much larger than the size of an independent machine, a cell-machine swap is usually not feasible. In this case, one or more machines are swapped with a cell as follows. The cell is temporarily moved to the location of the machine considered for the swap, Fig. (4.5). Any other machines encroached by the placement of the cell in the machine location will be moved to the cell's original location, Fig. (4.5). In this manner, the cell is swapped with one or more machines.

The general SA-based algorithm described earlier is employed to perform the shop layout. The part reassignment heuristic outlined above has been incorporated in the algorithm and used whenever an independent machine G_I^j is moved. In addition, the swap routine has been enhanced to cater for the cell-machine(s) interchange. The modified algorithm provides the following outputs:

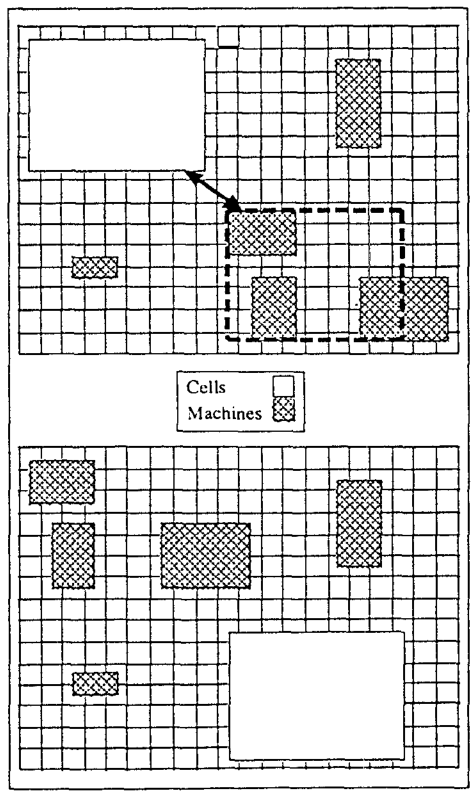

Figure 4.4: Swap between a cell and a group of machines

- The optimal or near-optimal shop layout.
- The flow paths of the optimal or near-optimal solution between each pair of resources.
- The final value of the objective function.
- The final part routings which specify the assignment of all operations to the most appropriate machines.

4.4 Example

Intra-cell Layout

The theoretical example of §3.5 is continued here. Two significant cells were identified by the cell evaluation stage of the algorithm, cells #1 and #3 (§3.5). The machines comprising these cells are given in Tables (4.2a) and (4.2b). The intra-cell analysis utilized the process plans of all parts visiting these corresponding cells. Entrance and exit operations were inserted in the process plans as per §4.3.1.

Table 4.2a: Machine data for cell #1

Machine Number	Length	Width	Side of Entrance	Location of Entrance[1]	Side of Exit	Location of Exit[2]
WC1	9.0	4.0	1	4.5	3	4.5
WC5	9.0	6.0	2	3.0	4	3.0
WC8	9.0	6.0	2	3.0	4	3.0
WC15(1)	2.0	6.0	1	1.0	3	1.0
WC3	19.0	14.0	3	4.5	3	4.5
WC6	29.0	16.0	2	3.0	4	3.0

Table 4.2b: Machine data for cell #3

Machine Number	Length	Width	Side of Entrance	Location of Entrance[2]	Side of Exit	Location of Exit[2]
WC7	9.0	6.0	2	3.0	4	3.0
WC16(1)	9.0	6.0	1	4.5	3	4.5
WC12	4.0	4.0	1	2.0	3	2.0
WC16(2)	9.0	6.0	1	4.5	3	4.5
WC15(4)	9.0	6.0	2	3.0	4	3.0

[1] As per Fig. (4.2).

The SA parameters for each of the two intra-cell analyses are given in Table (4.3):

Table 4.3: Simulated annealing parameters for intra-cell layout of cells #1 and #3

SA Parameter	Value
Random number seed	2
Minimum clearance between machines	4
Number of temperature iterations	100
Number of iterations at each temperature	200
Limiting number of successes at a temperature	200
Initial temperature	1000
Annealing factor	0.9

The initial layout was randomly generated by the program. The final layouts of cells #1 and #3 are shown in Figs. (4.5a) and (4.5b), respectively. The final objective function values for each of these cells were 5718 and 2352 units, respectively.

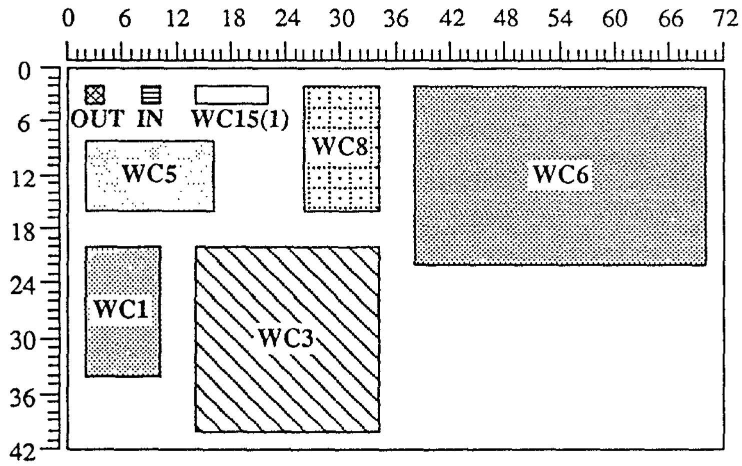

Figure 4.5a: Intra-cell layout of cell #1

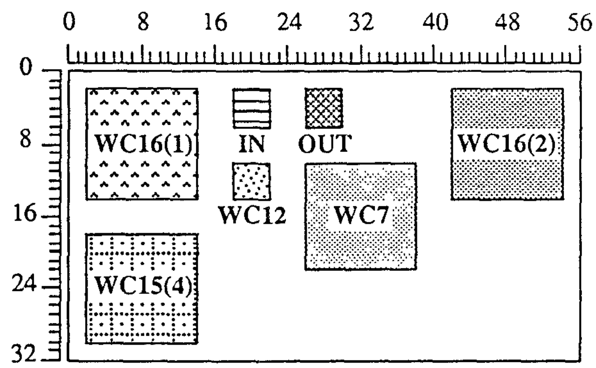

Figure 4.5b: Intra-cell layout of cell #3

Shop Layout

The two cells configured above and the remaining machines of the example shop were placed within the predefined shop grid given in Fig. (4.6). There are 12 resources in the entire shop, i.e. 2 cells and 10 machines. The dimensions of the cells are provided by the intra-resource layout analysis and are shown in Table (4.4) along with the machine information required by the algorithm. The SA parameters for this problem were the same as those used for the intra-cell analysis and are shown in Table (4.3). The final solution for the shop layout is shown in Fig. (4.7).

