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Methodology for the economic evaluation of part-presentation systems for robotic assembly

Chittajallu, Siva Kumar, Ph.D.

The Pennsylvania State University, 1989

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The Pennsylvania State University
The Graduate School
College of Engineering

METHODOLOGY FOR THE ECONOMIC EVALUATION OF PART-PRESENTATION SYSTEMS FOR ROBOTIC ASSEMBLY

A Thesis in
Mechanical Engineering

by
Siva Kumar Chittajallu

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

May 1989

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ABSTRACT

Kits and feeders/magazines are forms of part presentation devices commonly used to provide the accurate positioning of parts necessary for robotic assembly. In practice the degree to which each part presentation device is used varies because each offers a different set of advantages and disadvantages. This presents a problem of determining how much of each part presentation device to use in a hybrid part presentation system. With current manufacturing trends towards shorter product life-cycles and a larger range of products, it is important for these systems to be flexibile. There is currently no method to evaluate a part presentation system based on these part presentation device.

This study presents a methodology that can be adopted in the evaluation of part presentation system in uncertain production environments. It incorporates the flexibility of the system in the measure of system worth. The process consists of four stages: one, collection of the product and production data for the system; two, the design of the physical layout of the robot assembly cell; three, the development of cost relations for the part presentation system; and four, performing the system worth calculations.

The methodology has been demonstrated for the assembly of a control panel. It identifies the optimal initial kitting factor to be adopted given the production changes. The production changes are assumed to be design or product-mix changes.

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LIST OF SYMBOLS

α_f	Contribution to assembly time per feedable part on the kit
β	Contribution to assembly time per feedable part on the magazine
d_m	Difficulty factor for a feedeble part on the magazine
d_u	Difficulty factor for an unfeedable part on the kit
$d_{ij}^{(k)l}$	Shortest distance that vertex ’l’ on shape ’i’ can travel in direction ’k’ before making contact with shape ’j’
n_c	# of product changes in the study period
n_s	# of the production phases in the study period
o_{ij}	Overlap factor between shapes ’i’ and ’j’
p_i	Production phase at the end of which a production changes takes place
r	Growth rate
σ_{kl},η_{rs}	Langrangian multipliers
n_i	Number of vertices on shape ’i’
w_{ij}	Weighting between shapes ’i’ and ’j’
x_i,y_i	Coordinates of shape ’i’
AT	Assembly time per composite product
C_c	Capital cost
C_{ij}^k	C-distance of shape ’i’ with respect to shape ’j’ in direction ’k’
$C_o{}^i$	Operating cost for the i’th production phase
$C_a{}^i$	Alteration costs for the i’th production phase
CB_c	Capital cost for bins
CCF_c	Capital Cost for magazine handler

CCK_c	Capital Cost for conveyor due to feedable parts
CF_c	Capital cost for feeders
CKS_c	Capital cost for kits
CM_c	Capital Cost for magazines
CPB_c	Capital cost per bin
CPF_c	Capital cost per feeder
CPM_c	Capital cost per magazine
CPP_c	Capital cost of kit per feedable part
CPP_o	Operating cost per feedable part for kitting
CT	Cycle time per composite product
F_i	Radius adjustment factor for shape 'i'
FC	Feeder capacity
HC_k	Handler operating cost
HC_m	Magazine handler operating cost
$ICPP_k$	Incremental cost for the kit handler feedable part per minute
$ICPM_k$	Incremental cost for the magazine handler per feedable part per minute
KT_o	Operating cost for kit transportation
LC	Labor cost
MC	Magazine capacity
MT_o	Operating cost for transporting magazines
N	Number of parts in the composite product
NFP	Number of feedable parts
NFP_f	Number of feedable parts handled by feeder
NFP_k	Number of feedable parts handled by kit

NUFP	Number of unfeedable parts
$NFPT_f$	Number of feedable part types on magazines
$NFPT_k$	Number of feedable part types on the kit
NOF	Number of feeders
NOK	Number of kits
NOM	Number of magazines
OC_k	Kitting operation cost
OC_f	Operating cost for feeders
OC_{fs}	Feeder servicing cost
PV	Production volume per production phase
R_g, R_h	Penalty factors
R_i	Effective radius of shape 'i'
RC_0	Robot operating cost
RS	Robot speed
RT_k	Response time for the kit handler
RT_m	Response time for the magazine handler
ST	Service time
UOC_f	Unit operating cost for a feeder
UROC	Unit robot operating cost
$X\max_i, X\min_i$	Workspace limits in the X-direction for shape 'i'
$Y\max_i, Y\min_i$	Workspace limits in the Y-direction for shape 'i'

LIST OF ACRONYMS

AGV	Automated Guided Vehicle
AT	Assembly Time
CP	Composite Product
FP	Feedable Part
IKF	Initial Kitting Factor
MDS	Multi-Dimensional Scaling
SPDT	Single-Pole Double-Throw
SPST	Single-Pole Single-Throw
TSP	Translation Sub-Problem

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

1.1 Overview

Assembly, whether done automatically or manually, requires:

a. knowledge of the sequence of operations,
b. means of introducing parts into the workspace,
c. means of identifying the part to be used,
d. means of transferring and/or orienting parts, and
e. means of detecting misalignment of parts.

A human assembler equipped with sophisticated sensory information meets all these requirements, but with the need for increased productivity it has become necessary to build automated systems to do the same job at higher speeds while retaining qualities such as flexibility and insensitivity to batch size.

A robot-based assembly station meets the requirements of speed and flexibility, but with the absence of sophisticated sensory information - sight and touch - it becomes imperative to present components to the robot at the desired location and with the desired orientation. Once a part has been grasped correctly by the robot, program control can ensure the succesful completion of the assembly. In such a set-up, the problem of parts presentation takes on added importance.

An obvious approach to the problem would be to equip the robot with visual and tactile sensing. Tactile sensing has been used in handling unpositioned workpieces [Witwicki,1979], in automated container handling devices [Sugiyama et al.,1979] and in shape recognition on an intelligent underwater robot [Dixon et al.,1979]. On the other hand, vision systems that are in use, are practically limited to two-dimensional feature recognition [Tenebaum et al.,1979] under special conditions [Ward et al.,1979; Holland,1977; Vanderburg et al.,1979]. Some research has been directed at combining vision and tactile sensing [Takeyasu et al.,1977]. However, all these efforts have reported only limited success in non-laboratory environments.

An alternate approach is to mechanically orient and present the parts using a parts presentation device. Several part presentation devices, such as magazines, rotary indexing tables, vibratory bowl feeders and roller conveyors that are used in mass production have been used in batch production. All of these devices are based on two ways of supplying the necessary orientation: first, to align the parts through guides and ingenious fixturing; second, to preserve the part orientation obtained elsewhere in the system. In a batch assembly application, feeder and kitted concepts are the primary categories of part presentation devices.

The feeder concept is based on the natural resting aspect of parts [Boothroyd and Ho,1976; Redford and Boothroyd,1967]. This term is used to refer to the manner in which parts will generally come to rest if allowed to fall onto a horizontal surface. Vibratory bowl feeders employ the feeding concept [Redford and Boothroyd,1967]. These devices use tooling to ensure that only correctly oriented parts are fed. Tooling falls into two groups: "in-bowl" tooling and "out-of-bowl" tooling. "In-bowl" tooling is incorporated in the parts feeder to ensure that parts are fed in their natural resting aspects. All parts lying in any other orientation are rejected. The "out-of-bowl" tooling lies between the parts feeder and the work station. It maintains the orientation of the parts exiting the feeder. If necessary, active orienting devices are used to feed the parts in orientations other than their natural resting aspects.

Feeders have been widely used in mass production for parts feeding and orientation. There, workpiece orientation is usually accomplished by dedicated parts feeders [Automation,1972]. These feeders are generally tooled to orient and feed one specific part. They use special-purpose tooling which can be justified only by the high volume of parts put through the system. Vibratory bowl feeders are the most commonly used type because of the range of parts that can be fed. Programmable feeders [Maul and Goodrich,1983] have been developed for handling different components. Other types of feeders in use are oscillating feeders, rotary circular feeders and hopper feeders [Murch,1977; Stevens,1975].

The kitted concept involves the grouping of all the parts necessary for a single or a limited number of assemblies into a single package or kit, where the entire kit is presented to the assembly station as a single unit. This concept is based on the fact that if the position of the kit is known, the design of the kit would identify the orientation and position of all the parts within the kit. This concept has not received much attention from researchers, although there are at least two cases where the concept was evaluated as an alternative to feeding [Misul,1977; Assembly Engineering,1972].

Kit-based part presentation device are characterized by a number of access points. The kit transports a number of different parts to the assembly area and also has the ability to carry devices such as product-specific tooling. It can be prepared either by hand or automatically.

A feeder-based part presentation device on the other hand is characterized by a single access point. It provides identical parts and unlike the kit-based part presentation device, it does not have the ability to convey additional devices to the assembly area. A vibratory bowl feeder with a gravity chute or a preloaded magazine are such examples. From a programming standpoint, it is only necessary to identify the location at the base of the chute as the access point. For the same reasons a magazine that is preloaded using feeders at a remote location is also a feeder-based part presentation device.

1.2 Topic of the Research

Manufacturing is showing a trend away from mass production towards smaller lot sizes and frequent changes in production task. The response to this trend has been the recognition of the need for flexibility in the manufacturing system [Eversheim and Hermann, 1982; Warnecke,1980; Guenther,1979; Whitney,1984]. There are several systems in industry that assemble multiple products [Guenther,1979; Arya,1984]. Allen-Bradley employs a flexible assembly system to produce different versions of contactors and relays. The system consists of 26 automated assembly stations that produce two different sizes of the same unit from 200 different parts with 999 possible combinations of the parts [Bylinsky,1986]. However, these systems are sophisticated hard automation systems with the flexibility being achieved through the control network. Warnecke [1978] describes a system that is used for the assembly of 30 variations of a switching key. The system consists of two pick-and-place units and one feeder for each of the product variations. To produce a particular variation of the switching key, one or more of the pick-and-place units and the appropriate feeder are turned on. The remaining units are left off. Other approaches to obtaining this production flexibility are seen in the Hitachi tape-deck assembly line and the Sony Walkman assembly line [Whitney,1984]. These adopt the "gated station" and "station lockout" approaches respectively.

These systems perform well when the product line is reasonably fixed over the life of the system and the volume is high. However, when short life cycles and a large range of products are taken into consideration, the benefits of a robot-based assembly system can be realized [Warnecke, 1978; Boothroyd and Ho,1977]. While the robot meets the needs for flexibility, it still requires peripheral equipment for the neat arrangement and positioning of parts. From experience in robotic assembly, Fujitsu Ltd. notes that from the aspect of overall assembly cost, the robot accounts for some 20-30% of the cost, and the peripheral equipment for the remaining 70-80%, a situation that is greatly hindering the designing of assembly lines capable of responding flexibly with the new products that are undergoing rapid developments [Robotica, 1986].

Most of the knowledge of the use of feeders and kits as part presentation device for robotic assembly to date has been qualitative. The objective of this research is to provide a quantitative basis for the design of the part presentation system, composed of the two types of part presentation device, for a given production environment.

Typically a robot assembly system manufacturing a range of products will use a mixture of the two types of part presentation device. This research will provide the decision-maker with a tool to help design the part presentation system that is most suited to a certain production environment.

The methodology is aimed at systems producing a range of products that are characterized by short life cycles and a large number of feedable parts. It assumes that technical considerations such as equipment selection and control, and local issues such as part mating and assembly sequence, have been solved. The decision-maker is therefore confronted with "How many feedable parts are to be handled by each part presentation device?"

For this research it is assumed that the assembly system is producing products from the same family. The system assembles a range of products whose composition varies with time as new products are introduced and/or existing products are phased out. The system will adjust to the new demands placed on it as a result of these changes. It aims to capture this flexibility in arriving at a measure of cost for alternative part presentation system.

Whitney [1984] provides examples of products that are manufactured by a common set of parts. He identifies the global and local issues related to the design of an assembly system. The global issues are the potential volume growth, number of models, frequency of design changes, repairability, etc. The local issues are primarily technical, such as part-mating and assembly-sequence. This research is directed mainly at the global aspects, although the local aspects of process sequence, part size and weight are also considered in arriving at a measure of the cycle time to perform the assembly.

1.3 Statement of the Problem

The objective of this research is to provide an evaluation methodology that can be used to determine the optimal mix of kit and feeder based part presentation devices in an uncertain production environment. This research will do the following:

a. develop a simple economic analysis to evaluate the cost of alternative part presentation systems that are used to assemble a family of products,
b. develop a robotic cell layout optimization package to help predict minimum robot cycle time,
c. identify suitable constructs that may be used to study part presentation systems,
d. incorporate the intangible benefit - flexibility to product design and production change - in the evaluation process, and
e. demonstrate the use of the methodology for a practical problem.

1.4 Thesis Organization

The material presented in the thesis is organized as follows. Chapter 1 relates the importance of part presentation by relating it to the problem of robotic assembly. The problem is defined. In Chapter 2, the problem is discussed in detail and the design methodology is introduced. In Chapter 3, the work relating to the design of the physical layout of a robotic assembly based on process information and equipment geometry is presented. Chapter 4 describes a cost analysis model that was used to evaluate alternative robotic assembly systems. Chapter 5 contains an example demonstrating the use of this methodology. Finally, the conclusions and recommendations for future work are presented in Chapter 6.

CHAPTER 2

DESIGN METHODOLOGY

2.1 Assembly System Configuration and Operation

Figure 2.1 shows the schematic of a robotic assembly system. In the following discussion, the end-product of the assembly operation will be referred to as "the assembly". This may range from a sub-assembly to a finished product. A "work-carrier" refers to either a kit or a magazine that is used to transport parts through the system.

The robotic assembly cell for the purposes of this study consists of four units. The first is the parts inventory that serves as a storage for the parts or components necessary to assemble the desired products in the cell. The components may range from standard parts such as fasteners, to fabricated parts and sub-assemblies. The second and third units are the kit and feeder/magazine preparation units respectively. At these units the parts necessary for the manufacture of one or more assemblies are loaded onto work carriers based on the production schedule. The exact elements constituting these units differ from system to system. The end product of the kit preparation unit is a kit containing the components necessary for assembling one or more products, and the end product of the feeder/magazine preparation unit is an oriented part that can be made available to the robot via a gravity chute or a magazine. The final unit of the system is the assembly area. This consists of the robot(s) and

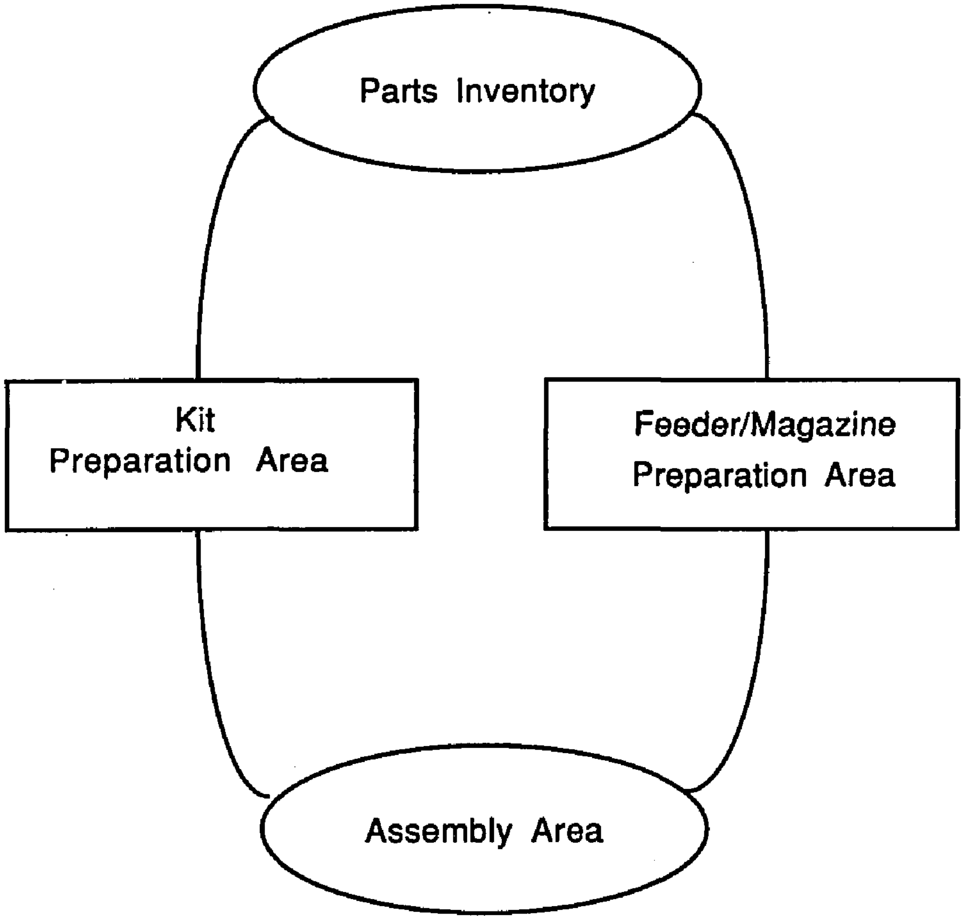

Figure 2.1 Schematic of a Robotic Assembly System

support equipment necessary to perform the assembly. The exact items composing this unit may also vary from system to system. The various units in the cell are linked by material handling systems that may vary from human labor to conveyors and automated guided vehicles. The material handling system serves only to physically transfer the material without performing any operations on it.

During production, in a totally automated floor, the supervisory computer, in accordance with the production requirements, must supply the necessary information to the parts inventory, and the kit and feeder/magazine preparation units so that appropriate work-carriers may be prepared. The loaded work-carriers move to the assembly area where they are operated on by the robot according to the control program which has been downloaded by the supervisory computer.

In the general case, this cell assembles a range of products. The products being assembled consist of feedable and unfeedable parts. The unfeedable parts must be supplied to the assembly area in kits. It is then necessary to determine how many of the feedable parts, if any, that need to be supplied by kits.

2.2 Parameters of Interest

The choice of the part presentation system for the robotic assembly cell depends on the products being assembled. Although several other criteria such as the positioning accuracy, space considerations, existing manufacturing facility, and capital ceiling may be relevant in specific applications, they have not been considered in this research. It is assumed that this analysis addresses a start-up system with access to adequate funds and space.

Technical issues such as positioning accuracy are ignored. In reality, the positional accuracy that can be obtained with each form of part presentation is different. When considering this factor it is necessary to consider not only the variability in the positioning of the parts within the kit and feeder, but also the variability of the positioning of the magazines and kits in the workspace, and the repeatability and accuracy of the robot.

During assembly, the problem is minimized for a feeder-based device that is characterized by a single delivery/access point. Kits on the other hand have several delivery/access points. This presents problems from an application point of view. First, it is necessary to identify the relative location of the control points from one or more calibration posts and second, there is a variability in this information from one kit to another.

For example, calibration of assembly robots drifts with time and it is necessary to recalibrate periodically [Ho, 1982]. Practical experience has shown that this recalibration may need to be repeated every four hours. The variability in the kit positioning in the workspace is handled with calibration posts mounted on the kit.

This problem is typically addressed by either incorporating appropriate control structures in the robot program, using physical aids such as chamfers in association with tactile sensors or end-effector compliance, and positive locating surfaces to ensure accurate grasping during critical stages in the assembly task. This matter is a local issue and of a technical nature [Whitney, 1984]. This thesis assumes that this problem has been suitably handled and the two part presentation devices can be used without a significant difference in the reliability of the cell.

With the knowledge of the products, product mix and an estimate of the production volume, decisions regarding the choice of main equipment (non-material handling component, e.g., robot, jigs, fixtures) and their sizing can be done. Production information such as the assembly sequence, nature of operations, and assembly directions enable the choice of the robot and the support equipment necessary. These decisions are of a purely local nature and can be made independent of the choice of the part presentation system.

Since the products being assembled have a significant bearing on the choice of the part presentation system, it is necessary to characterize the product information. The kitting factor is defined for this purpose.

The kitting factor is defined as the fraction of the feedable parts in a composite product that are transferred by a kit. Since the feedable parts can be handled either by a kit or by a feeder/magazine, the lower and upper limits of the kitting factor are zero and one respectively. The use of this factor is demonstrated in Chapter 5.

Since the design decisions are based solely on the part presentaton system once a product mix has been specified, it will only be necessary to itemize the cost elements that are influenced by the kitting factor and establish the functional relationships. To implement the methodology for a system, it is necessary to identify the specific segments that are influenced by a change in the amount of handling by kits or feeders. This can only be done when a preliminary hardware and configuration design is available. This preliminary design is based on production requirements, process requirements and other technical reasons. The methodology may be applied to other alternative designs independently in the search for the best solution.

The ktting factor influences the part flow volume through the kitting and magazine preparation areas. This impacts on factors in these areas that are affected by flow volume. Kit preparation time, magazine preparation time, number of magazines and kit size are some of the affected factors. The specific factors that are affected and the relative degrees are system specific.

2.3 Evaluation Methodology

Several researchers have considered the problem of robot-based manufacturing system evaluation in varying degrees of detail. However, robotic assembly has received little attention. Robots have typically been used for material handling, applications where accuracy and repeatability requirements were comparatively lax, and jobs that had to be performed in adverse environments. In the U.S., under 5% of the robots, are being used in assembly [Nof, 1985]. It is only recently that it has started receiving attention. Several papers pertaining to various aspects of robotic assembly have been published in the past few years. Most models for evaluating robotic assembly systems have been focused on the comparison of a robot-based assembly system with a hard automation system and/or a manual assembly system [Lynch, 1976; Gustavson, 1983; Carter and Carter, 1987; Funk, 1986; Funk, 1988]. They vary in the degree of detail and the number of estimates that need to be made in order to perform the analysis. For this study, no effort was made to compare the robot-based assembly system with a manual system or hard automation.

The methodology for the evaluation of part presentation system consists of four stages as shown in Figure 2.2. The methodology is general and specific applications require suitable modifications. The end-product of the methodology is a figure-of-merit for the optimal part presentation system. Uncertainty analyses may be performed to determine the sensitivity of the solution to errors in estimates.

The first stage involves the calculation and collection of the production information relevant to the problem. This includes the products to be manufactured, the assembly sequences, the product-mix, physical volume/mass characteristics of the components, estimates of frequency of design changes, etc. From this information, the composite product characteristics and capital costs can be determined. This is demonstrated in Chapter 5.

The second stage is the layout design stage. Here the production information and the dimensions of the peripheral devices at the assembly area are used to obtain an optimal layout from a cycle time standpoint. The optimal layout is the starting point for calculations regarding the flexibility of the cell when there is a change in product, design or product-mix.

The third stage involves cost modelling. In this stage, the segments of the assembly system that are influenced by the part presentation system are identified. Using the information gathered in this stage the designer should be able to draw the functional relationships between the various segments and the part flow. In order to do that, estimates of various cost elements have to be made. Since data on these costs are

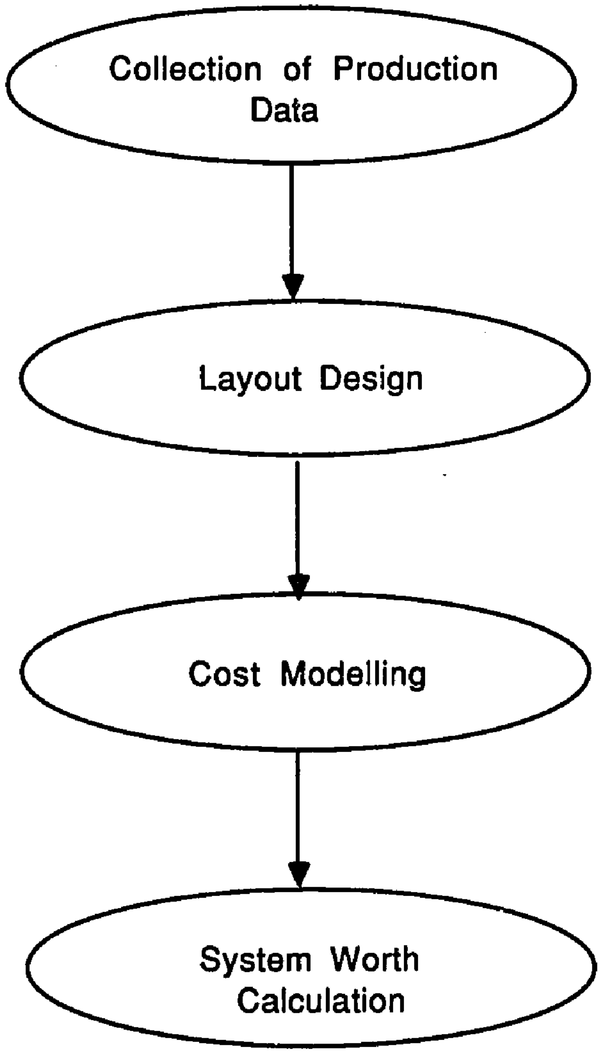

Figure 2.2 Part Presentation System Evaluation Methodology

generally not available in the literature, a detailed understanding of the system is necessary. Economic factors such as growth rate and life of the system must also be determined.

The fourth stage involves the calculation of the system cost measure. The various costs that are influenced by a change in the production environment are itemized. These are related to the flow volume and the production change. The system cost measure is determined for the system. Evaluation of the system cost measure for various kitting factor will indicate the trend in the system worth. This will give the optimal kitting factor for the specified system.

Estimation of the cycle time when there is a production change is an integral part of this methodology. This requires the user to design the physical layout of the system. A physical layout design program that can be used to assist the designer has been developed. Irrespective of whether this tool is used, it is necessary to estimate the cycle time for the assembly of a composite product for a specific kitting factor and also to estimate the new cycle time when there is a production change.

CHAPTER 3

LAYOUT DESIGN FOR CYCLE TIME EVALUATION

3.1 Introduction

The layout of a robotic cell influences the economic analysis in terms of the space used and the cycle time. Other factors that are influenced by the layout design are such intangibles as maintainability, safety, and integrability. For the purpose of this study, it is assumed that the cycle time is the dominant factor in the analysis.

Assembling a complex product can involve a large number of operations. These operations require the robot to move to various points in its workspace to either access or deliver components. In order to help the robot perform the assembly, additional active/passive devices are employed. These may be feeders, kits, jigs/fixtures, tool racks, presses, locating surfaces, etc. Consequently, the physical location of these devices in the robot workspace influences the total distance travelled by the robot and hence the cycle time for performing the assembly.

It is assumed that the "best" physical layout is the one that minimizes the total distance travelled by the robot. With small assemblies involving a small number of operations and simple interactions between devices it may be possible to manually determine the optimal layout. However, for large assemblies involving complex interactions between devices the optimal layout problem is not trivial.

The objective of this section is to develop a program to help design the layout of an assembly cell given the components and assembly sequence. Large manufacturing systems consist of machines arranged in a regular fashion, without a resulting appreciable change in the cycle time because of the magnitudes of the inter-device distances. But, in the case of robotic assembly, the positions and orientations of the various devices in the cell have a significant impact on the cycle time and the throughput. Hence, to make a comparison of the performance of alternative cell designs, a layout design program is necessary.

3.2 Background

The layout design problem is of an interdisciplinary nature and has been used in fields as varied as architecture, business administration, civil engineering, computer science, and graphics. Some of the computer programs that have been developed are given in Table 3.1.

More recently, there have been attempts to design layouts for robot assembly. Drezner and Nof [1984] studied the problem of sequencing move-pick-insert operations for robotic assembly. They solve the problem of assigning the optimum slots in the bin (i.e., kit) for parts being used in the assembly but the layout of the cell itself is not considered. Sarin and Wilhelm [1984] consider the problem of optimally placing devices with differing demands in the workspace of a robot working in polar coordinates. The devices are approximated by circles and are assumed to occupy a sector of the robot workspace. The problem is modelled as a quadratic assignment problem.

Table 3.1 Sampling of Layout Design Programs
(Adapted from Moore, 1974)

ALDEP (Seehof and Evans)	LAYOPT (Matto)
CASS	LAYOUT (Gero)
COLO2	LSP
COMP2 (Teicholz)	MAT (Edwards et al)
COMPROPLAN (Stewart and Lee)	OFFICE (Vollman et al)
CORELAP (Lee and Moore)	RUGR (Krejicirik)
CRAFT (Armour)	PLAN (McRoberts)
DOMINO (Dillon)	PLANET (Deisenroth)
FRAT (Khalil)	PREP (Anderson)
GENOPT	RMA Comp I (Muther)
Hillier-Connors	SISTLAP (Warnecke)
IMAGE (Johnson)	SUMI (Spillers)
KONUVER (Warnecke)	Terminal Sampling Procedure

3.3 The Characteristics Particular to This Problem

In designing the robotic assembly cell, the following factors must be borne in mind:

a. Size/Weight of Parts: The size/weight of a part being transported influences the speed of the robot and hence the travel time of the robot over that motion segment.

b. Irregular Shape of Devices: The part presentation devices used in a cell may have odd shapes. This introduces the problem of mathematical representation of shape to preclude physical interference or overlap of these devices in the layout.

c. Device Location Constraints: Physical constraints demand that devices should not overlap each other, and should be located so that the robot can access them. Additional constraints may restrict the location of various devices to specific areas in the robot work envelope.

d. Device Interaction: The interaction between devices is dictated by the assembly sequence. Repeated movement between a pair of devices indicates a high interaction and suggests that they should be placed close to each other.

e. Access by Robot: Reality demands that the devices be arranged so that the robot can reach delivery/access points on the devices without a collision. This imposes a requirement that the devices not be located too close to each other yet must be contained within the robot workspace.

f. Robot Geometry: This work has centered on the use of a cartesian coordinate gantry style robot with a rectangular work envelope to reduce the complexity associated with the mathematical representation of the robot workspace. It assumes that the robot can dexterously reach all points in its workspace with any desired end-effector attitude.

3.4 The Requirements of the Layout Design Algorithm

The problem may best be formulated, to determine the optimal layout for an assembly operation using a cartesian coordinate robot, given the geometry of the devices in the workcell, the product mix, the operation sequence and the size and weight of parts involved. The criterion of optimality will be to minimize the total statistically weighted distance that is travelled in the process of completing the assembly operation.

In addition, because this program is to design a layout optimally around either a kit or a feeder based system, it should be able to do the following:

a. Fix the location of one or more devices in the layout,
b. Allow the user to specify areas in the workspace that are not available,
c. Allow one or more devices to be fixed so that they lie either partly or completely outside the confines of the workspace, and
d. Allow the user to specify areas in the workspace that are desirable locations for a device.

In order to meet the above requirements, the layout design program must contain the following four elements:

a. A scheme for the representation of devices that incorporates considerable detail, is memory efficient and convenient for extensive processing,

b. A method for detecting the overlap of devices and the violation of boundary constraints,
c. An algorithm that is computationally efficient, and
d. A provision for graphic output of the solutions.

Since several techniques are based on the optimal placement of two-dimensional objects, the devices are approximated by their footprints. So for the rest of this chapter, the devices and their footprints will be referred to as shapes.

3.5 Background on Approaches That Were Studied

Four approaches were studied for the problem of layout design for a robotic assembly cell. Each of the approaches were coded and tested on simple problems to study their suitability for the purpose. Each approach adopted a different shape representation scheme, and offered advantages either in the representation of shape and free space or in the mathematical formulation and algorithm for solving the problem.

3.5.1 Assignment Approach

Here the workspace is divided into a matrix of uniform cells, with each shape being defined in terms of an aggregate of cells. The information about the whole workspace is stored as a matrix of values. The value of each matrix element identifies the shape occupying the corresponding cell in the workspace. This value can be used to detect overlap of shapes.

The objective function is formulated as the weighted sum of the distances between sites on devices as identified by the assembly sequence. Because the problem is modelled as an assignment problem, the collision/overlap and boundary constraints are handled automatically. The integrity of the shape is maintained by assigning a key cell to each shape, with respect to which all the other cells forming the shape are defined. The assignment problem is handled with just the key cells, except that whenever an assignment is made, the cells in the workspace occupied by the other cells composing the shape are tagged as having been assigned. In addition, it is necessary to account for the orientation of the device.

Other methods of storing shape information using this cellular approach are hierarchical arrays, string representation and variable arrays [Eastman,1979]. All of these identify free space and detect overlap, but only the variable array allows reasonable detail, significantly faster processing and less memory. However, it is only possible to use uniform sized cells in the assignment problem formulation.

The conclusion is that all of these representations adopting the cellular definition are convenient for shapes having sharp edges that are perpendicular to the coordinate axes. Because of the nature of the problem, an exhaustive search of the solution space has to be performed. In addition, it is not possible to investigate orientations of the shapes other than integral multiples of 90 degrees without significant loss of fidelity in shape descriptions.