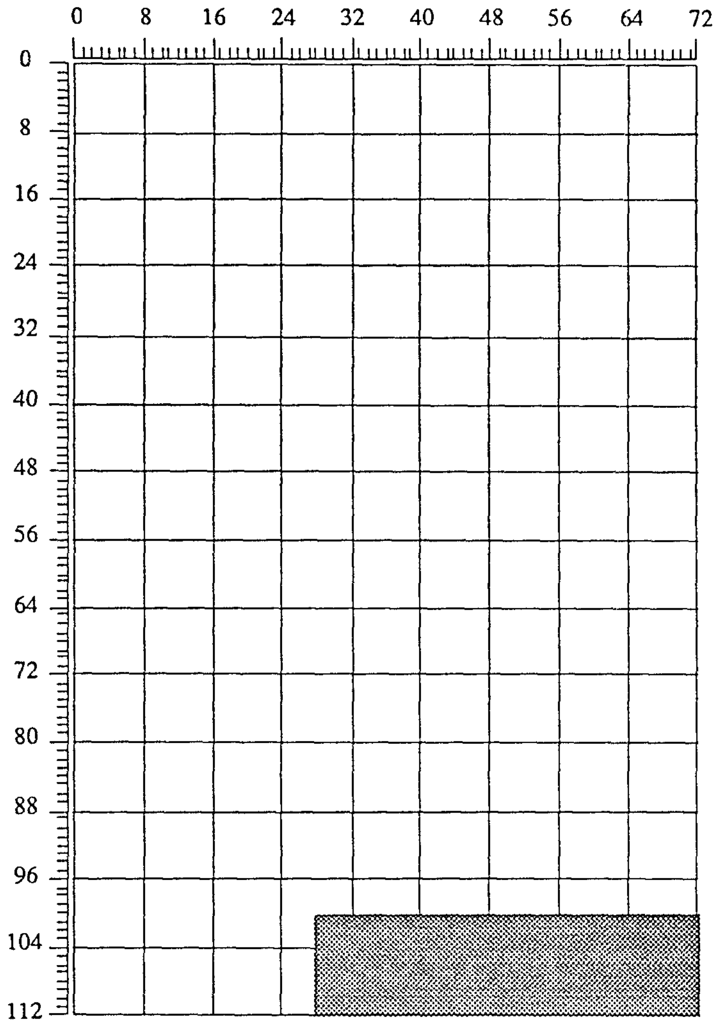

Figure 4.6: Example shop size with restrictions

Table 4.4: Dimensions of entities utilized for the inter-cell layout analysis

Machine Number	Length	Width	Side of Entrance	Location of Entrance	Side of Exit	Location of Exit
WC2	9.0	4.0	1	4.5	3	4.5
WC4	9.0	6.0	2	3.0	4	3.0
WC9	4.0	4.0	1	2.0	3	2.0
WC10	4.0	4.0	1	2.0	3	2.0
WC11	4.0	4.0	1	2.0	3	2.0
WC13	4.0	4.0	1	2.0	3	2.0
WC14	2.0	6.0	1	1.0	3	1.0
WC15(2)	2.0	6.0	1	1.0	3	1.0
WC15(3)	9.0	6.0	1	4.5	3	4.5
WC15(5)	9.0	6.0	1	4.5	3	4.5
Cell #1	72.0	42.0	1	9.0	1	3.0
Cell #3	56.0	32.0	1	20.0	1	28.0

It is noted that the locations of the entrance and exit of the machines, although not designated in the figure, face the material handling corridors, c_1 and c_2. Additionally, material can readily flow from any resource to any other resource. The width of the material handling corridors was specified in the input to allow the largest type of material handling system to operate freely.

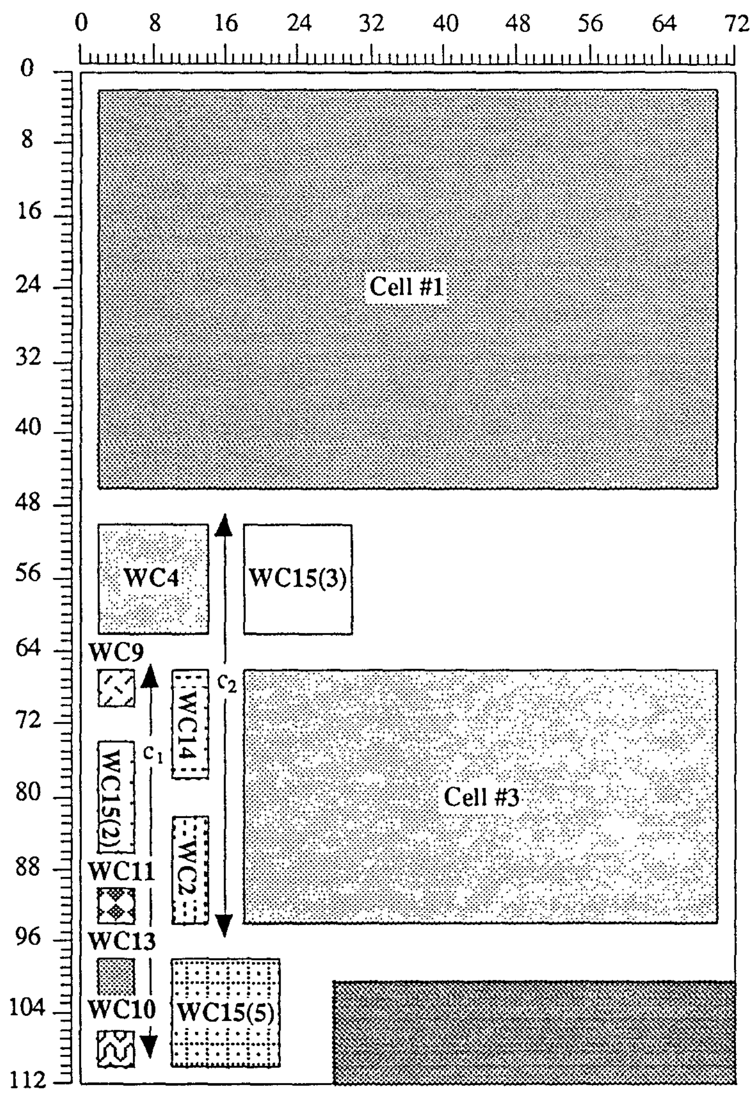

Figure 4.7: Inter-cell layout of example shop

Chapter 5

Case Study: Redesign of a Large Shop

The integrated methodology for hybrid shop design was utilized to partially rearrange the existing radar antenna production facility of Westinghouse ESG. The redesign effort included both manufacturing cell formation and design of the shop layout. The approach and the solutions obtained are discussed in this chapter.

5.1 Integrated Software

The methodology developed in this thesis and outlined in Chapters 3 and 4 was implemented in a five-stage integrated software package, the architecture of which is shown in Fig. (5.1). The software has been written in the C programming language and runs on a Unix SUN-OS platform. The entire package and its input-output requirements are fully described in a separate software manual [Lu, 1993]. Due to the complexity and size of the shop design problem the software is computationally expensive. It is noted however, that design, or redesign, of a shop is not a real time application, and therefore, run time is not a primary concern.

5.2 Case Background

Westinghouse ESG (Electronic Systems Group) is the division of the multi-national Westinghouse Corporation that manufactures ground and airborne radars for military and commercial use. Westinghouse ESG includes two major production areas; the radar chassis facility and the electronic radar component facility. This case study focuses on the former.

At any given time more than 14,000 different parts are active in the MRP II system of the radar chassis facility. These parts span a wide variety of shapes and a large range of sizes. The production shop consists of approximately 160 workcenters, some of which include more than one machines. It is functionally arranged and includes lathes, breaks, welding stations, assembly stations, painting stations, plating stations, and bonding stations. In addition, the functional areas are grouped into budget centers, each containing machines which perform similar processes. For example, the sheet metal budget center consists of the punch press, deburr, shear, and break functional areas.