3.5.2 Cspace Approach

The concept of Cspace is promising for implementation in an algorithm for the improvement of the layout. This approach, which is used in trajectory planning problems, transforms the problem of moving an object in a region containing polyhedral obstacles to a problem of moving a point in a space containing configuration obstacles [Udupa, 1977; Lozano-Perez, 1981; Lozano-Perez, 1983]. The approach derives its name from the configuration space or Cspace which is the term used to refer to the solution space of the altered problem.

In this approach, the devices are approximated as polygonal shapes. Each shape is associated with a local coordinate system with respect to which the delivery/access points are defined. A Cspace algorithm that was coded and tested in this research consists of four parts:

a. Internal Representation of Shapes: Each shape is stored as an ordered sequence of vertices, defined with respect to a local coordinate system on the part presentation device. The boundary of each shape is traversed in a counterclockwise fashion. This helps in differentiating between the interior and the exterior of the shape, for detecting the extent of overlap. All the delivery/access points on each shape are also defined in the local coordinate system.

b. Overlap Detection and Depth of Overlap Determination: Overlap detection is done by checking each line segment joining two consecutive vertices of a shape against every line segment of every other shape. In the event of an overlap, the overlapping shapes are converted into a string representation from which the depth of overlap is determined.

c. C-distance Calculation: The C-distance $C_{ij}{}^{(k)}$, of shape "i" with respect to shape "j" in a direction "k" is defined as the distance that shape "i" can traverse in direction "k" without causing an overlap with shape "j." For two shapes "i" and "j," this is determined by finding the points of intersection of lines drawn through each of the vertices of shape "i" and "j" parallel to direction "k" as shown in Figure 3.1. If $d_{ij}{}^{(k)l}$ is the shortest distance that vertex "l" on shape "i" can travel in the direction "k" before making contact with shape "j," and $d_{ji}{}^{(k)m}$ is the corresponding distance for vertex "m" on shape "j", then the C-distance $C_{ij}{}^{(k)}$ is given by

$$Min([d_{ij}{}^{(k)l}, i=1,..,n_i],[d_{ji}{}^{(k)m}, m=1,..,n_j])\ ,$$

d. Determination of the Pair of Shapes Contributing the Most to the Objective Function: The total weighted distance travelled between shapes "i" and "j" divided by the frequency of travel between the two shapes is used to identify the pair that makes the highest contribution to the objective function.

e. Algorithm:

    i. Find the pair of shapes {i,j} contributing the most to the objective function.

    ii. Find the direction of improvement "k" of the objective function. It is given by the direction of the line joining the origins of the local coordinate systems of the pair {i,j}.

    iii. Find the C-distance $C_{ij}{}^{(k)}$ for the pair {i,j}.

    iv. Move the shape "i" by the C-distance in direction "k".

    v. Is there an overlap with other shapes?

        1. If yes, determine the depth of overlap and correct the overlap.

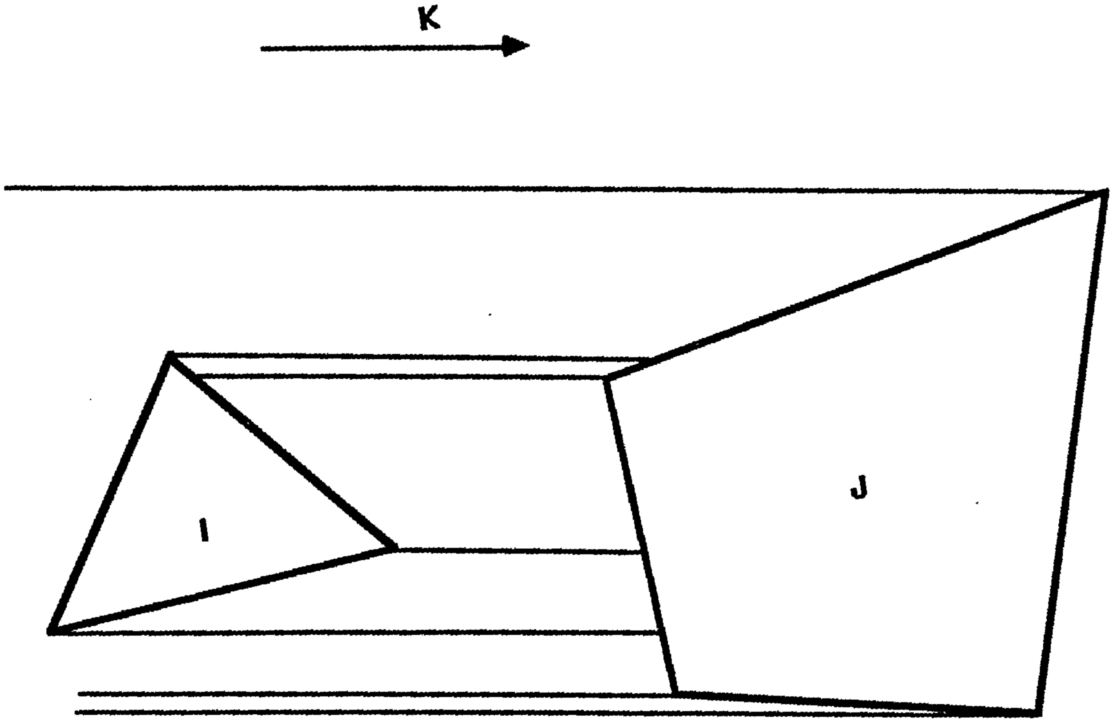

Figure 3.1 Calculation of the C-distance for Two Polygonal Shapes

        2. If no, continue.

    vi. Is it possible to improve the layout without overlapping shapes?

        1. If yes, go to Step 1.
        2. If no, output layout.

The advantages of the Cspace method are threefold.

a. It integrates the layout improvement with overlap detection,
b. It is computationally simple and is memory efficient, and
c. It allows complex shapes to be handled with relative ease.

The disadvantages of this method are:

a. The algorithm is highly dependent on initial layout estimation and converges to a local optimum. This problem can be minimized by the use of alternate initial layouts.
b. The algorithm does not account for three-way, four-way, etc. interactions in determining the C-distance. This may result in a toggling of the layout between equivalent but alternate configurations.
c. It is not possible to incorporate rotation of shapes with respect to each other.

In conclusion, this method cannot be used easily in determining the layout for a large number of shapes but it can be used to refine a layout obtained previously by other means.

3.5.3 Multi-Dimensional Scaling and Graph Theory Approaches

Both multi-dimensional scaling (MDS) and graph theory use a relationship analysis that aims at obtaining a configuration of the shapes to satisfy a relationship or interaction chart.

The graph theory approach is based on the observation [Nozari and Enscore, 1981; Seppanen and Moore, 1970] that the dual of a graph that satisfies the relationship chart is the facility plan. A necessary and sufficient condition for the feasibility of a facility plan is that the graph of the shape relationships must be planar. Though this approach is very useful in determining the topological relations of the shapes needed to satisfy the relationship chart, it does not produce the final layout. It is necessary to adopt an improvement type of layout design algorithm using the solution obtained from the graph theory approach as an initial solution estimate.

The multi-dimensional scaling approach is similar except that it forces the graph of the shape relationships to a plane. The objective of the algorithm is to minimize the stress in the graph resulting from forcing the solution graph to be planar. The user specifies the estimates of the distances between the shapes along with the statistical weight on each distance. Overlap of shapes can be minimized by specifying the distances between them to be the sum of their effective radii.

It is also possible to represent each shape as an aggregate of points that have a high interaction weightage. This transformation converts the problem of locating shapes to one of locating a number of points. The weight on the distance between point "i" and point "j" is used to reflect whether they are on the same or different shapes.

Multi-dimensional scaling is an attractive means for layout design, for the following reasons:

a. It eliminates the need for shape representation,

b. It is efficient in terms of memory usage and computation,

c. It finds a global optimum, and

d. Mathematical formulation of the problem is simple.

However, multi-dimensional scaling suffers from two serious drawbacks:

a. It is possible to have mirror shape artifacts which result in a pseudosolution.

b. When there are a large number of shapes involved in the layout, the user is responsible for using his judgement in setting distances between points. This may result in infeasible solutions, because no specific overlapping constraint is incorporated in the algorithm.

3.5.4 Conclusions on Alternative Approaches

The methods outlined above have all been coded for simple layout design problems to compare their relative merits. Each of the methods studied had several advantages and disadvantages as summarized in Table 3.2 according to a numerical scale. These ratings are based on the results obtained from testing the approaches. It was found that there was a considerable tradeoff between degree of detail in the representation of shapes, the ease in mathematically formulating the problem and the computational load.

Table 3.2 Summary of the Investigation of Alternative Methods for Solving the Layout Design Problem

Points of Comparison	Cellular Approach	Cspace Approach	MDS and Graph Theory	Super-Shape Approach
1. Ease in Shape Representation				
a. Amount of Detail	1	3	5	4
b. Use of Memory	3	5	2	1
c. Processing Needed to Update Shape Information	5	3	2	1
2. Ease in Formulating the Problem	3	5	2	1
3. Layout Improvement	4	5	3	1
4. Overlap Detection	1	2	5	1
5. Ease in Defining Fixed Shapes and Reserved Areas in the Workspace	1	3	5	1

Shape representation schemes such as variable arrays and ordered vertices, provided sufficient detail, but posed problems in the mathematical formulation and the algorithm. They required complicated algorithms even though they were memory efficient. They are very sensitive to the initial layout configuration. The ordered vertices representation used in the Cspace approach, is considerably more useful once a good initial solution is obtained.

Other schemes such as multi-dimensional scaling and graph theory, allow considerably simpler means for mathematically modelling the problem. However, they are susceptible to shape artifacts and overlapping of shapes because of the weakness in overlap detection and lack of shape integrity checks.

3.6 The Super-Shape Approach

By modelling the devices as cylinders, the layout problem is transformed into one of locating circles in a specified area, which can be solved using conventional optimization methods. This form of shape representation has been used by Moravec [1982], in path planning for a mobile robot. This is the first time that this approach has been applied to the problem of layout design for robotic assembly cells.

With the use of circular super-shapes, the layout design involves optimally placing devices enveloped in circles within a rectangular region. This problem has been broken down into a translation sub-problem and a rotation sub-problem. This was done by approximating the points of delivery/access to the center of the super-shape in the translation sub-problem and using "link-associated centroids" for the rotation sub-problem. (These terms will be explained in Section 3.6.3.1). The assumption is that the inter-device motion has two components - a major component, which is a function of the distance between the centers of the super-shapes, and a minor component due to the distance of the delivery/access points from the center of the super-shape. The translation sub-problem minimizes the major component and the rotation sub-problem minimizes the minor component.

3.6.1 Mathematical Formulation of the Translation Sub-Problem

The translation sub-problem consists of locating a set of circles with specified interactions in a given plane. The objective function is the total weighted inter-shape distance. There are two sets of constraints - collision constraints, to prevent the overlapping of two components, and boundary constraints, to prevent shapes from falling outside the available area. This subproblem ignores the rotation of shapes by placing the aggregated access and delivery points for each shape at the center of the circle. Hence, this can be considered as the translation sub-problem.

The mathematical formulation of this sub-problem is as follows

$$\text{Minimize} \sum_{i=1}^{n-1}\sum_{j=i+1}^{n}[(x_i-x_j)^2+(y_i-y_j)^2](w_{ij})^2$$

subject to the collision constraints

$$(x_i-x_j)^2+(y_i-y_j)^2 \geq \left(\frac{R_i+R_j}{o_{ij}}\right)^2, \qquad i,j=1,..,n$$

and the boundary constraints

$$(X_{\min})_i+R_iF_i \leq x_i \leq (X_{\max})_i-R_iF_i, \quad i=1,..,n$$

$$(Y_{\min})_i+R_iF_i \leq y_i \leq (Y_{\max})_i-R_iF_i, \quad i=1,..,n$$

$$(X_{\min})_i+R_iF_i \le x_i \le (X_{\max})_i-R_iF_i, \quad i=1,..,n$$

$$(Y_{\min})_i+R_iF_i \le y_i \le (Y_{\max})_i-R_iF_i, \quad i=1,..,n$$

3.6.2 Mathematical Formulation of the Rotation Sub-Problem

Once the translation sub-problem has been completed, the circles representing the shapes are assigned "link-associated centroids." The circles are rotated about their centers to determine the best relative orientations, which is the set of shape orientations that will minimize the weighted sum of the distances between link-associated centroids. The number of variables involved is "n."

Mathematically, the problem can be formulated as: Determine the set of angles $\{\theta_1, \theta_2,.., \theta_n\}$, so as to minimize the function

$$fo = \sum_{j=i+1}^{n} \sum_{j=1}^{n-1} (d_{ij} * w_{ij})^2$$

The terms d_{ij} denote the distance between the corresponding link-associated centroids on shapes "i" and "j" respectively. Since, the cartesian coordinates of all link-associated centroids on shape "i" are known in local coordinates (x_i, y_i), the global coordinates can be calculated given the global positions (X_i, Y_i) of the shapes as follows:

$$[C]^{(i)} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & X_i \\ \sin\theta_i & \cos\theta_i & Y_i \end{bmatrix} * \begin{bmatrix} x_i & x_2 & \cdots & x_n \\ y_i & y_2 & \cdots & y_n \\ 1 & 1 & \cdots & 1 \end{bmatrix}$$

For shape "i", x_i and y_i are set equal to zero. From the matrices $[C]^{(i)}$, for shapes i=1,..,n, the distances d_{ij} are given as:

$$d_{ij}^2 = [C_{1j}^{(i)} - C_{1i}^{(j)}]^2 + [C_{2j}^{(i)} - C_{2i}^{(i)}]^2$$

The constraints on the problem are:

$$0^o \leq \theta_i \leq 360^o,\ i=1,..,n$$

3.6.3 Algorithm for the Layout Design

The input consists of the shapes in the cell, part characteristics, and the routing sequence necessary to complete the assembly. The output will be the layout of the cell which will provide near optimal cycle time for the assembly.

This consists of three stages:

a. A conversion of input data into a suitable format,
b. Determining the layout using circles to represent the shapes to simplify the problem (i.e. translation sub-problem), and
c. Obtaining the optimal layout with the circles replaced by the shapes (i.e. rotation sub-problem).

3.6.3.1 Preprocessing Input Data

Each shape is approximated as a circle with all access and delivery points on it being aggregated into one location. The amount of interaction between shapes in the cell - obtained from the routing sequence - is used to determine the weightings on the appropriate distances.

Based on the routing sequence and the physical weight and/or physical size of the parts involved in the transfer, the centroid of the points on shape "i" involved with (i.e., having material transfers to/from) shape "j" is calculated and assigned the tag "j". The corresponding centroid on shape "j" is also calculated and assigned the tag "i". Since the centroids are associated with a link between shapes, they are referred to as link-associated centroids. The given input is thus transformed so that each shape has (n-1) link-associated centroids.

The statistical weights are calculated with information obtained from the routing sheet as described below. The statistical weights are composed of two components: one, the interaction component which is based on the frequency of travel between shapes, and two, the mass multiplier component, which accounts for the physical mass and/or physical size, and other practical considerations involved in the motion of a part. The accumulated weight assigned to a pair of devices is the product of the interaction factor and the mass multiplier.

The interaction factors are equated to the number of trips ocurring between two devices, without any regard to the location on the device that is accessed. A trip is defined as a move from point A on device "i" to point B on device "j". A round trip between the two points would result in a weightage of two. Due to the higher weightage, resulting from the interaction factor, the influence of mimimizing the objective function is to draw the devices together.

In addition to the frequency of interaction between the devices other practical considerations such as the physical mass, physical size and collision avoidance must be considered in the layout design. These factors are incorporated into the weightage through the mass multipliers. These multipliers in effect account for the variation of the speed and the trajectory of the robot in moving between two delivery/access points. The physical mass of the part may influence the speed of the robot motion. If in a particular portion of the assembly cycle the robot must move a part with a large mass which requires it to move at half the operating speed, the motion segment can be scaled by using a mass multiplier of two. The physical size of the component or the presence of obstacles in a delivery/access motion, that requires the robot to deviate from a direct line-of-sight trajectory, can also be handled using the mass multiplier. The magnitudes of the multipliers must be estimated based on the knowledge of the specifics of the case.

3.6.3.2 Algorithm for the Translation Sub-Problem

The algorithm adopted is a penalty function method for solving constrained optimization problems. The constraints are incorporated into the objective function and the resulting penalty function is handled as an unconstrained function. The resulting penalty function for this case is:

$$P_f = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} [(x_i - x_j)^2 + (y_i - y_j)^2](w_{ij})^2$$

$$+ R_g \sum_{k=1}^{n-1} \sum_{l=k+1}^{n} \{<[(x_k - x_l)^2 + (y_k - y_l)^2 - (\frac{R_k + R_l}{okl})^2] + \sigma_{kl}>^2 - (\sigma_{kl})^2\}$$

$$+ R_h \sum_{r=1}^{n} \sum_{s=1}^{4} [<h_s(u_r) + \eta_{rs}^{(t)}>^2 - (\eta_{rs}^{(t)})^2]$$

where

$h_1(u_r) = x_r - ((X_{\min})_r + R_r{*}F_r),$

$h_2(u_r) = ((X_{\max})_r + R_r{*}F_r) - x_r,$

$h_3(u_r) = y_r - ((Y_{\min})_r + R_r{*}F_r),$

$$h4(u_r) = ((Y_{\max})_r - R_r{*}F_r) - y_r$$

The bracket notation <...> used in the penalty function is defined as follows:

$$\langle f \rangle = 0 \text{ , if } f \geq 0$$
$$= f \text{ , if } f < 0$$

The σ_{kl} and η_{rs} mutiplier estimates for the (t+1)'st stage are formed according to the rules:

$$\sigma_{kl}^{(t+1)} = \langle g_j(U_l) + \sigma_{kl}^{(t)} \rangle \text{ , k=1,..,n-1 and l=k+1,..,n}$$
$$\eta_{rs}^{(t+1)} = \langle h_s(u_r) + \eta_{rs}^{(t)} \rangle \text{ , r=1,..,n and s=1,..,4}$$

The first term in the penalty function form is the original objective function, while the second and third terms represent the penalty forms of the collision and boundary constraints. The problem as formulated involves two penalty constants R_g and R_h, n(n-1)/2 multiplier estimates for the collision constraints, 4n multiplier estimates for the boundary constraints, n(n-1)/2 function evaluations of $g_k(u_l)$ and 4n function evaluations of $h_s(u_r)$.

The algorithm consists of a sequence of stages involving the same set of operations. At stage "t", the penalty function $P_f^{(t)}$ is optimized, while holding the multipliers σ_{kl} and η_{rs} constant. To start the next stage, the multipliers are updated according to the rules specified and the penalty function is optimized. The sequences σ_{kl} and η_{rs}, the solution estimate vector (x_i, y_i), and $P_f^{(t)}$ are used to determine the convergence criterion.

3.6.3.3 Algorithm for the Rotation Sub-Problem

This problem is the optimization of a non-linear function with linear constraints. The International Mathematical and Scientific subroutine Library [1981] has subroutines applicable to this type of problem.

3.7 Examples of the use of the Super-Shape Approach

This section details the procedure involved in designing the robotic cell layouts using the super-shape approach for three problems. The algorithm described above have been incorporated in a layout design program.

3.7.1 Wire-Harness Assembly

The example chosen is an assembly application involving the manufacture of a sub-assembly of single-ended wire-harnesses. The operation sequence is shown in Figure 3.2, and is outlined below:

a. Pick up the connector from the gravity feeder and place it in the fixture.
b. Move over to the wire-cutter and pick up the free end of the wire.
c. Move over to the stripping machine and strip the free end.
d. Move over to the crimping machine and crimp the free end.
e. Insert the crimped wire into the appropriate hole in the connector.
f. Repeat the steps b. thru e. until the connector is completely assembled.

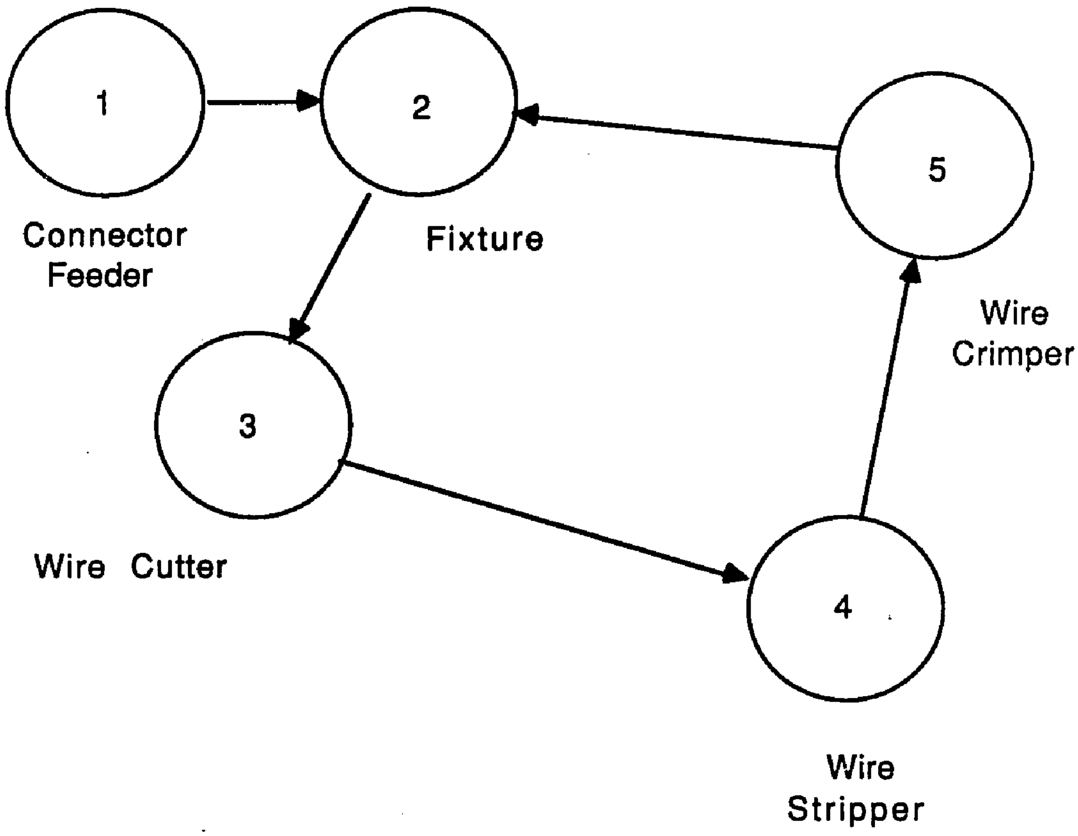

Figure 3.2 Operation Sequence for the Assembly of Single-Ended Wire Harnesses

The list of pertinent devices that are to be considered in the layout problem, and their effective radii are given in Table 3.3. Figures 3.3-3.7 show the approximate shape and dimensions of each device. The circular targets on each shape denote the delivery/access points associated with it. The overall weighting matrix is built up from the interaction and weight multiplier matrices. Because all the components in the assembly are small and light, the appropriate elements in the weight multiplier matrix are set to unity as shown in Table 3.4a. Assuming that the harness uses 6-pin connectors, the interaction matrix is given by Table 3.4b. The overall weighting matrix is then given by Table 3.4c.

The translation sub-problem and the rotation sub-problem are solved using the weights given in Table 3.4c. The solution to the translation sub-problem is shown in Figure 3.8. This is the locally optimal relative location of the devices. It is necessary now to find the optimal relative orientation of the devices. The solution to the rotation sub-problem and the optimal layout for the wire-harness assembly devices is given in Figure 3.9. The dotted line in Figure 3.9 denotes the robot path.

The relative positions and orientations of the devices can be verified by an examination of the interaction matrix. The position and orientation of the gravity feeder(device 1) is determined only by that of the fixture(device 2), so in the optimal layout the gravity feeder should lie next to the fixture and be oriented so that the access point on the feeder is closest to the delivery point at the fixture. In addition, the repeated pattern of operations involving visits to the wire-cutter, the stripping machine, the crimping machine and the fixture in sequence suggests that they should, if possible, be located so that the robot always moves in the same direction without any to-and-fro motion. The orientations of each of the devices in this cyclic sequence of operations is

Table 3.3 Effective Radii of Wire-Harness Stations

Device #	Device Name	Effective Radius (in inches)
1	Connector Feeder	4.7
2	Fixture	3.35
3	Wire Cutter	8.8
4	Wire Stripper	5.3
5	Crimping Machine	12.2

Table 3.4 Calculation of the Overall Weighting Matrix
(Wire-Harness Assembly)
a. Mass Multiplier Matrix
b. Interaction Matrix
c. Overall Weighting Matrix

$$\begin{array}{ccccc} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 \end{array} \qquad \begin{array}{ccccc} 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 6 & 0 & 6 \\ 0 & 6 & 0 & 6 & 0 \\ 0 & 0 & 6 & 0 & 6 \\ 0 & 6 & 0 & 6 & 0 \end{array} \qquad \begin{array}{ccccc} 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 6 & 0 & 6 \\ 0 & 6 & 0 & 6 & 0 \\ 0 & 0 & 6 & 0 & 6 \\ 0 & 6 & 0 & 6 & 0 \end{array}$$

(a) (b) (c)

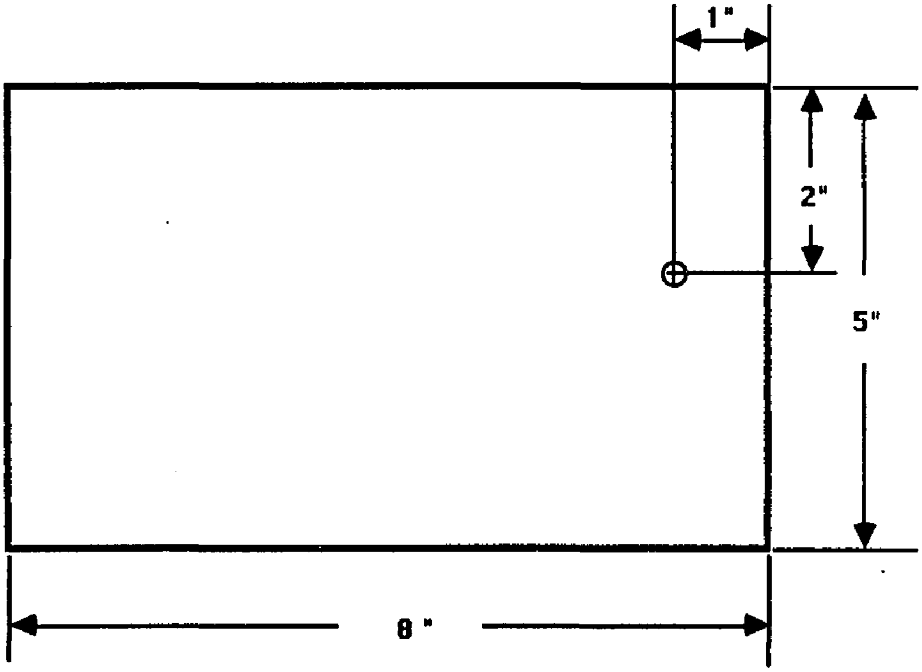

Figure 3.3 Connector Feeder Footprint in the Wire-Harness Assembly Problem
⊕ denotes delivery/access points

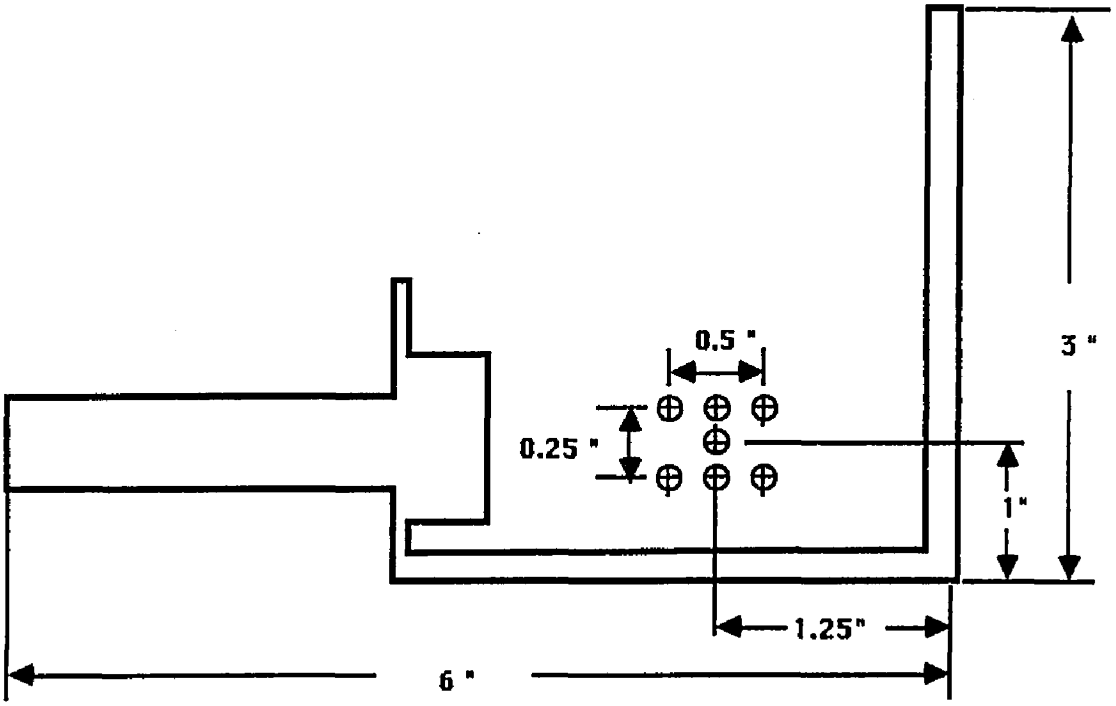

Figure 3.4 Fixture Footprint in the Wire-Harness Assembly Problem
⊕ denotes delivery/access points

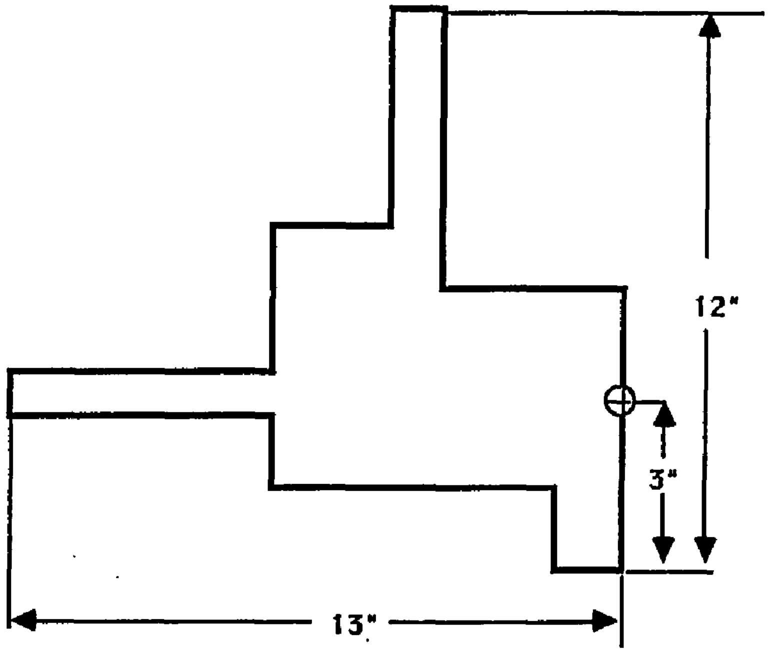

Figure 3.5 Wire Cutter Footprint in the Wire-Harness Assembly Problem
⊕ denotes a delivery/access point

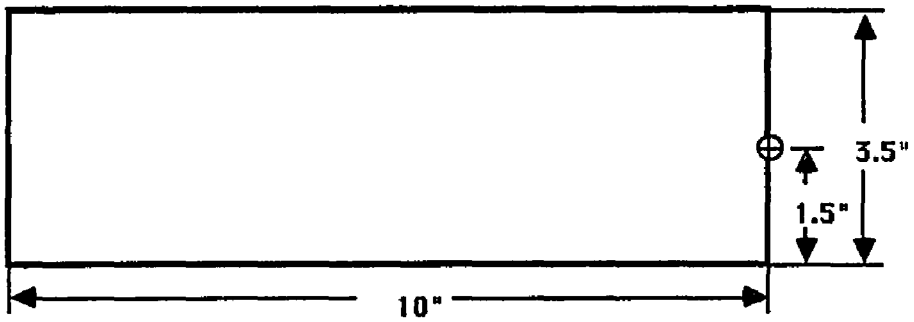

Figure 3.6 Wire Stripper Footprint in the Wire-Harness Assembly Problem
⊕ denotes a delivery/access point