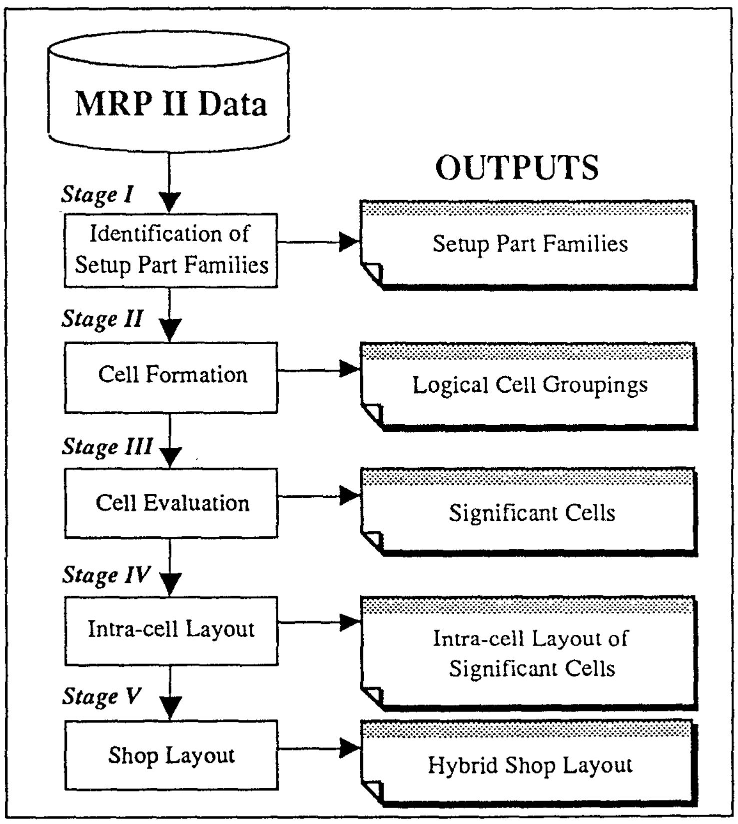

Figure 5.1: Integrated software architecture

5.3 Case Analysis

In order to rearrange the radar chassis assembly facility, the following data were required: (1) The list of 160 workcenters, of which 17 are multi-machine workcenters. (2) The production volume of each of the 14,247 active parts in the MRP II system over a six-year time horizon (1990-1995); actual production volumes were provided for the years 1990, 1991, and 1992, and demand forecasts were provided for 1993, 1994, and 1995. (3) The average production batch size and pallet size for each part. (4) The routings of all parts, including the setup and run times for each operation. Note that functionally identical machines were represented by common designations in the part routings. This implied that an operation could be processed by any machine in a multi-machine workcenter.

The data were obtained directly from the MRP II system in files which were pre-processed to conform to the input requirements of the software system. The pre-processed input data were provided in three separate files: (1) list of operations, (2) list of parts and associated information, and (3) list of workcenters.

The Westinghouse industrial engineering personnel suggested the following modifications in the data in order to simplify the analysis, and to accurately reflect the current situation in the shop:

- Parts with zero demand during the selected horizon were removed from the parts list. Similarly, unused workcenters were removed from the workcenter list.
- Inspection workstations were given a moveability status E and were removed from the workcenter list; the corresponding operations were removed from the part routings. It is noted that special inspection equipment cannot be assigned to any particular cell.

- Several workcenters were consolidated, including: (1) The machines of the model shop; the resulting workcenter was given a moveability status of C. (2) The plating baths, which are always visited by the parts in sequence. The resulting workcenter was given a type D moveability status. It is noted that most manufactured parts are processed through this workcenter.
- 169 pairs of routings were consolidated following current company guidelines.
- Sequential operations requiring the same workcenter were consolidated.

In addition, the analysis used the following assumptions:

- The redesign was based on the production volumes for the years 1993 and 1994. The demand for 1995 was not utilized due to the uncertainty associated with it. The actual demands for previous years (1990-1992) were used to test the robustness of the cell formation solution (§5.4).
- The capacity of each machine was set to 8,320 hours; over the two year horizon this corresponds to two 8-hr. shifts per day, five days per week.
- A limiting cell size of six was selected for the cell formation stage after consulting with company personnel.

After pre-processing, the redesign problem included 69 workcenters, containing a total of 103 machines, and 3,271 parts.

Setup Family Formation

The setup family utility of the software system, described in §3.2, provided a list of workcenters and their utilization. This information identified: (1) underutilized workcenters, (2) bottleneck workcenters, and (3) workcenters that spend a significant portion of their available capacity in setup. Table (5.1) shows the first 32 workcenters included in this list. Columns 3 and 4 provide the measures presented in §3.2; i.e. for each workcenter the percentage of operating time spent in setup, and the overall

Table 5.1: List of workcenters ranked according to percentage of time consumed by setup

	Workcenter	SU/(SU+RU)	(SU+RU)/CP
1	FDHJ02	98.002%	0.016%
2	FDHJ01	95.029%	0.145%
3	FDGB01	92.308%	0.008%
4	FDHF02	86.483%	0.279%
5	FDHG01	85.860%	5.039%
6	FDHB01	82.525%	7.626%
7	FDHF01	78.406%	2.877%
8	FDHB02	77.804%	6.643%
9	FJKD01	74.622%	0.035%
10	FDHP01	73.072%	0.143%
11	FJKC01	64.888%	0.268%
12	MAFE12	63.155%	4.752%
13	FDGE01	61.757%	0.127%
14	FJBH99	59.866%	0.148%
15	FJRD01	59.524%	0.010%
16	FDHR01	54.645%	0.002%
17	MABF01	53.854%	0.513%
18	FJKB02	49.779%	11.191%
19	FDJA01	48.644%	2.570%
20	MAFE03	43.871%	4.982%
21	FDHK01	42.935%	15.903%
22	MAFE05	41.777%	8.406%
23	FDFJ04	40.887%	3.718%
24	FDJH01	39.500%	0.948%
25	FJDN01	39.185%	0.005%
26	FDYC01	36.089%	0.426%
27	MAFF12	34.145%	2.551%
28	FDYA01	33.789%	1.632%
29	FDHN01	32.442%	5.166%
30	FJRE02	28.289%	0.059%
31	DCSA01	27.083%	1.957%
32	FDHB03	25.050%	69.407%

utilization of the workcenter. Furthermore, for each workcenter, a list of all parts that are processed by it was generated. These parts were ranked in descending order of the ratio of setup time to total time (setup and run time) required for the corresponding operations. Table (5.2) shows the ranked parts for workcenter FDHB03 (#32 of Table 5.1). The latter was chosen for further analysis due to its high utilization. The 44 parts which visit this workcenter were examined to determine similarities in setup and to standardize their jigs and fixtures. Other potential workcenters to be analyzed are workcenters FJKB02 (#18) and FDHK01 (#21).

Table 5.2: Parts utilizing FDHB03 ranked by percentage of processing time required in setup

	Part Number	SU/(SU+RU)
1	3D60822H01	93.46%
2	612J728G01	70.59%
3	612J724G01	49.95%
4	612J726G01	48.87%
5	613J123G01	44.44%
6	3D55187G01	36.54%
7	3D55422G01	33.58%
8	613J014G01	30.62%
9	3D55426G01	28.38%
10	3D55421G01	26.95%
11	3D55425G01	23.09%
12	613J125G01	23.08%
13	159C469H01	22.72%
14	3D55424G01	22.50%
15	3D55423G01	22.50%
16	3D55418G01	9.09%
17	612J729G01	4.76%
18	613J017G01	4.52%
19	613J001G01	4.40%
20	613J124G01	4.40%
21	613J012G01	3.55%
22	613J011G01	3.55%
23	613J010G01	3.55%
24	613J009G01	3.55%
25	613J008G01	3.55%
26	613J007G01	3.55%
27	613J006G01	3.55%
28	613J005G01	3.55%
29	613J004G01	3.55%
30	613J013G01	3.55%
31	613J003G01	3.55%
32	613J002G01	3.55%
33	613J021G01	3.41%
34	613J023G01	3.33%
35	613J022G01	3.33%
36	613J020G01	3.33%
37	613J019G01	3.33%
38	613J018G01	3.33%
39	613J016G01	3.33%
40	613J015G01	3.33%
41	612J725G01	0.00%
42	612J596G01	0.00%
43	3D58640G01	0.00%
44	612J727G01	0.00%

The lists generated by this software utility were employed by industrial engineering personnel at Westinghouse for the study of setups. Due to the labor-intensive nature of searching for similarities in the part process plans, this information was unavailable at the time of this analysis.

5.4 Cell Formation Results

The pre-processed manufacturing data were provided as inputs to the cell formation stage of the software system. This module identified 27 cells, 11 of which consisted of six machines. The GT Efficiency of the proposed cellular arrangement was 50.11%. Note that a major source of inter-cell traffic in the proposed solution is the plating workcenter, which (1) cannot be included in any cell and (2) is visited by the majority of parts in the system. If the unavoidable inter-cell traffic to and from this workcenter is not considered in the calculation, the resulting efficiency value increases to 65.24%.

The proposed cells were ranked by the number of parts processed by each cell (as a percentage of the total number of parts in the system). Table (5.3) shows the seven most significant cells with the corresponding part ratio measure (total number of parts = 3271). Table (5.4) lists the machines contained in each of these cells. The index in parenthesis following some of the machine numbers identifies the particular member of a multi-machine workcenter.