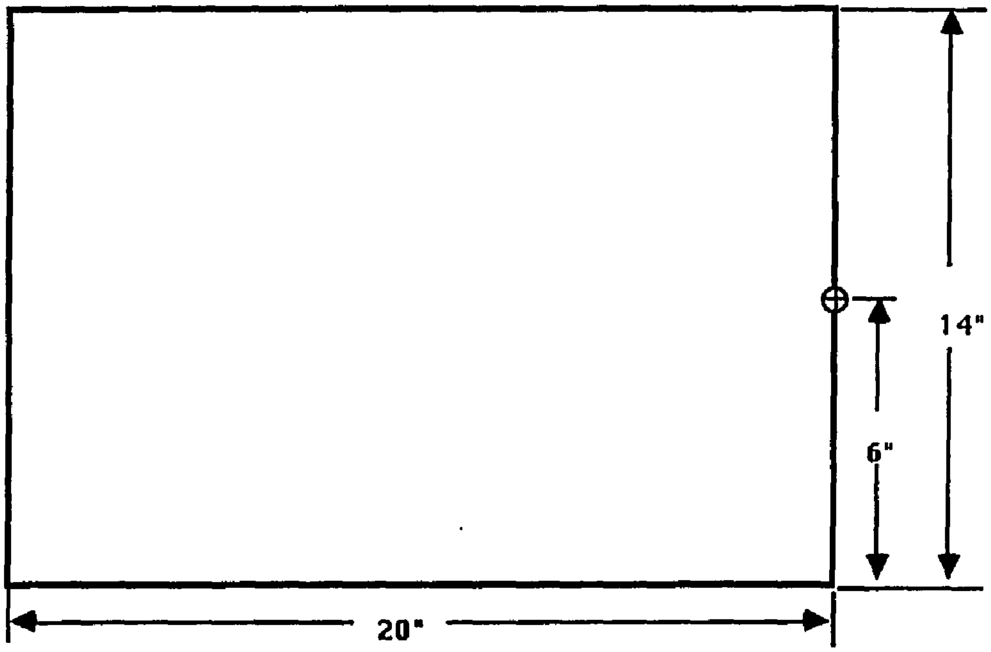

Figure 3.7 Crimping Machine Footprint in the Wire-Harness Assembly Problem
⊕ *denotes a delivery/access point*

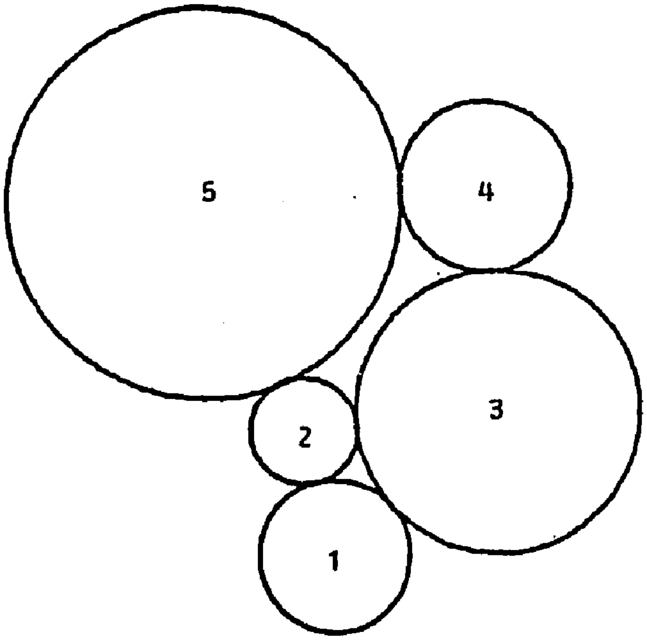

Figure 3.8 TSP Solution to the Wire Harness Assembly Problem

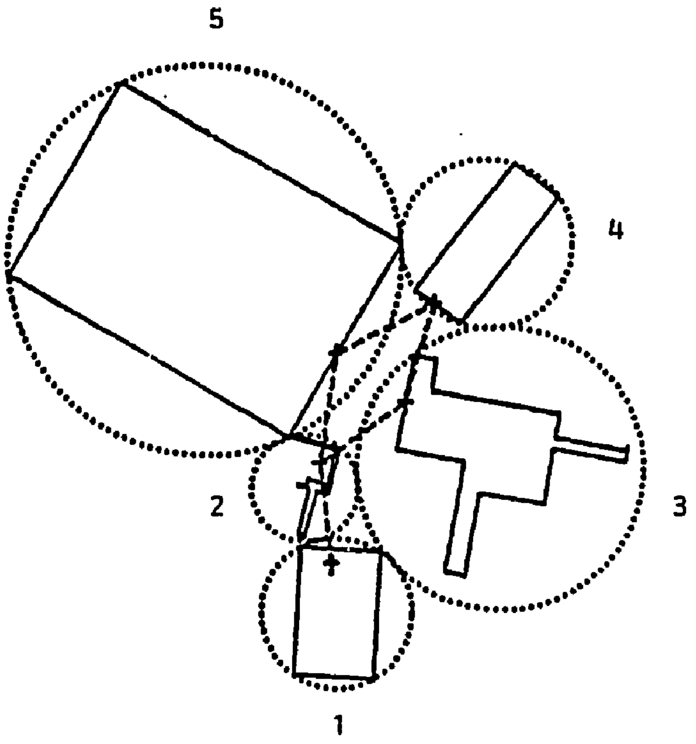

Figure 3.9 Optimal Solution to the Wire Harness Assembly Problem

only influenced directly by the previous and the succeeding devices in the sequence. All these conclusions made from an examination of the operation sequence are apparent in the optimal layout obtained from the algorithm.

3.7.2 Office-Equipment Assembly

The second example involves the assembly of an office equipment item shown in Figure 3.10. The components of the product were supplied to the robot by a kit. The problem is now to find the optimal relative location of the components on the kit. This example differs from the previous example in the number, and range of the physical size and aspect ratio of the devices in the cell as shown in Figure 3.11. The assembly of this product requires an assembly fixture and 17 different devices for presenting the components.

The list of the devices and their effective radii is given in Table 3.5. The assembly sequence is shown in Table 3.6. From this, the interaction component matrix is determined, and is shown in Table 3.7. The mass multiplier matrix was taken as a unity matrix, so the overall weighting matrix is the same as the interaction matrix. For the solution of the translation sub-problem, the assembly fixture was fixed at the center of the kit, and the optimal locations of the other devices were found with respect to it. This was done because the assembly fixture had the most interaction with the other devices. The local optimal solution for the translation sub-problem is shown in Figure 3.12.

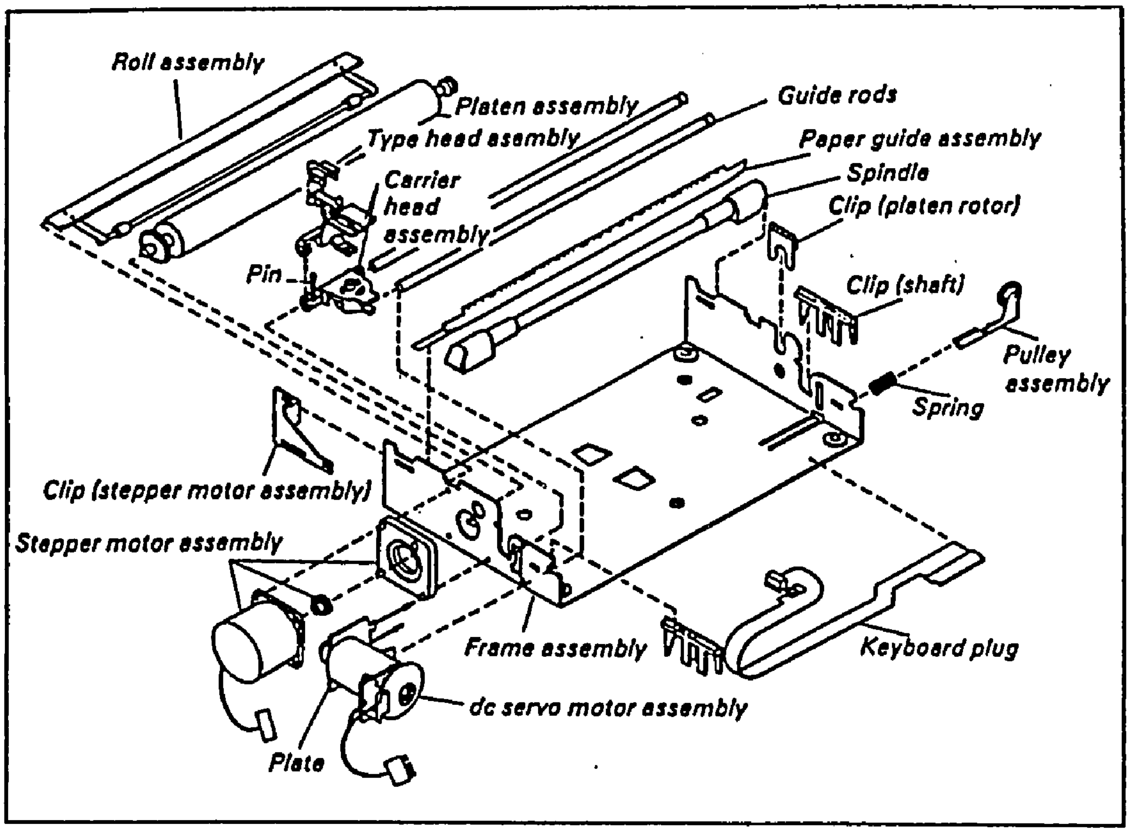

Figure 3.10 Exploded View of the Office-Equipment Assembly

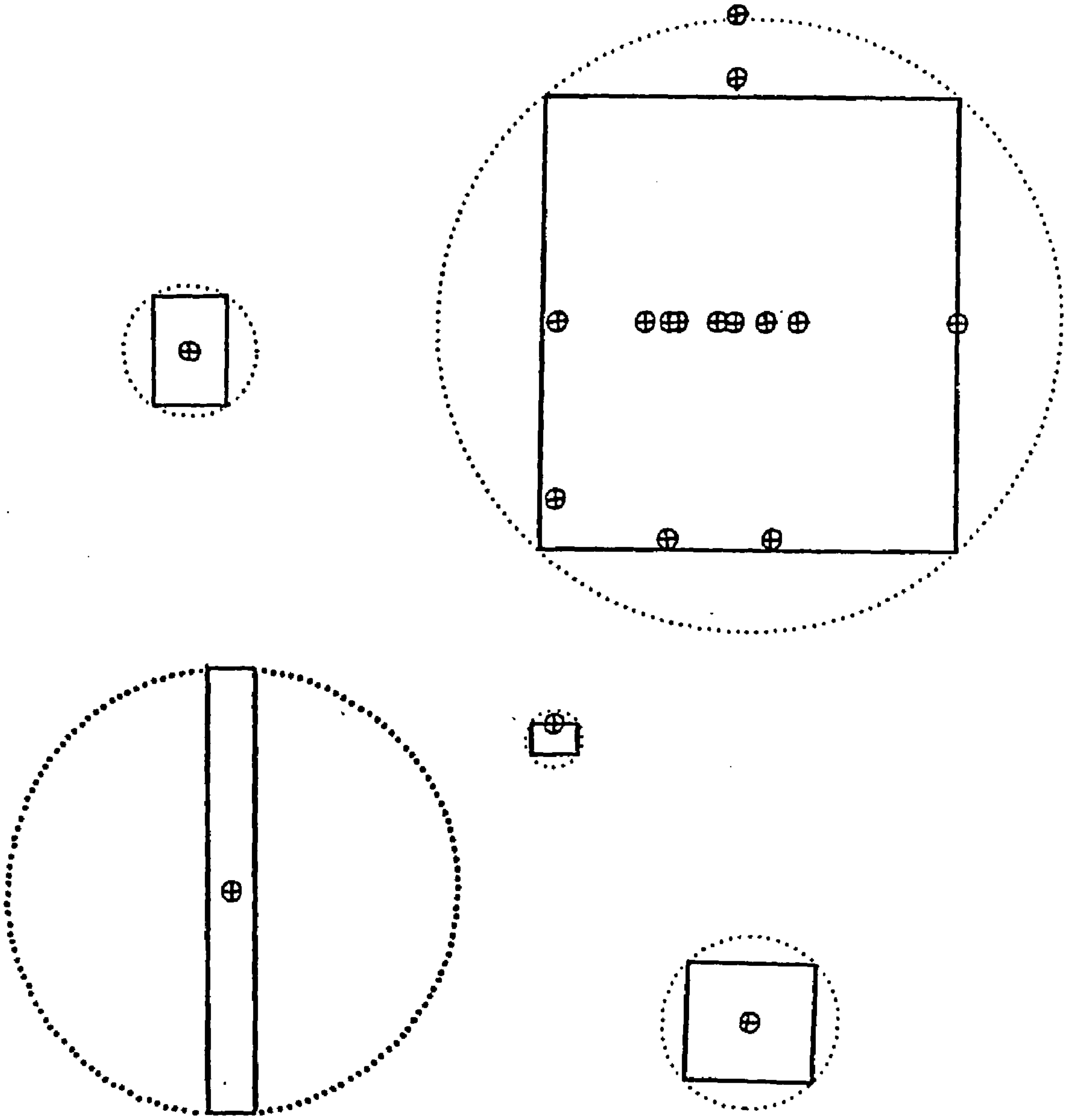

Figure 3.11 Footprints for Several of the Devices in the Office-Equipment Assembly Problem

Table 3.5 Effective Radii of Office-Equipment Stations

Device #	Device Name / Part Being Presented	Effective Radius (in inches)
1	Keyboard	7.89
2	Guide Rod	7.00
3	Guide Rod	7.00
4	Roll Assembly	7.00
5	Spindle	7.00
6	Platen Assembly	7.00
7	Paper Guide	7.00
8	DC Servomotor Assembly	2.83
9	Carrier Head Assembly	1.95
10	Stepping Motor Assembly	2.74
11	Retaining Clip	2.08
12	Platen Ring Clip	0.90
13	Pulley Assembly	1.68
14	Spring	1.07
15	Stepping Motor Clip	1.62
16	Auxiliary Gripper	1.46
17	Frame Assembly	7.95

Table 3.6 Operation Sequence (Office-Equipment Assembly)

17 --> 18 --> 10 --> 18 --> 8 --> 18
--> 7 --> 18 --> 14 --> 18 --> 13
--> 18 --> 2 --> 18 --> 3 --> 9
--> 18 --> 11 --> 18 --> 11 --> 18
--> 1 --> 18 --> 15 --> 18 --> 16
--> 6 --> 18 --> 16 --> 12 --> 18
--> 4 --> 18 --> 5 --> 18

Table 3.7 Calculation of the Overall Weighting Matrix
(Office-Equipment Assembly)

1	x	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
2		x	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
3			x	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
4				x	0	0	0	0	0	0	0	0	0	0	0	0	0	2
5					x	0	0	0	0	0	0	0	0	0	0	0	0	2
6						x	0	0	0	0	0	0	0	0	0	1	0	1
7							x	0	0	0	0	0	0	0	0	0	0	2
8								x	0	0	0	0	0	0	0	0	0	2
9									x	0	0	0	0	0	0	0	0	1
10										x	0	0	0	0	0	0	0	2
11											x	0	0	0	0	0	0	4
12												x	0	0	0	0	1	1
13													x	0	0	0	0	2
14														x	0	0	0	2
15															x	0	0	2
16																x	0	2
17																	x	1
18																		x

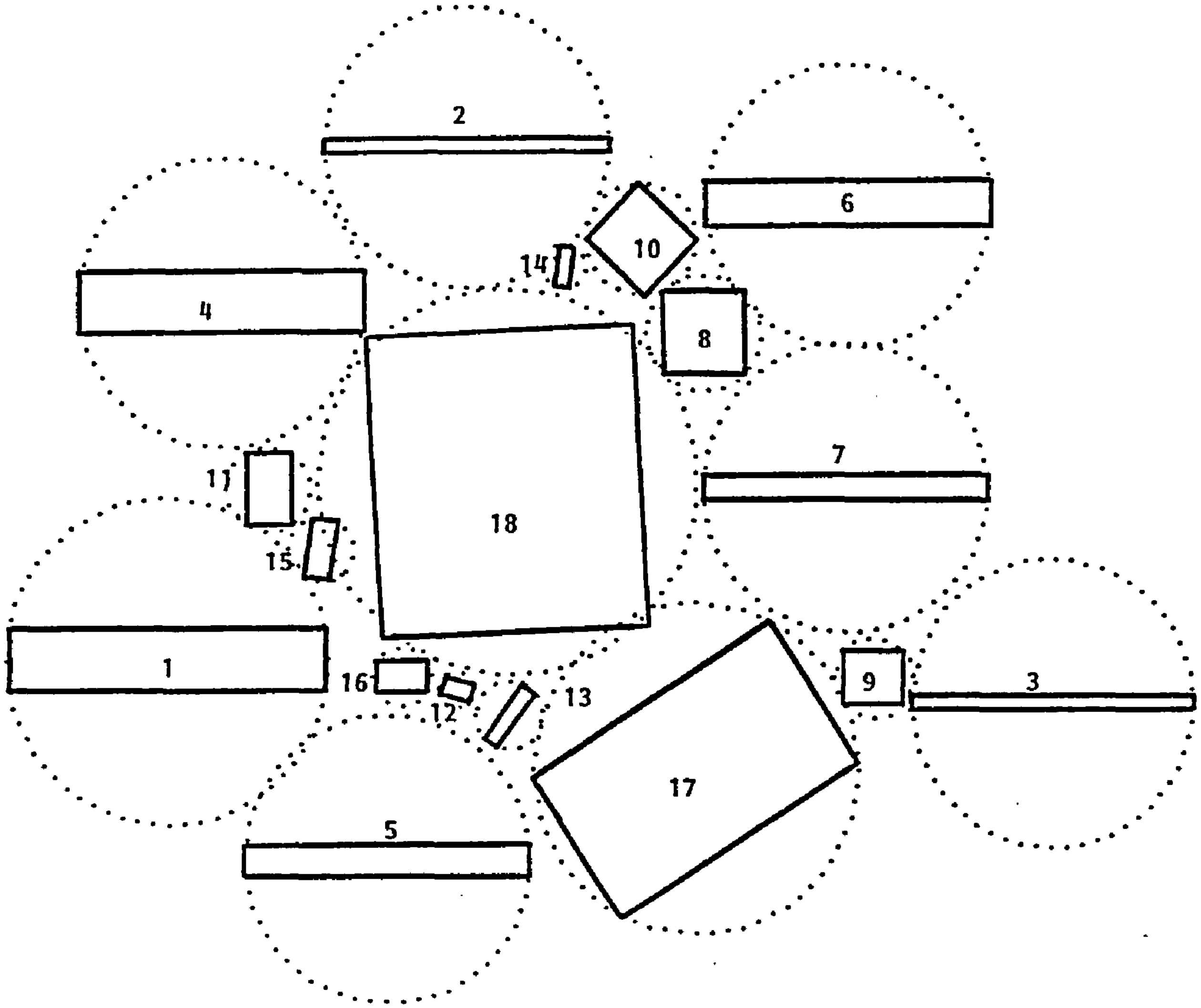

Figure 3.12 TSP Solution to the Office-Equipment Assembly Problem

For the solution of the rotation sub-problem several devices whose link-associated centroids coincided with the center of the super-shape, were excluded. This reduces the order of the problem from a non-linear minimization problem with 18 variables to one of 11 variables. The devices that were excluded from the problem were arbitrarily assigned a zero orientation. In implementing the layout, these devices could be assigned any orientation. The devices that have been fixed, can be seen in the solution of the rotation sub-problem, the final layout, shown in Figure 3.13. This solution is a local optimum.

3.7.3 Control Panel Assembly

This example involves the assembly of a control panel for use on line-printers. The exploded view of the assembly is shown in Figure 3.14. The control panel consists of a frame that has 13 delivery/access points at which sub-assemblies are inserted. The sub-assemblies come in five different types: display button, push button (long plunger), push button (short plunger), toggle switch (single-pole single-throw) and toggle switch (single-pole double-throw) sub-assemblies. Models of the control panel differ in the combination of sub-assemblies used, and in the locations on the frame where they are inserted.

The control panel assembly consists of 13 basic components. Table 3.8 lists the components, their item numbers and dimensions. A list of the components used to build up each of the sub-assemblies is shown in Table 3.9. Not all the components in the assembly are feedable. Table 3.10 identifies the feedable parts and the unfeedable parts. The unfeedable parts are transported to the assembly area on the kit. The

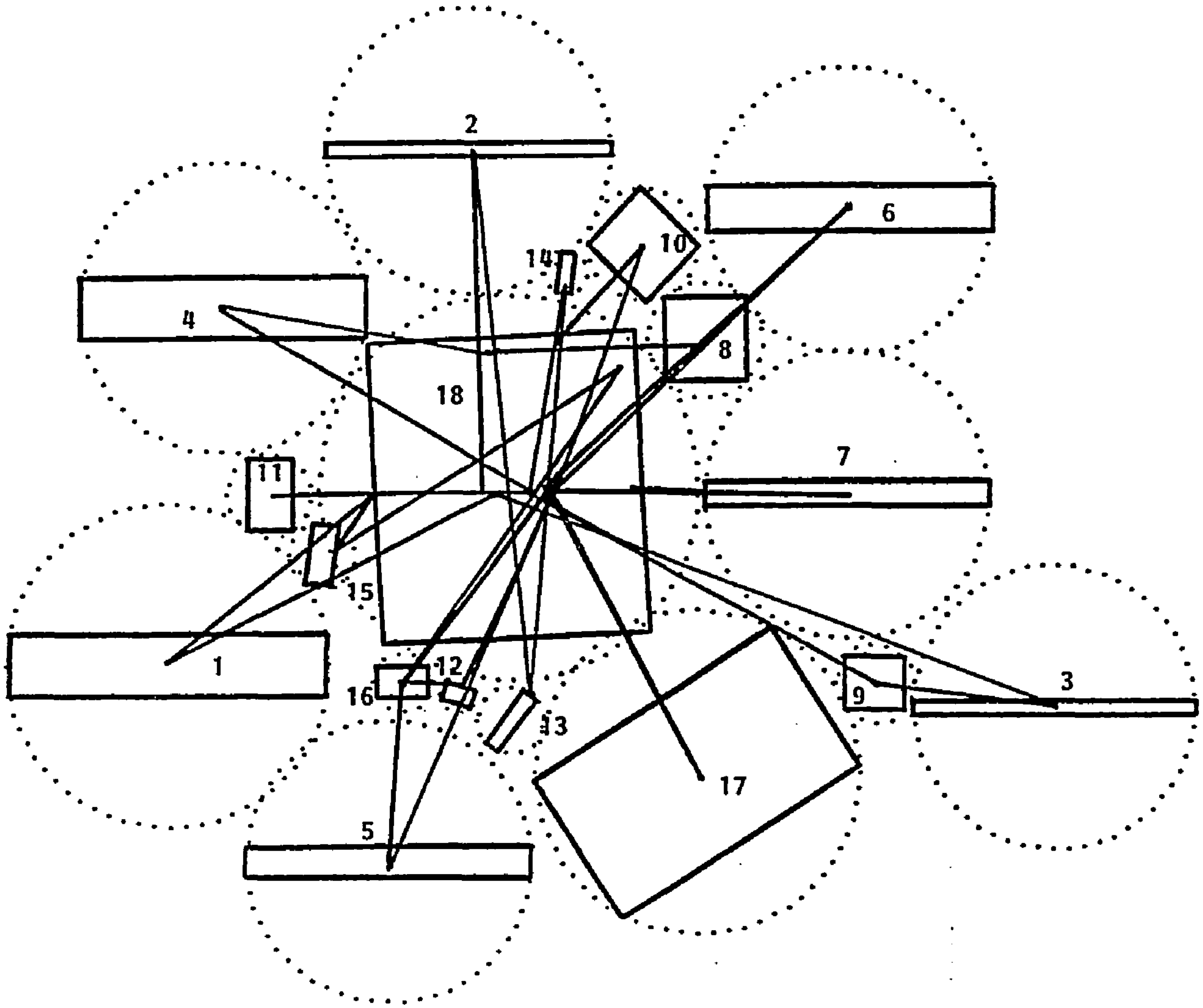

Figure 3.13 Optimal Solution to the Office Equipment Assembly Problem

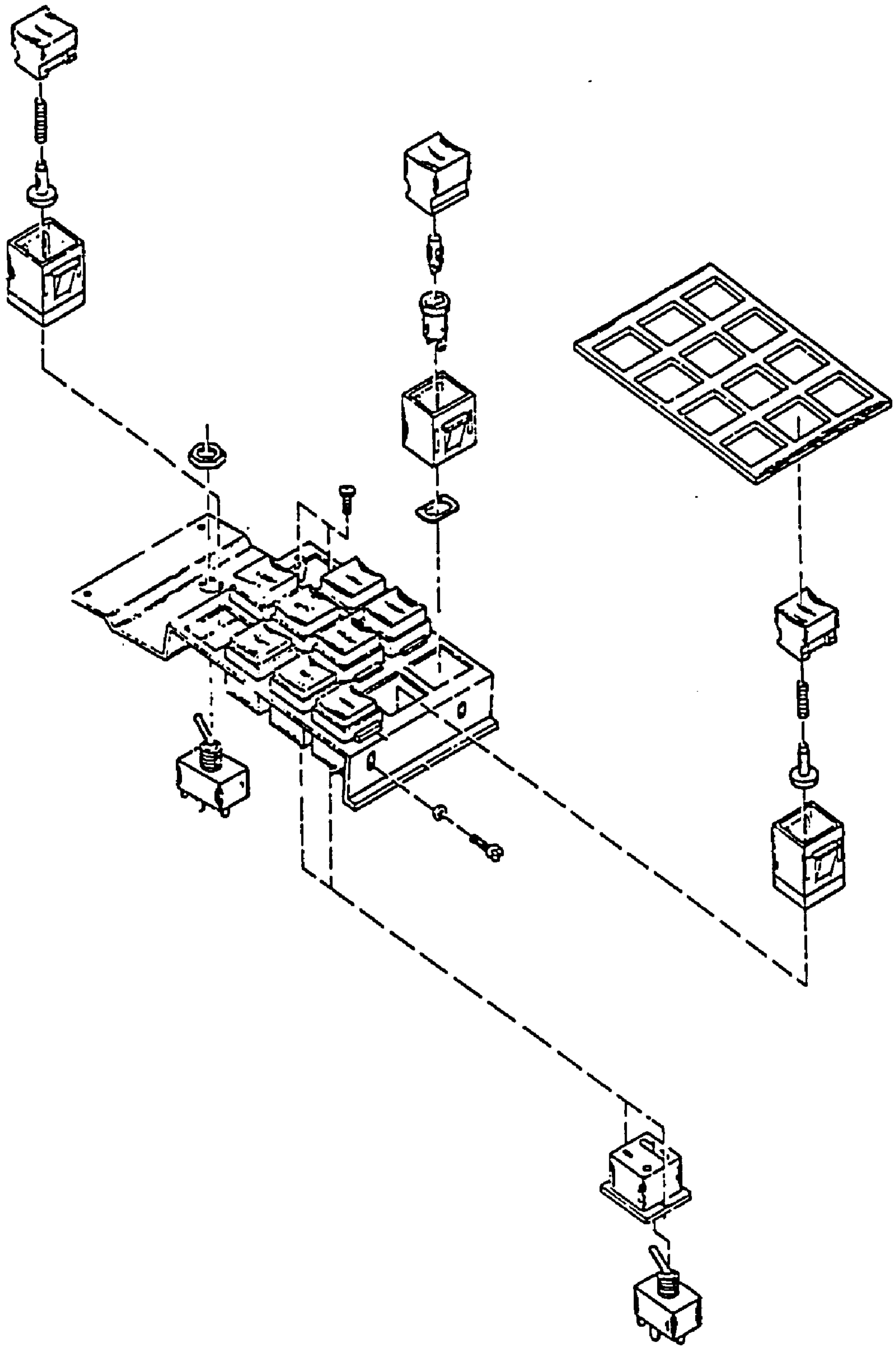

Figure 3.14 Exploded View of the Control Panel Assembly

Table 3.8 List of Control Panel Assembly Components

Item Number	Item Name	Dimension L x W x D (cms)
1.	Lamp	-
2.	Frame	15x26x5
3.	Screw	-
4.	Spring	-
5.	Push Button	3x3x3
6.	Lamp Holder	1.5x1.5x3
7.	Plunger, Long	1.5x1.5x3
8.	Plain Hex Nut	-
9.	Plunger, Short	1.5x1.5x2.5
10.	Display Button	3x3x4
11.	Retaining Clip	-
12.	Switch Assembly	3.5x3.5x6
13.	Acoustic Material	15x20x0.5
14.	Toggle Switch, SPST	3x3x6
15.	Toggle Switch, SPDT	3x3x6
16.	Display Housing	3.5x3.5x5
17.	Toggle Housing	4x4x4

Table 3.9 Sub-Assembly Components

Push Button Sub-Assembly	Display Button Sub-Assembly	Toggle Switch Sub-Assembly
Push Button Spring Plunger Switch Assembly	Display Button Lamp Lamp Holder Display Housing Retaining Clip	Toggle Housing Toggle Switch

Table 3.10 Feedable and Unfeedable Parts in the Control Panel Assembly

FEEDABLE PARTS	UNFEEDABLE PARTS
Display Button	Lamp
Push Button	Spring
Long Plunger	SPST Toggle Switch
Short Plunger	SPDT Toggle Switch
Lamp Holder	Frame
Display Housing	
Toggle Housing	
Switch Assembly	

Table 3.11 Assignment of Parts to Kit and Feeder

FEEDER	KIT
Display Button (10)	Switch Assembly (12)
Push Button (5)	Toggle Housing (17)
Plunger, Short (9)	Spring (4)
Plunger, Long (7)	Display Housing (16)
Lamp Holder (6)	Lamp (1)
	Toggle Switch, SPST (14)
	Toggle Switch, SPDT (15)
	Acoustic Material (13)
	Frame (2)

Table 3.12 Number Assignment for the Control Panel Assembly Devices

Device Number	Device Name	Effective Radius (in cms)
1	Kit	28
2	Fixture #1	7
3	Fixture #2	7
4	Display Button Magazines	8
5	Push Button Magazines	8
6	Short Plunger Magazines	2
7	Long Plunger Magazine	2
8	Lamp Holder Magazine	4

feedable parts, however, have been arbitrarily assigned to the kit and feeder. The assignment of parts is given in Table 3.11. The kit is assumed to carry the assembly fixtures and end-effector tooling.

In order to facilitate robotic assembly, the product has been redesigned to allow for unidirectional assembly. Sub-assemblies are built using two fixtures that are located in the robot workspace. Fixture 1 is used to assemble the push button and display button sub-assemblies, while Fixture 2 is used for the toggle switch sub-assemblies. The completed sub-assemblies are transported to the kit and inserted in the appropriate location on the frame. Figure 3.15 shows the devices to be placed in the robot workspace. Each device has been assigned a number that is to be used in the layout design process. The numbering scheme is given in Table 3.12. The procedure for assembling each of the sub-assemblies and the interaction matrices associated with each sub-assembly is shown in Table 3.13.

Two models of the control panel are to be assembled in equal quantities. The sub-assemblies that make up the models, and the delivery/access points at which they are to be inserted are given in Table 3.14. From the data in Table 3.14, and the fact that the models are being produced in equal quantities, a composite product can be identified, as given in Table 3.15. The layout design will be based on the assembly of the composite product. The overall interaction matrix in Table 3.16 is built up for the composite product. Since the physical mass and size of the components is small and there is no great change in the height of the devices in the workspace, the overall weighting matrix is the same as the overall interaction matrix.