Table 5.3: Potentially significant manufacturing cells

Cell	Cell Utilization
Cell #20	14.41%
Cell #9	13.80%
Cell #15	9.65%
Cell #2	8.52%
Cell #27	8.15%
Cell #6	8.15%
Cell #19	7.42%

Three of these cells, #15, #19, and #20, already existed in the facility. The fact that the cell formation method yielded these three cells is significant since (1) it validates the cell formation criterion with respect to company expectations and (2) it validates the cell formation algorithm. The four remaining significant cells, #2, #6, #9, and #27, were proposed for implementation. The existing cells (#15, #19, and #20), the new ones proposed for implementation (#2, #6, #9, and #27), and the plating workcenter (#11) are visited by 81.25% of the parts in the system.

Table 5.4: Machines included in potentially significant cells

Cell	Machines
Cell #20	FDGA01 FDHK01 (1) FDHK03 FDHN01 FDHB03 FDHB02
Cell #9	FJLA01 FJLB01 (1) FJKB02 (1) FDMB01 (1) FJLB01 (2) FDMB01 (7)
Cell #15	MAFE12 MAFH01 MAFJ04 (1) FJDC02 (1) FJDC01 (1) MAFE03
Cell #2	FJBK99 FDMC01 FDVM01 FDMB01 (9)
Cell #27	FDMD01 (1) FJKB02 (2) FDMB01 (2) FJDB01 (1) FDMB01 (3) FJKB02 (3)
Cell #6	F2 FDJX01 (1) FDMB01 (4) FDMB01 (6) MAFD50 (1) MAFJ04 (3)
Cell #19	FDFJ04 FDHB01 FDHG01 FDHF01 (1) FDYC01 MABF01 (2)

The benefit of creating the proposed four cells was evaluated by calculating the expected reduction in inter-cell traffic using the technique described in §3.3. The initial configuration of the facility yielded the following shop traffic over the two-year horizon:

Number of Inter-group Moves:	30,190	(78.82%)
Number of Intra-group Moves:	8,112	(21.18%)
Total Number of Moves:	38,302	

Intra-group moves are those within a budget center or an existing cell and inter-group moves are those between budget centers and/or existing cells. Note that each inter-group move consists of: (1) transfer from a budget center (cell) to an inspection station, (2) transfer to the dispatch center, and (3) transfer to the next budget center (cell). Thus, by confining inter-group moves within cells, the material handling within the shop as well as the corresponding logistics are dramatically reduced. The implementation of the proposed four new cells results in the following part traffic values:

Number of Inter-cell Moves:	22,587	(59.00%)
Number of Intra-cell Moves:	15,705	(41.00%)
Total Number of Moves:	38,302	

Thus, the creation of these cells yields a reduction of 7,603 inter-group moves (25.18% of the inter-group moves).

The second evaluation test examined the robustness of the proposed cellular formation with respect to changes in production volumes and/or changes in part mix. All annual production volume data provided by Westinghouse were used in this analysis. Three time horizons, each spanning a four-year interval, were utilized to determine the effectiveness of the solution with respect to savings in material handling. These horizons included the demands between 1990-1993, 1991-1994, and 1992-1995. For each time horizon a separate arrangement was obtained using the cell formation stage of the method: A_1 for 1990-1993, A_2 for 1991-1994, and A_3 for 1992-1995.

The results of the robustness analysis are shown in Table (5.5). Each entry, a_{ij}, of the matrix represents the G.T. Efficiency of cellular arrangement A_j over time horizon i. Thus, the column corresponding to each arrangement shows the change in G.T. Efficiency under different production volumes.

Table 5.5: Robustness analysis results

Time Horizon	A_1	A_2	A_3
1990-1993	44.19%	43.35%	44.56%
1991-1994	44.62%	43.95%	45.31%
1992-1995	44.37%	43.68%	45.49%

Notice that the differences among the matrix elements are not statistically significant. Thus, for this case, the efficiency of the cells is unaffected by changes in the production volume and part mix.

Currently, one of the four proposed cells has been constructed in the Westinghouse facility. The implementation of the three remaining significant cells is in a cost-evaluation stage. It is expected that these cells will be constructed in the near future.

5.5 Shop Layout Results

The intra-cell layout of each of the significant cells given in Table (5.3) was determined using the method described in §4.3.1. Table (5.6) shows the values of the simulated annealing parameters used for the intra-cell layout study. Table (5.7) provides the sizes of the machines included in each cell as well as the locations of the entrance and exit of each machine.

Table 5.6: Simulated annealing parameters for intra-cell layout

SA Parameter	Value
Random number seed	2
Minimum clearance between machines	4
Number of temperature iterations	100
Number of iterations at each temperature	200
Limiting number of successes at a temperature	200
Initial temperature	10000
Annealing factor	0.9

Fig. (5.2) shows the layout of cell #2. Note that this cell is arranged compactly in a triple row configuration. This solution provides for short material handling distances between the machines of the cell. Table (5.8) provides the traffic between all pairs of machines in this cell. Note that the largest intra-cell traffic value corresponds to machines FDVM01 and OUT which have been placed in adjacent locations within the cell. In general a high intra-cell traffic value between two machines corresponds to an adjacent placement.

Table 5.7: Size and location of exit and entrance of machines of each cell

Machine Number	Length	Width	Side of Entrance	Location of Entrance[1]	Side of Exit	Location of Exit[1]
MANUFACTURING CELL #20						
FDGA01	19.00	19.00	3	9.50	3	9.50
FDHK01(1)	60.00	29.00	4	4.00	4	4.00
FDHK03	33.00	20.00	1	16.50	1	16.50
FDHN01	10.50	15.00	3	5.00	3	5.00
FDHB03	28.00	18.00	3	14.00	3	14.00
FDHB02	18.00	22.00	1	9.00	1	9.00
MANUFACTURING CELL #9						
FJLA01	34.0	61.00	1	6.00	1	6.00
FJLB01(1)	6.50	7.00	2	3.50	2	3.50
FJKB02(1)	7.00	4.00	1	3.50	1	3.50
FDMB01(1)	6.00	8.00	3	3.00	3	3.00
FJLB01(2)	6.50	7.00	2	3.50	2	3.50
FDMB01(7)	6.00	8.00	3	3.00	3	3.00
MANUFACTURING CELL #15						
MAFE12	15.00	12.00	1	7.50	1	7.50
MAFH01	10.00	6.00	1	5.00	1	5.00
MAFJ04(1)	9.00	8.00	3	4.50	3	4.50
FJDC02(1)	6.50	6.00	2	3.00	2	3.00
FJDC01(1)	7.00	6.50	1	3.50	1	3.50
MAFE03	24.00	22.00	1	12.00	1	12.00
MANUFACTURING CELL #2						
FJBK99	9.00	6.00	1	4.50	1	4.50
FDMC01	7.00	7.00	2	3.50	2	3.50
FDVM01	13.50	17.0	3	7.00	3	7.00
FDMB01(9)	6.00	8.00	3	3.00	3	3.00
MANUFACTURING CELL #27						
FDMD01(1)	4.00	7.00	2	3.50	2	2.50
FJKB02(2)	7.00	4.00	1	3.50	1	3.50
FDMB01(2)	6.00	8.00	3	3.00	3	3.00
FJDB01(1)	6.50	6.50	1	3.25	1	3.25
FDMB01(3)	6.00	8.00	3	3.00	3	3.00
FJKB02(3)	7.00	4.00	1	3.50	1	3.50
MANUFACTURING CELL #6						
F2	1.00	1.00	1	0.50	1	0.50
FDJX01(1)	10.0	14.0	3	5.00	3	5.00
FDMB01(4)	6.00	8.00	3	3.00	3	3.00
FDMB01(6)	6.00	8.00	3	3.00	3	3.00
MAFD50(1)	17.0	12.0	1	7.50	1	7.50
MAFJ04(3)	9.00	8.00	3	4.50	3	4.50
MANUFACTURING CELL #19						
FDFJ04	13.00	5.00	3	2.00	3	2.00
FDHB01	23.00	19.00	1	11.50	1	11.50
FDHG01	17.00	11.50	4	6.00	4	6.00
FDHF01(1)	7.50	17.50	3	3.75	3.	3.75
FDYC01	9.00	12.00	3	4.50	3	4.50
MABF01(2)	13.00	8.00	1	6.50	1	6.50