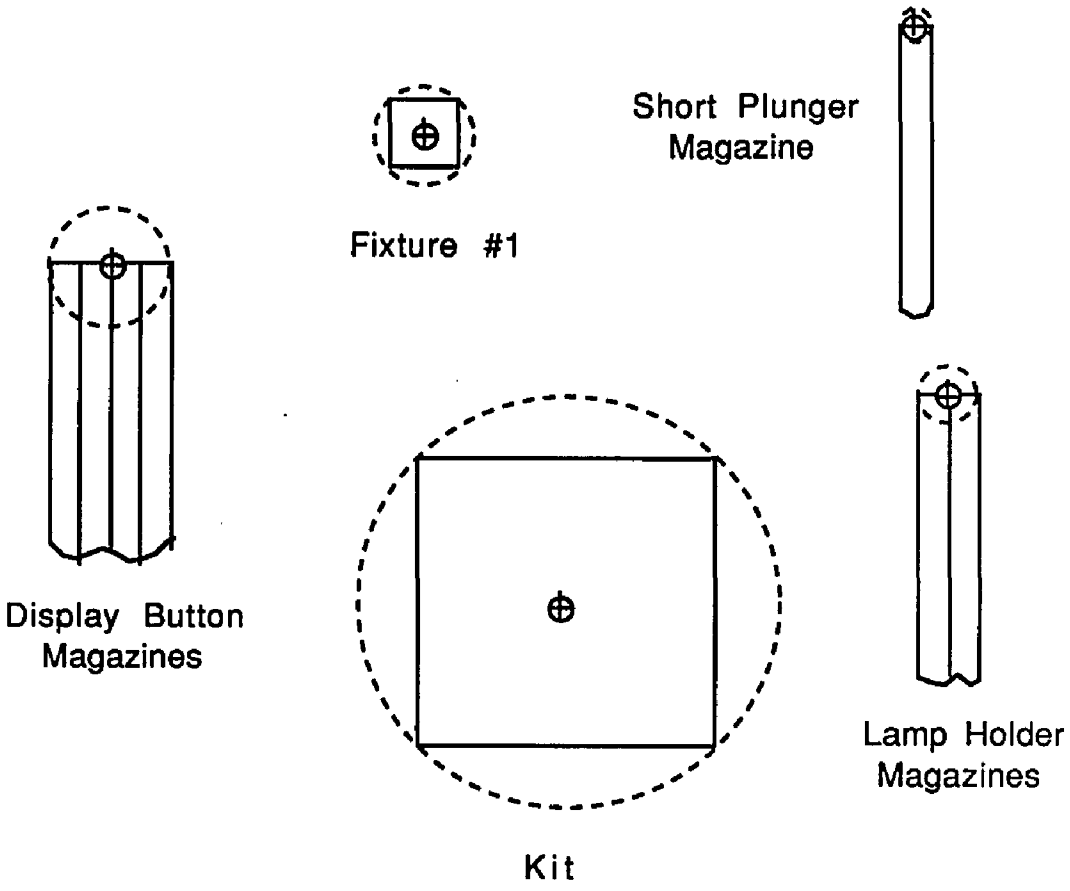

Figure 3.15 Footprints for Several Devices in the Control Panel Assembly Problem
⊕ denotes delivery/access points

Table 3.13 Assembly Sequence and Interaction Matrices
for the Sub-Assemblies
a. Display Button Sub-Assembly
b. Push Button Sub-Assembly (Short/Long Plunger)
c. Toggle Switch (SPST) Sub-Assembly
d. Toggle Switch (SPDT) Sub-Assembly

Pick up the display housing	(1)
Insert in fixture #1	(2)
Pick up the lamp holder	(8)
Insert in fixture #1	(2)
Pick up the end-effector	(1)
Pick up the lamp	(1)
Insert in fixture #1	(2)
Return the end-effector	(1)
Pick up the display button	(4)
Insert in fixture #1	(2)
Insert completed sub-assembly in the frame	(1)

$$\begin{array}{c} 1\\ 2\\ 3\\ 4\\ 5\\ 6\\ 7\\ 8 \end{array} \begin{bmatrix} x & 5 & 0 & 1 & 0 & 0 & 0 & 0 \\ & x & 0 & 1 & 0 & 0 & 0 & 2 \\ & & x & 0 & 0 & 0 & 0 & 0 \\ & & & x & 0 & 0 & 0 & 0 \\ & & & & x & 0 & 0 & 0 \\ & & & & & x & 0 & 0 \\ & & & & & & x & 0 \\ & & & & & & & x \end{bmatrix}$$

(a)

Pickup Switch Assembly	(1)
Insert in fixture #1	(2)
Pickup short/long plunger	(6/7)
Drop in fixture #1	(2)
Pickup the spring	(1)
Insert in fixture #1	(2)
Pick up push button	(5)
Insert into switch assembly	(2)
Insert the sub-assembly in the frame	(1)

$$\begin{array}{c} 1\\ 2\\ 3\\ 4\\ 5\\ 6\\ 7\\ 8 \end{array} \begin{bmatrix} x & 4 & 0 & 0 & 0 & 0 & 0 & 0 \\ & x & 0 & 0 & 2 & 2 & -2 & 0 \\ & & x & 0 & 0 & 0 & 0 & 0 \\ & & & x & 0 & 0 & 0 & 0 \\ & & & & x & 0 & 0 & 0 \\ & & & & & x & 0 & 0 \\ & & & & & & x & 0 \\ & & & & & & & x \end{bmatrix}$$

(b)

Pickup toggle switch(SPST)	(1)
Insert into the frame	(1)

(c)

Pick up toggle switch(SPDT)	(1)
Insert in fixture #2	(3)
Pick up toggle housing	(1)
Insert in fixture #2	(3)
Insert completed sub-assembly in frame	(1)

$$\begin{array}{c} 1\\ 2\\ 3\\ 4\\ 5\\ 6\\ 7\\ 8 \end{array} \begin{bmatrix} x & 0 & 4 & 0 & 0 & 0 & 0 & 0 \\ & x & 0 & 0 & 0 & 0 & 0 & 0 \\ & & x & 0 & 0 & 0 & 0 & 0 \\ & & & x & 0 & 0 & 0 & 0 \\ & & & & x & 0 & 0 & 0 \\ & & & & & x & 0 & 0 \\ & & & & & & x & 0 \\ & & & & & & & x \end{bmatrix}$$

(d)

Table 3.14 Product Description

Delivery/ Access Point	Model A	Model B
1	e	e
2	d	c
3	d	a
4	d	d
5	a	a
6	a	a
7	a	a
8	b	d
9	b	a
10	b	a
11	c	c
12	b	b
13	c	a

Table 3.15 Composite Product Description

Sub-Assembly Type	Model A	Model B	Composite Product
a	3	4	(3+4)/2=5.0
b	4	1	(4+1)/2=2.5
c	2	2	(2+2)/2=2.0
d	3	2	(3+2)/2=2.5
e	1	1	(1+1)/2=1.0

Table 3.16 Overall Interaction/Weighting Matrix for the Control Panel Assembly

1	x	43	4	5	0	0	0	0
2		x	0	5	9	4	5	10
3			x	0	0	0	0	0
4				x	0	0	0	0
5					x	0	0	0
6						x	0	0
7							x	0
8								x

From the production requirements, it has been determined that four magazines of display buttons, four magazines of push buttons, two magazines of lamp holders, and one magazine each of short plungers and long plungers are required for the robot to operate for 1.25 hour without the need for replenishing the magazines. (See the appendix) From the data on the devices in the layout, the effective radii are calculated and are given in Table 3.12.

The solution to the translation sub-problem is shown in Figure 3.16. The various devices in the cell have been confined to specific sections of the workspace. The magazines have been confined to rectangular area at thc top of the figure, while the two fixtures are allowed in the left region in the workspace and the kit to the right region in the workspace. This was done in order to allow the kit free entry and exit to and from the robot workspace. More detailed explanation of this figure is provided in Section 3.8. The rotation sub-problem was not solved since the orientations of the magazines have been defined, and the orientations of the fixtures does not influence the travel time. It was decided that it is convenient to have the kit oriented at zero degrees. Therefore, the final layout of the cell is given in Figure 3.17.

As in the case of the wire-harness assembly, it is possible to relate the overall weighting matrix and the relative location of the devices. The matrix suggests that fixture 1 (shape 2) has a heavy interaction with the magazines (shapes 4,5,6,7,8) and the kit (shape 1), and should therefore be centrally located with respect to them. It also suggests the position that Fixture 2 (shape 2) has taken in the layout.

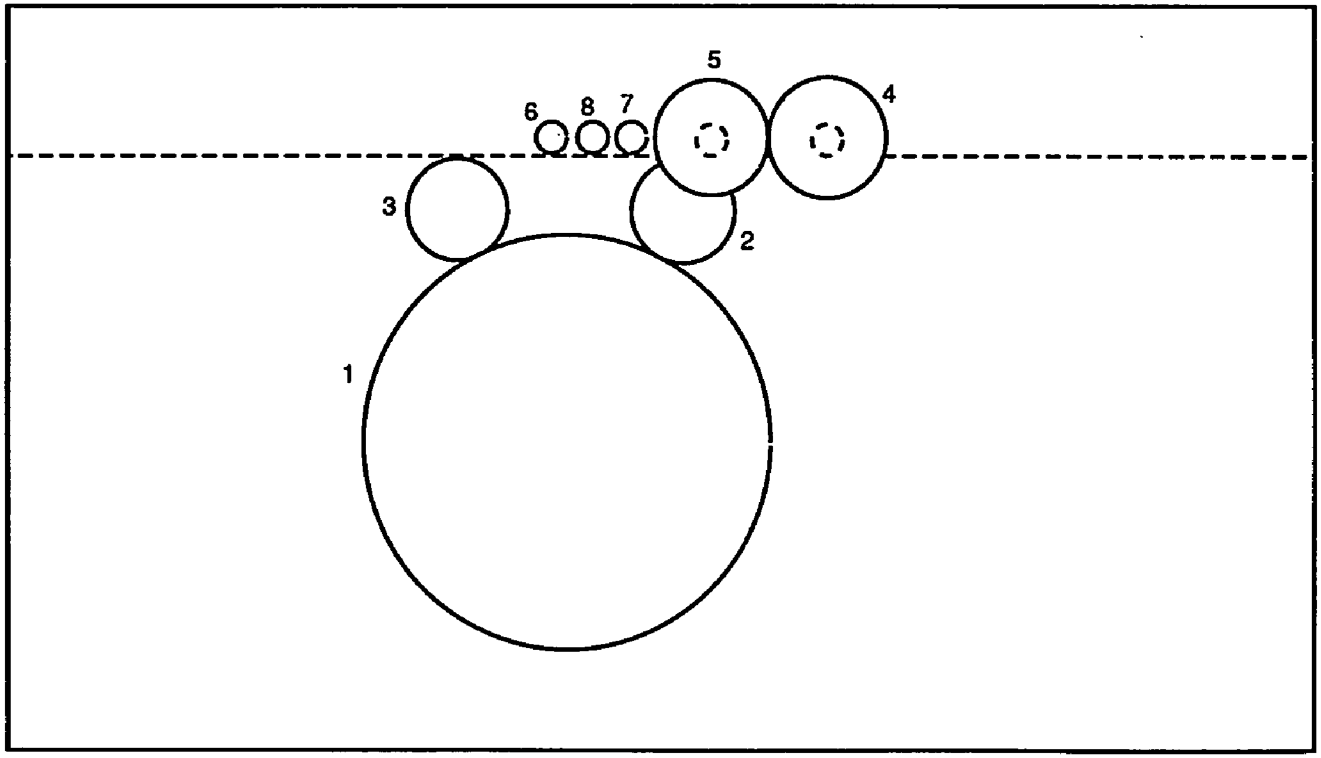

Figure 3.16 TSP Solution for the Control Panel Assembly Problem
(Device Numbers refer to Table 3.12)

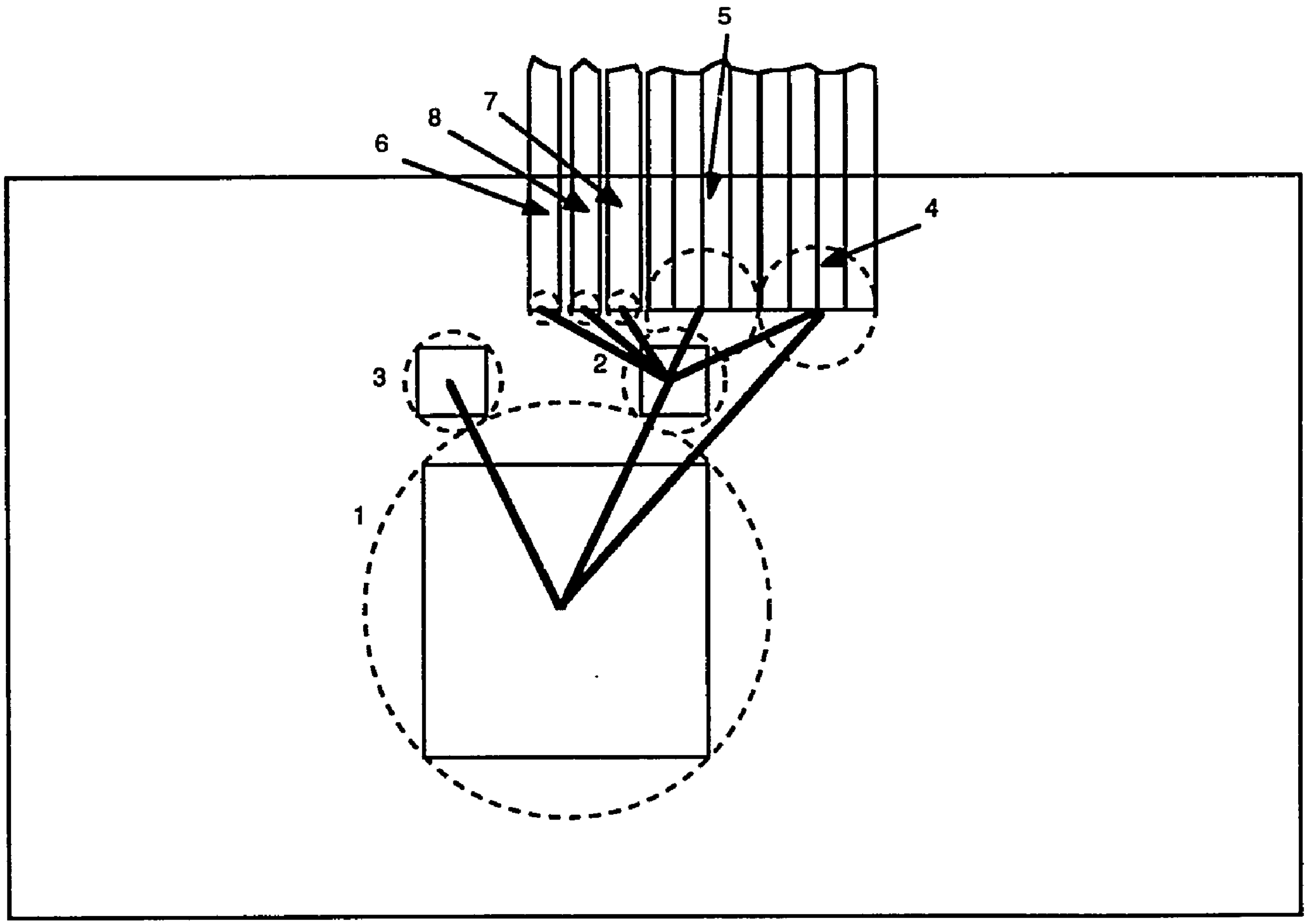

Figure 3.17 Final Layout for the Control Panel Assembly Problem with Robot Travel Path (Device Numbers refer to Table 3.12)

3.8 Conclusions on the Super-Shape Approach

Though the idea of modelling objects as cylinders or spheres has been used in path planning problems, this is the first time that the super-shape approach has been applied to layout design. The super-shape approach was found to be superior to the alternative approaches outlined in Section 3.5. It allows a simple analytical formulation of the problem, which can be solved using standard non-linear optimization methods. The simplicity of the formulation allows the user to handle each of the four criteria itemized in Section 3.4 and repeated below.

a. Fixing the Location of One or More Devices: This is done by removing the (x,y) coordinate pair of the fixed device from the list of optimization parameters. The objective function is evaluated using the user-specified coordinates for the fixed devices. The device overlap constraints remain the same as before. Since the user is free to choose the location of the fixed devices, it is possible to place devices partly or completely outside the confines of the workspace. This also allows certain parts to be assigned apriori locations with the kits.

b. Making Areas of the Workspace Inaccessible: The manner in which an inaccessible area is handled depends on its location and form. It could be located in the center of the workspace or at the periphery, and its form could vary from a small portion (as in the case of a physical obstruction), to a strip running through (as in the case of a conveyor) the workspace. A small inaccessible area can be modelled with dummy super-shapes. These super-shapes are not entered in the objective function, but the overlap constraints are included with the existing ones. This results in additional overlap constraints that depend on the number of dummy super-shapes. A strip of the workspace for conveyors, etc. can be made inaccessible to devices by introducing appropriate linear constraints on the location of the devices.

c. Allow One or More Devices to be Fixed: The location of any of the devices can be fixed in the robot workspace. These super-shapes, however, are entered into the objective function. The associated position constraints are dropped, while the overlap constraints are retained to prevent collision with the other devices that are to be located in the workspace. This results in the reduction in the number of position constraints. When there is more than one fixed shape, there is also a reduction in the number of overlap constraints.

d. Allow the Specification of Desirable Areas for Devices: The linear position constraints can be used to specify zones in the workspace where a device, D, can be located. This can be done by placing appropriate position constraints. This does not introduce any new constraints. An alternative approach, would be to weight the device to certain areas of the workspace by introducing 'gravity-points'. These are one or more dummy super-shapes of zero radius that are weighted with respect to A so as to influence the area of the workspace in which it resides. This does not introduce any position or location constraints, but it does increase the number of terms in the objective function.