1 As per Fig. (4.2)

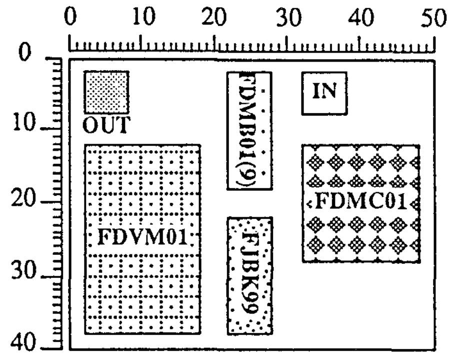

Figure 5.2: Intra-cell layout of manufacturing cell #2

Table 5.8: Traffic between machines of cell #2

	IN	FDVM01	FJBK99	FDMB01(9)	FDMC01	OUT
IN	0					
FDVM01	139	0				
FJBK99	273	533	0			
FDMB01(9)	1405	456	753	0		
FDMC01	1064	138	422	83	0	
OUT	0	1835	23	124	13	0

There are three distinct areas in the cell which are left empty: the top right, the top left, and the bottom right areas. This is due to the shapes and sizes of the machines in the cell. These areas can be utilized as buffers for materials entering or leaving the cell. The results of the remaining cells are given in Appendix A.

The final stage of the hybrid facility design is the placement of the significant manufacturing cells and the remaining individual machines in the shop floor. The sizes of the manufacturing cells and the locations of their entrance and exit were determined from the intra-cell layouts and are given in Table (A.1) of Appendix A. The sizes of the individual machines and their entrance and exit data are given in Table (A.2) of Appendix A. The dimensions of the shop area as well as the restricted shop sub-areas were determined from the detailed shop drawings. The grid representing this area was provided to the software as input and is shown in Fig. (5.3).

In the first step of the analysis, the machines with moveability status C and the cells that contain such a machine were placed first in the shop grid. These resources remain immovable throughout the execution of the algorithm, since they have been designated by the industrial engineering personnel of Westinghouse as very costly to move. Both these restrictions and the immovable machines are appropriately identified in the figure. The simulated annealing parameters employed by the algorithm are given in Table (5.9).

Table 5.9: Simulated annealing parameters for inter-resource layout

SA Parameter	Value
Random number seed	5
Minimum clearance between machines	4
Number of temperature iterations	50
Number of iterations at each temperature	200
Limiting number of successes at a temperature	200
Initial temperature	75000
Annealing factor	0.9

The final layout of the facility is shown if Fig. (5.4). To validate this solution, the pairs of resources which have high traffic were examined to ensure that they were located adjacent to one another. Table (5.10) shows the five pairs with the highest inter-resource traffic. Notice that all of these resources are adjacent to one another.

Table 5.10: Pairs of resources with high inter-resource traffic

Resource Pair	Inter-resource Traffic
CELL #9 (64) - CELL #6 (63)	2408
FJBH99 (1) - CELL #20 (68)	2066
CELL #15 (66) - CELL #20 (68)	1701
CELL #19 (67) - CELL #20 (68)	1338
CELL #19 (67) - CELL #27 (70)	942

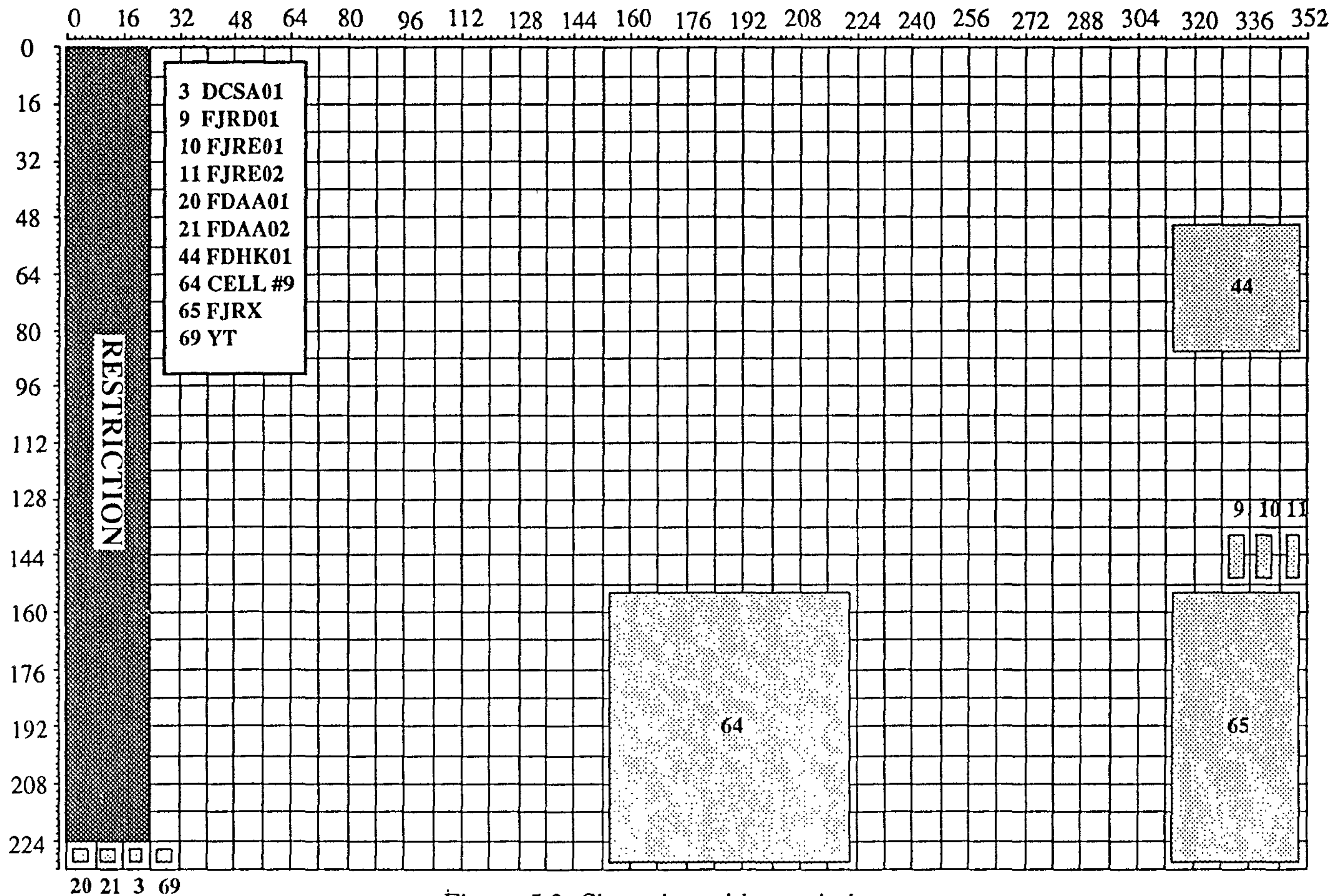

Figure 5.3: Shop size with restrictions

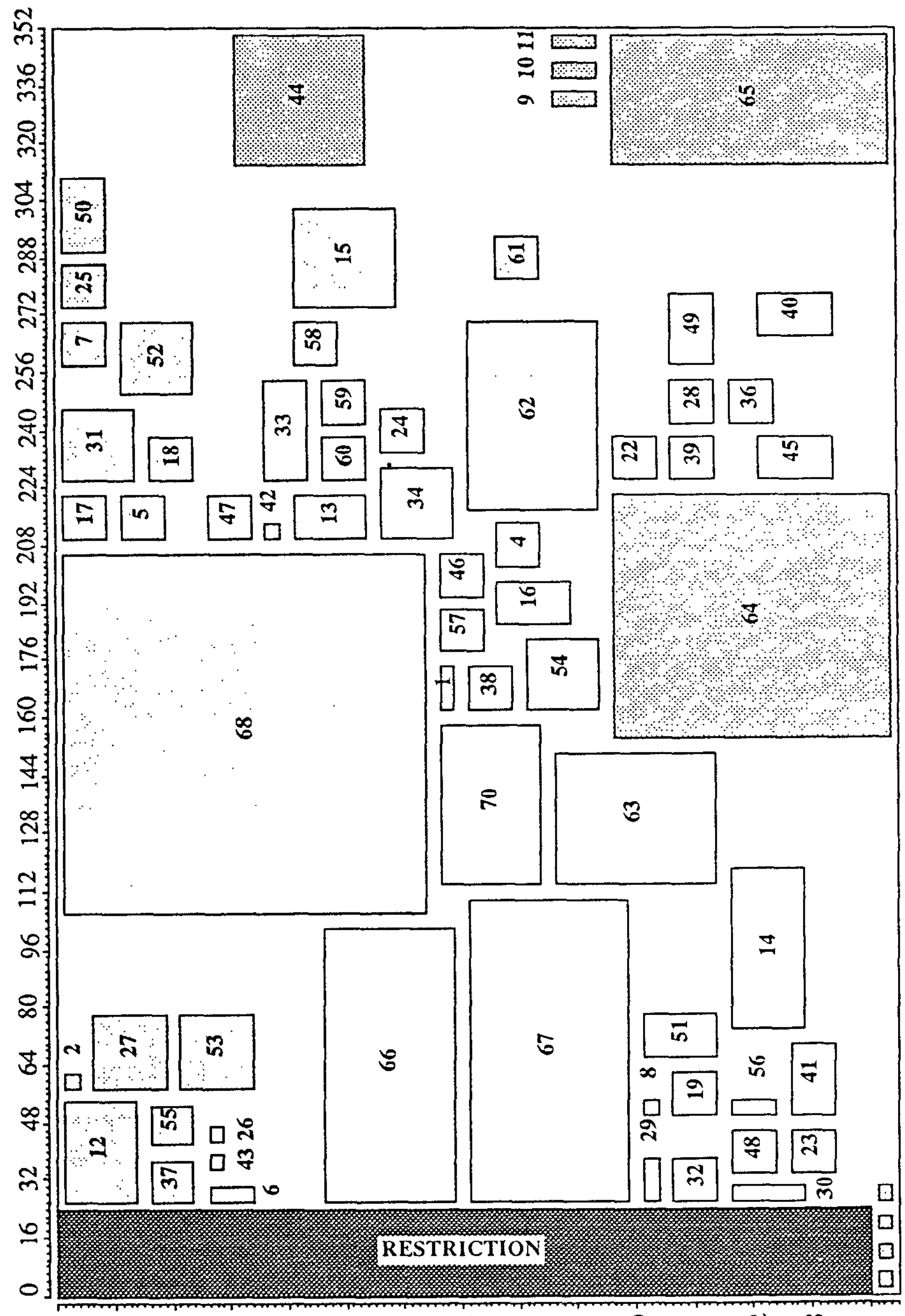

Figure 5.4: Hybrid facility layout

Table 5.11: Reference table for Fig. (5.4)

Index Number	Machine Number	Index Number	Machine Number
1	FJBH99	36	FDMB01(5)
2	ABMP01	37	FDMB01(8)
3	DCSA01	38	FDMB01(10)
4	FJDN01	39	FDMB01(11)
5	FJKA01	40	FDJX01(2)
6	FJKC01	41	FDJX01(3)
7	FJKD01	42	FDJA01(1)
8	FJMB01	43	FDJA01(2)
9	FJRD01	44	FDHK01
10	FJRE01	45	FDHF01
11	FJRE02	46	MAFJ04
12	MAFD14	47	MAFF04(1)
13	MAFD15	48	MAFF04(2)
14	MAFD20	49	MAFE05(2)
15	MAFE03	50	MAFE05(3)
16	MAFF07	51	MAFD50
17	MAFF12	52	MAFD12(2)
18	MAFH02	53	MAFD12(3)
19	MAFM01	54	MAFD12(4)
20	FDAA01	55	FJLB01
21	FDAA02	56	FJKB02
22	FDBD01	57	FJDC02(1)
23	FDBE01	58	FJDC02(2)
24	FDGB01	59	FJDC01(1)
25	FDGE01	60	FJDC01(2)
26	FDHF02	61	FJDB01
27	FDHJ01	62	Cell #2
28	FDHJ02	63	Cell #6
29	FDHP01	64	Cell #9
30	FDHR01	65	FJRX
31	FDJH01	66	Cell #15
32	FDMR01	67	Cell #19
33	FDYA01	68	Cell #20
34	FDYB01	69	YT
35	FDMD01	70	Cell #27

The unoccupied space between the resources may be explained by the large variation in resource size and the immovability of some of the resources.

This layout may further be improved with user manipulation. Note that in the present study, inter-resource corridors are defined from the shortest paths between the corresponding entities, which may potentially create a very large number of corridors.

User intervention may shift some entities to create inter-cell avenues, on which the majority of material should flow.

Additionally, the success of the workcenter reassignment heuristic may be validated by the process plan of part 774R371G01 which requires the following machine sequence: FDHB01-MAFJ04-MAFH01; MAFJ04 is a member of a multi-machine workcenter. Notice from Table (5.4) that FDHB01 is a member of cell #19 and MAFH01 is a member of cell #15. Initially, the operation requiring workcenter MAFJ04, is assigned to machine #46 (200, 112 on the grid of Fig. (5.4). However, at the completion of the shop layout analysis this operation is assigned to MAFJ04(1), which is also a member of cell #15. The original distance from FDHB01 (cell #19) to MAFJ04 to MAFH01 (cell #15) is larger than the distance of the new sequence FDHB01 (cell #19) - MAFJ04 (1) (cell #15) - MAFH01 (cell #15). The process plans of several other parts, that underwent reassignment were also examined and found to follow shorter paths.

Due to the great cost associated with relocating the machines in the shop a new study is currently under way to determine a phased implementation plan for the redesign of the shop during the next few years [Harhalakis and Minis, 1993].

Chapter 6

Conclusions and Recommendations

6.1 Summary and Contributions

An integrated methodology for hybrid facility design is presented in this thesis. It may be used for both the redesign of existing shops and the design of planned facilities with forecasted product demands and pre-defined process routings. The methodology comprises four stages: (1) formation of logical manufacturing cells, (2) evaluation of significant cells, (3) determination of the intra-cell layout, and (4) determination of the hybrid inter-resource layout.

The first step in the cell formation process consists of identifying parts with similar setup requirements, which if assigned to a specific member of a multi-machine workcenter would reduce its setup workload considerably. The cell formation stage utilizes an existing algorithm that minimizes traffic flow within the shop by disaggregating machines from functional areas into manufacturing cells. During the cell formation, parts are assigned to a specific member of a multi-machine workcenter respecting the capacity and part setup constraints. This step is considerably enhanced in the present study, since both the setup family constraint and the criterion for part assignment are new. The resulting cell arrangement yields:

- Reduction in material handling
- Simplification of material flow
- Reduction in setup times

The cell evaluation stage is novel and considers two attributes: (1) savings in material handling effort and (2) the robustness of the cellular arrangement to changes in part demand. It facilitates construction of only significant cells and evaluates the robustness of the proposed solution.

Having selected the most significant manufacturing cells, the next step is to determine the location of the machines within each cell, as well as the location of the cell's entrance and exit. This step also provides the size and shape of each cell and is performed utilizing an SA-based algorithm that minimizes material traffic and distance. The actual distance between workcenters is determined using a shortest path algorithm. The latter accounts for physical obstacles while creating the flow paths from the exit of one machine to the entrance of another. In addition to determining the inter-entity distance in a precise manner, this stage considers fully the machine shape and size. These two contributions are significant to the intra-cell layout, since they lead to near-optimal solutions that can be readily implemented on the shop floor.

Once the sizes and shapes of the significant cells are determined, the shop layout is designed to minimize the traffic and distance travelled by the parts within the shop. The latter consists of both cells and independent machines. The SA algorithm is once again used to iteratively swap, translate, or rotate resources until a near-optimal solution is obtained. Operations are re-assigned to functionally identical machines according to material handling considerations when appropriate. The major contributions of this stage include (1) consideration of both machines and cells in a unified manner, (2) consideration of physical constraints, such as the actual shop shape and size as well as its obstacles, and (3) reassignment of operations to appropriate functionally identical machines.

The proposed layout method overcomes the major drawback of other methods which address this problem: the dependence of the final solution on the initial shop configuration. The solution obtained typically corresponds to a global optimum or a near-optimal solution. Additionally, several alternate layouts of nearly the same quality are obtained, the most suitable among which can be selected for implementation.

One of the most important contributions of this methodology is its practicality. Major features include: (1) pre-processing the data according to current shop practices, (2) formation of practical cells while respecting machine capacity and preserving part families with similar setups, (3) evaluation of cells with respect to savings in material handling and robustness in demand changes; it is noted that robust cells are appropriate for implementation in practice, (4) design of a hybrid shop layout consisting of machines and cells. The latter is the most appropriate type of layout for the majority of practical manufacturing systems.

6.2 Conclusions

The following conclusions were obtained from the development and application of the hybrid facility design methodology:

- A pure cellular arrangement is not practical in typical industrial environments.
- The hybrid (cellular/functional) facility design problem is conveniently decomposed in a sequence of subproblems, i.e. cell formation and evaluation, cell layout, and shop layout.
- These subproblems may be solved more than once to arrive at a good solution.
- It is necessary to consider a consistent objective for all stages of the facility design problem.

- Practical issues, such as similarities in setups and changes in production mix, should be considered if the final solution is to have practical significance.
- Setup part families are necessary to reduce cycle-times and to standardize fixtures and jigs on machines.
- The objective of minimizing material handling within the shop is a critical one. This was validated by the fact that some of the proposed cells in the Westinghouse case study were already implemented in the facility.
- The proposed methodology addresses critical practical issues and provides solutions that result in high shop performance.

6.3 Recommendations for Further Work

Important issues that, if addressed, will enhance the applicability and practicality of the hybrid facility design methodology, as well as the quality of the solutions obtained, are discussed below. In the cell formation stage such issues include: (1) incorporation of economic considerations, such as, cost estimates associated with machine relocation, and (2) incorporation of workload considerations, such as machine utilization and load balancing. Specific criteria which quantify these issues could be addressed by the grouping algorithm and considered while assigning parts to machines.

In the inter-cell layout stage, a potentially important issue is the design of a shop traffic corridor system which (1) prevents material handling congestion and (2) is cost effective. In this study, inter-resource corridors are defined from the shortest paths between the corresponding entities. However, this may potentially create a very large number of corridors, which is clearly a cost-ineffective solution. In addition, the flow along these corridors may be unbalanced resulting in highly congested and/or rarely used flow-paths.

To address these issues emphasis should be given to determining inter-cell avenues, on which the majority of material should flow.

Another issue in hybrid shop design is the inter- and intra-cell material handling systems. A well-designed cell or shop with an inefficient material handling system may perform poorly. If certain material handling systems are already in place, the rearranged shop layout could be created with these systems in mind. Alternatively, a methodology that identifies opportunities to use new material handling systems is desirable. Obviously, the cost of implementing these material handling systems should also be considered.

Finally, the identification of setup part families can be greatly facilitated by group technology (GT) part coding. The integration of GT coding with this methodology may result in a powerful tool which would standardize products, as well as production methods, and will lead to an almost pure decoupling of the manufacturing system to independent cells. As a result, planning and scheduling would be greatly simplified, since the dimensionality of these problems will be greatly reduced.

While this thesis proposes a robust design methodology for hybrid shops, the above enhancements are important in developing optimal or near-optimal solutions with high practical impact for both the facility redesign and new facility synthesis problems.

Appendix A: Case Study Results

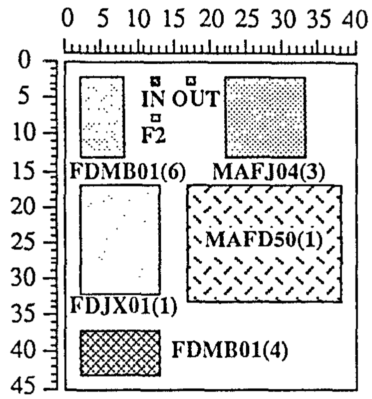

Figure A.1: Intra-cell layout for manufacturing cell #6

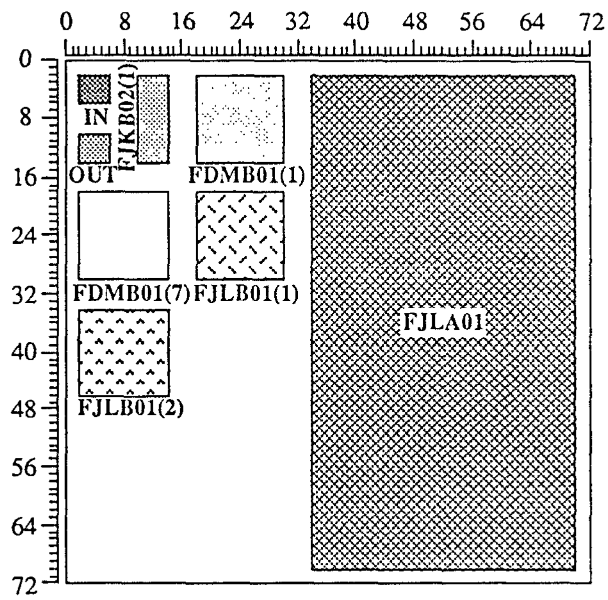

Figure A.2: Intra-cell layout for manufacturing cell #9

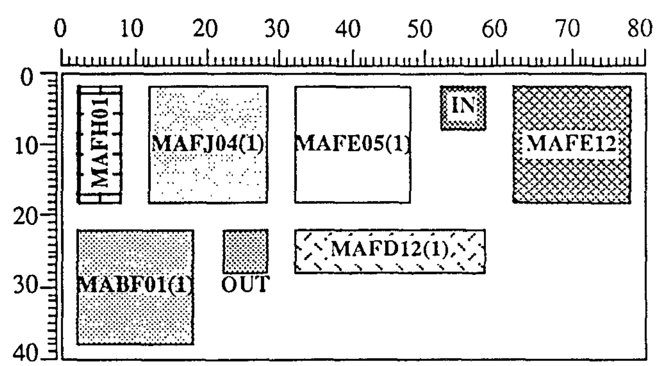

Figure A.3: Intra-cell layout for manufacturing cell #15

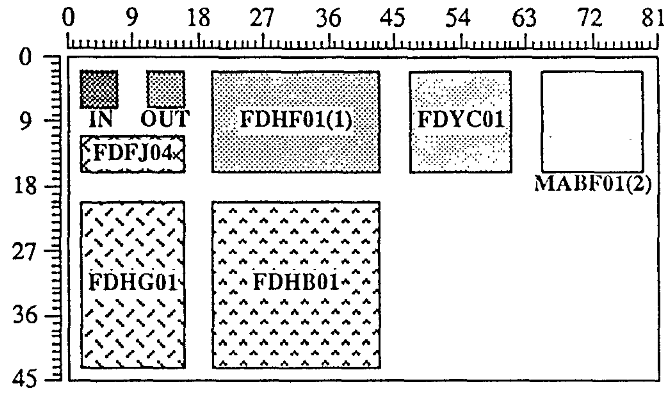

Figure A.4: Intra-cell layout for manufacturing cell #19

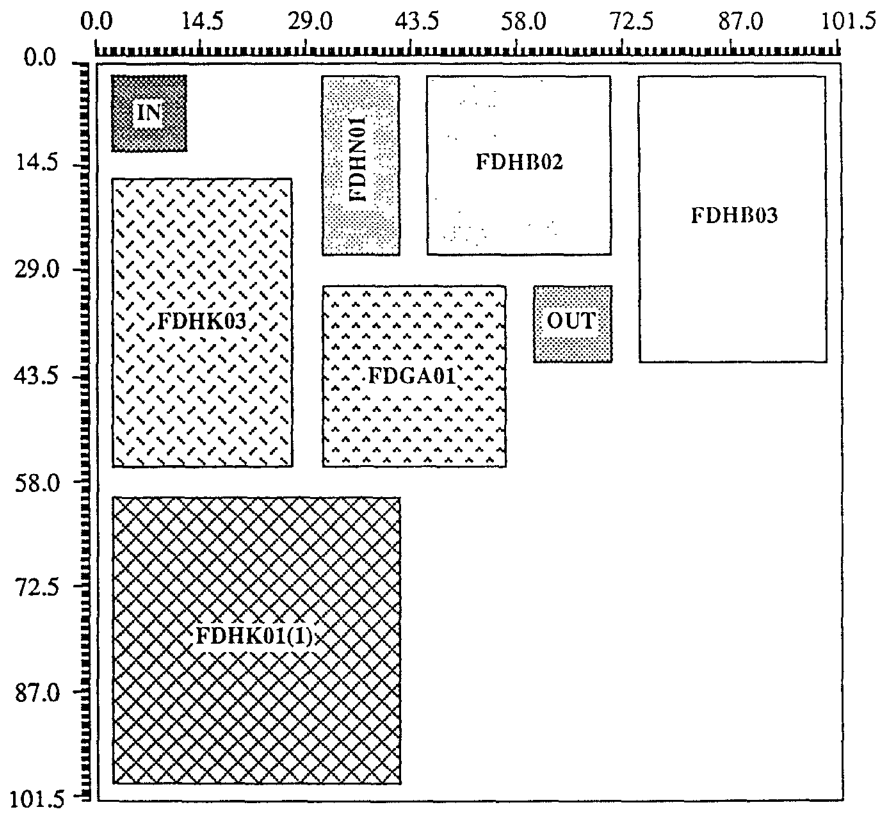

Figure A.5: Intra-cell layout for manufacturing cell #20

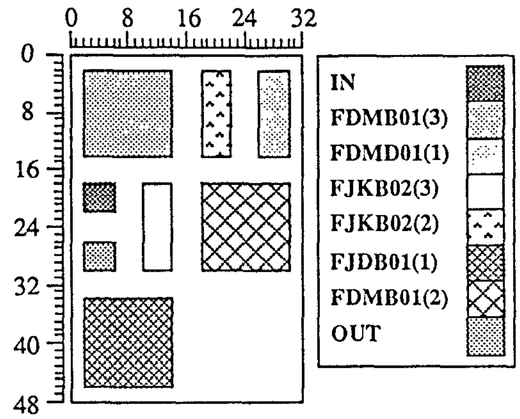

Figure A.6: Intra-cell layout for manufacturing cell #27

Table A.1: Cell data for significant cells

Cell Number	Length	Width	Side of Entrance	Location of Entrance	Side of Exit	Location of Exit
Cell #2	50.00	40.00	1	35.00	1	5.00
Cell #6	40.00	45.00	1	12.50	1	17.50
Cell #9	72.00	72.00	1	4.00	4	60.00
Cell #15	80.00	40.00	1	55.00	3	55.00
Cell #19	81.00	45.00	1	4.50	1	13.50
Cell #20	102.00	102.00	1	7.25	3	36.25
Cell #27	32.00	48.00	3	28.00	3	20.00

Table A.2: Machine data for independent machines

Machine Number	Length	Width	Side of Entrance	Location of Entrance	Side of Exit	Location of Exit
ABMP01	1.0	1.0	1	0.50	1	0.50
DCSA01	1.0	1.0	1	0.50	1	0.50
FDAA01	1.0	1.0	1	0.50	1	0.50
FDAA02	1.0	1.0	1	0.50	1	0.50
FDBD01	9.5	9.0	2	4.50	2	4.50
FDBE01	9.5	8.0	3	5.00	3	5.00
FDGB01	9.5	8.0	1	5.00	1	5.00
FDGE01	8.0	7.0	2	3.50	2	3.50
FDHF01(2)	7.5	17.5	3	3.75	3	3.75
FDHF02	1.0	1.0	1	0.50	1	0.50
FDHJ01	13.0	20.0	1	6.50	1	6.50
FDHJ02	10.0	10.0	1	0.50	1	0.50
FDHK01(2)	30.0	29.0	4	4.00	4	4.00
FDHP01	10.5	3.0	4	1.50	4	1.50
FDHR01	4.0	15.5	3	2.00	3	2.00
FDJA01(1)	1.0	1.0	1	0.50	1	0.50
FDJA01(2)	1.0	1.0	1	0.50	1	0.50
FDJH01	20.0	13.5	3	10.00	3	10.00

Table A.2: Machine data for independent machines (cont.)

Machine Number	Length	Width	Side of Entrance	Location of Entrance	Side of Exit	Location of Exit
FDJX01(2)	10.0	14.0	3	6.00	3	6.00
FDJX01(3)	10.0	14.0	2	2.00	2	2.00
FDMB01(5)	6.0	8.0	3	3.00	3	3.00
FDMB01(8)	6.0	8.0	3	3.00	3	3.00
FDMB01(10)	6.0	8.0	3	3.00	3	3.00
FDMB01(11)	6.0	8.0	3	3.00	3	3.00
FDMD01(2)	4.0	7.0	2	3.50	2	2.50
FDMR01	5.0	7.0	4	3.50	4	3.50
FDYA01	26.0	10.0	1	13.00	1	13.00
FDYB01	17.0	20.0	3	8.50	3	8.50
FJBH99	9.0	4.0	1	4.50	1	4.50
FJDB01(2)	6.5	6.5	1	3.25	1	3.25
FJDC01(1)	7.0	6.5	1	3.50	1	3.50
FJDC01(2)	7.0	6.5	1	3.50	1	3.50
FJDC02(1)	6.5	6.0	2	3.00	2	3.00
FJDC02(2)	6.5	6.0	2	3.00	2	3.00
FJDN01	7.0	7.0	3	3.50	3	3.50
FJKA01	6.5	6.0	3	3.50	3	3.50
FJKB02(4)	7.0	4.0	1	3.50	1	3.50
FJKC01	4.0	5.5	3	2.00	3	2.00
FJKD01	6.5	6.0	3	3.50	3	3.50
FJLB01(3)	6.5	7.0	2	3.50	2	3.50
FJMB01	1.0	1.0	1	0.50	1	0.50
FJRD01	8.0	4.0	1	5.00	1	5.00
FJRE01	8.0	4.0	1	4.00	1	4.00
FJRE02	8.0	4.0	1	3.50	1	3.50
FJRX	72.0	31.0	1	4.00	1	4.00
MAFD12(2)	19.0	16.0	1	12.00	1	12.00
MAFD12(3)	19.0	16.0	1	12.00	1	12.00
MAFD12(4)	19.0	16.0	1	12.00	1	12.00
MAFD14	24.0	19.5	4	10.00	4	10.00
MAFD15	20.0	12.0	3	10.00	3	10.00
MAFD20	20.0	40.0	2	20.00	2	20.00
MAFD50(2)	17.0	12.0	1	7.50	1	7.50
MAFE03	24.0	22.0	1	12.00	1	12.00
MAFE05(2)	15.5	12.0	3	6.00	3	6.00
MAFE05(3)	15.5	12.0	3	6.00	3	6.00
MAFF04(1)	6.0	8.0	1	3.00	1	3.00
MAFF04(2)	6.0	8.0	1	3.00	1	3.00
MAFF07	19.0	8.0	3	9.50	3	9.50
MAFF12	8.0	10.0	3	4.00	3	4.00
MAFH02	7.0	7.0	1	3.50	1	3.50
MAFJ04(2)	9.0	8.0	3	4.50	3	4.50
MAFM01	9.5	11.0	1	5.00	1	5.00
YT	1.0	1.0	1	0.50	1	0.50

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