The rough shape representation of a circular super-shape influences the overlap and device position constraints. The shape representation can be modified to handle special cases by the use of radius adjustment and overlap factors. These factors effectively allow the user to employ different radii for a super-shape depending on whether a device location constraint is being evaluated or an overlap constraint is being evaluated. These have been introduced in order to enable the user to design layouts where there is a severe space limitation.

To understand the use of radius adjustment factors in device position constraints, consider Figure 3.18. The high aspect ratio of the actual device results in a crude representation of the device. In the event that the device orientation is not known apriori, the algorithm will place the corresponding super-shape inside the dashed line. This is a wasteful use of the available space. But this can be minimized when the device orientation is known apriori. This situation may arise out of a technical necessity or because it is at the discretion of the designer. The latter situation arises when the delivery/access points on the device are at the center of the super-shape.

When the device orientation is known as shown in Figure 3.19, a more efficient use of space is possible if the radius shown in the dotted line is used in the position constraint. The radius adjustment factor enables the user to do this. It is the user-provided multiplier that is applied to the effective super-shape radius when determining position constraint violations.

Similarly, it is possible to allow super-shapes to overlap by user-specified levels. This level is specified by the user for each pair of super-shapes in the form of an overlap factor. For example, two super-shapes of radii one and two inches respectively would have an overlap factor of one, when the minimum allowable distance between the shapes is the sum of their radii, i.e., (1+2) = 3 inches. If it is felt that the minimum allowable distance (three inches) that is based on the effective radii is inappropriate, an overlap factor of 1.5 would allow the super-shapes to have a minimum allowable distance of $\frac{3}{1.5}=2$ inches. The user can selectively allow a pair of devices to overlap by specifying the appropriate overlap factor.

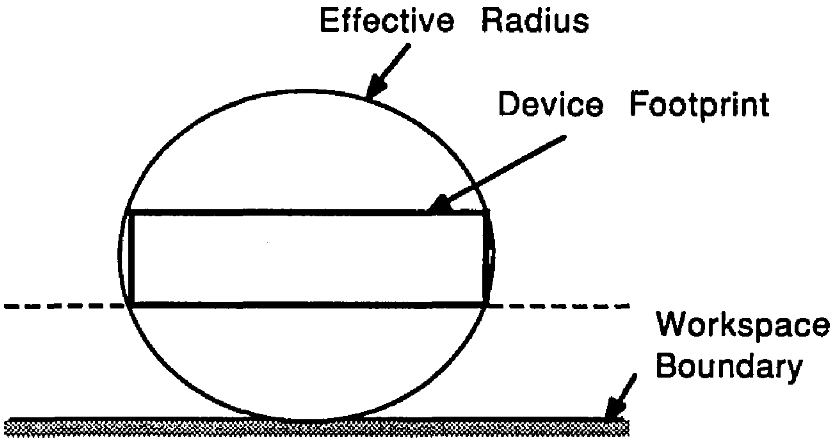

Figure 3.18 Example of the Inadequacy of Effective Radii

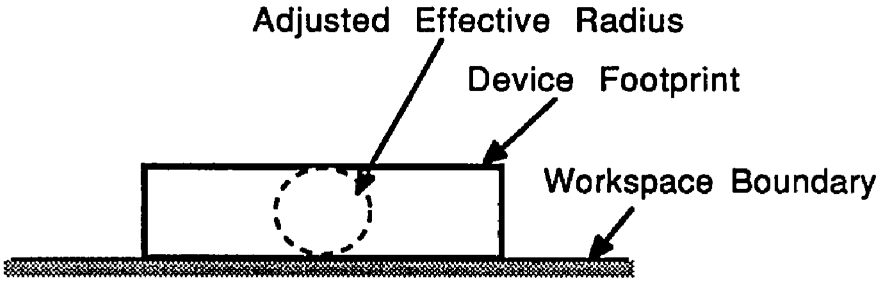

Figure 3.19 Use of Radius Adjustment Factors

Both the radius adjustment factors and the overlap factors were used in the design of the control panel assembly cell layout. The radius adjustment factors were used for the display housing magazines. It was necessary to have 4 magazines of display housings in the layout. Since, it was decided that the magazines should be arranged along one side of the workspace, it was possible to approximate each magazine by the small section located at the delivery end as shown in Figure 3.20. Each of the magazines is therefore approximated by a super-shape (effective radius = 4cms) shown in dotted lines, and the group is represented by the super-shape (effective radius = 16cms) shown in bold. Since the orientation of this group is known apriori to be parallel to the edge of the workspace, a radius adjustment factor of $\frac{4}{16} = 0.25$ was used. The effect can be seen in Figure 3.20.

Without the overlap factor, between super-shape 5 (push button magazines) and super-shape 2 (fixture 1), the super-shape approximation for device 5 would prevent the use of otherwise accessible space as shown in Figure 3.17.

The super-shape approach provides a locally optimum layout from which to develop the implemented layout. It helps to sort complex device interactions that are not easily done otherwise. While the exact shape representation suffers from the crude representation of devices with large aspect ratios by circles, this apparent drawback is offset by practical considerations that require clearance around a device so that the robot gripper can gain access to it without fear of a collision. The most significant advantage of the super-shape approach is that it does not require an initial solution. The chief drawback, is that the solution is a local optimum. The example of the office-equipment assembly demonstrates these aspects.

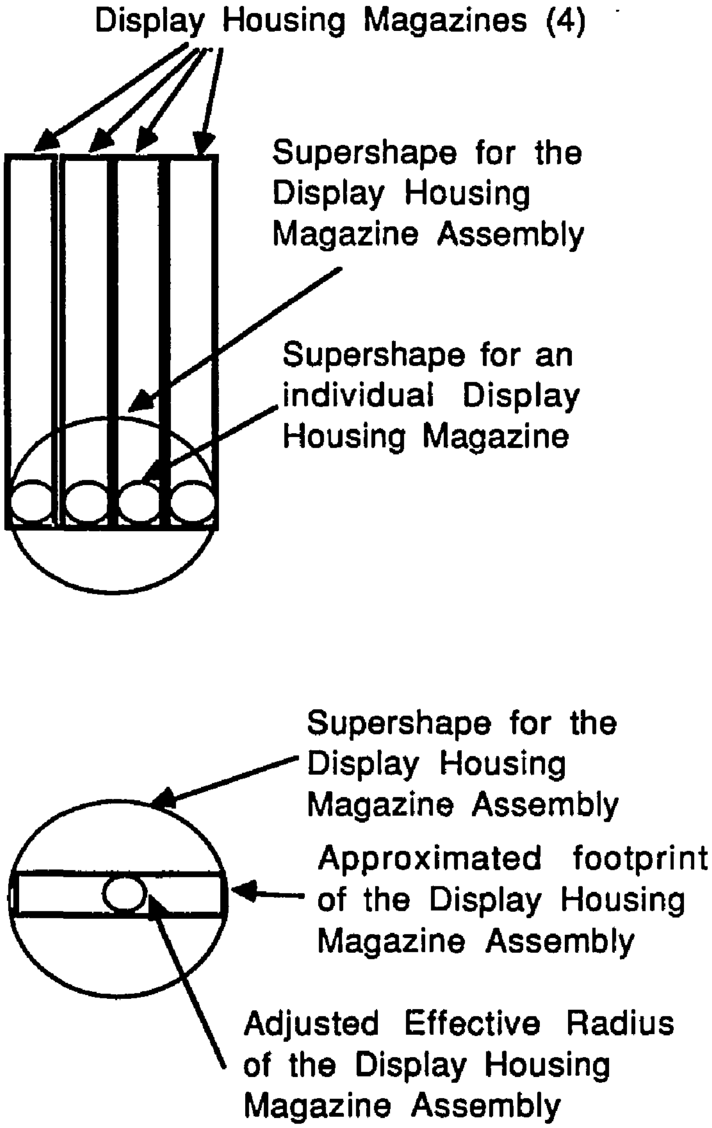

Figure 3.20 Example of the Use of Effective Radii and Radius Adjustment Factors

3.9 Layout Measure from the Layout Optimization

The physical layout obtained from the layout optimization provides a weighted robot travel distance for assembling the composite product. Since the variation of the robot speed in the assembly process has been factored into the overall weighting matrix, the travel time and the assembly time can be determined from the weighted robot travel distance and the robot speed. This is covered in detail in Section 4.8.

CHAPTER 4

SYSTEM AND COST ANALYSIS MODEL

4.1 Introduction

Evaluation of advanced automation systems requires an awareness of their differences from conventional systems. Evaluation procedures should give due consideration to these factors in arriving at a measure of worth. Goldhar [1984] notes that short product life-cycles, high variety product lines, flexibility, and demand for quality and reliability are characteristics of computer-integrated manufacturing systems. He recommends the need to move away from "manufacturing's traditional focus on cost per unit and to a system that evaluates the factory in terms of its ability to contribute to the profitability and the long-term competitiveness of the firm as a whole." He suggests minimum changeover costs and time, maximum flexibility and quick turnaround, minimum downtime for maintenance, and maximum product family range as alternate criteria of factory value. Kulatilaka [1984] in discussing investment decisions related to advanced automation, identifies the lower vulnerability to product-mix variations, improved quality and system reliability, reduced waste and higher capital utilization as issues.

These studies emphasize the need to evaluate advanced automation systems differently from conventional systems. Due weightage needs to be given to intangible benefits that result. For the purpose of this study the only intangible considered is the flexibility of the system to changes in the demands made on the system. The manner in which the unit cost measure varies over the range of part presentation systems is of interest. Based on this curve, a decision-maker can pick out the appropriate levels of feedable parts to be kitted. Although there are a number of capital budgeting techniques adopted in industry, the approaches most commonly used in the industry are the payback period method, rate of return method and the net present worth method [Fujita and Turvaville,1984]. Most firms conduct sensitivity analyses to handle uncertainities. Other approaches that are used include Monte Carlo techniques and other probabilistic methods [Fujita and Turvaville,1984]. In this study, the net present worth wethod is used. Future events are handled probabilistically as demonstrated in Chapter 5.

The net present worth method attempts to discount current and future cash flows to the present. The proposal with the highest net present worth is the most attractive. A net present worth that is negative or zero corresponds to a loss. This approach differs from the internal rate of return method in that it uses a growth rate - a rate at which the value of investment grows - for discounting future cash flows. The drawback of the net present worth method is that it requires the decision-maker to estimate an average growth rate in the value of future and current cash flows. However, it is always possible to employ uncertainity analysis techniques to study the influence of the growth rate estimate on the final results. The advantages of this method are that it takes into account the entire life of a project and different risk profiles can be incorporated.

4.2 General Model of the Part Presentation System

The model used in analyzing the part presentation system is shown schematically in Figure 4.1. Parts necessary for assembling the desired products enter the system through the kit/magazine preparation area. The unfeedable parts and some of the feedable parts (as determined by the analysis) are moved to the kitting area preparatory to being placed on kits. The remaining feedable parts are moved to the feeding area preparatory to being loaded into magazines.

Parts are loaded into kits by a processor that would depend on the system. It could be human labor, robots, a combination of robots and humans, etc. Completed kits are stored in the kitting area waiting to be transported to the assembly area. Similarly, the parts that are loaded into magazines are handled by another processor and are stored in the feeding area. The kits and magazines are shuttled between the assembly area and the kitting and feeding areas respectively. The handler could be human, conveyor, AGV, robot, etc.

The loaded kits and magazines are buffered at the assembly area awaiting processing at the assembly cell. The assembly cell itself could consist of robots or a mixture of robots and humans. After the assembly is completed, the empty kits are returned to the kitting area. Empty magazines are returned to the feeding area when fresh magazines are delivered. Kit and magazine delivery and return are in general asynchronous events.

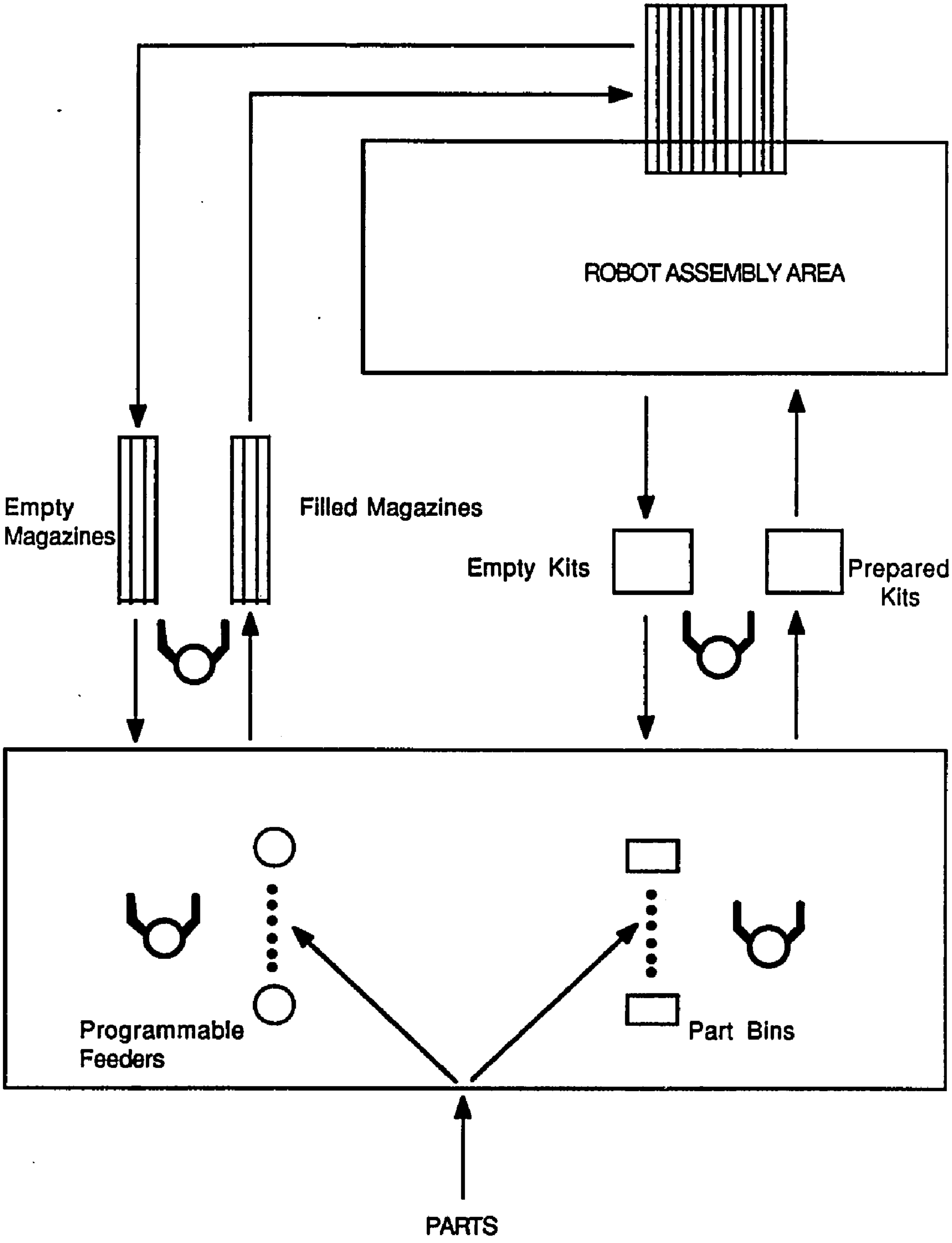

Figure 4.1 Schematic for the Assembly System

When constructing a model to evaluate a part presentation system, it is important to recognize that the unfeedable parts will be handled by kits irrespective of the feedable parts. Therefore, it is sufficient to consider the impact of the feedable parts on the system. It is then necessary to relate the impact on the system due to the quantity of parts being handled by the feeders. This includes equipment costs, processing costs and costs incurred down the line due to future production changes. This process would necessarily depend on the complexity and configuration of the system. The procedure is demonstrated in Chapter 5 for the assembly of control panel assemblies.

4.3 Information Required in the Methodology

In order to perform the analysis, it is necessary to obtain information on the products and the production scenario. This information can be obtained in-house (e.g. growth rate, planning horizon) or in published literature (e.g. the cost of a material handler) or it must be estimated (e.g. the change in the product mix). A sampling of the elements on which information needs to be gathered is itemized as shown in Table 4.1. The determination and the use of each of these factors is shown by example in Chapter 5.

4.4 Cost Breakdown

All of these part presentation system costs may be broken down into three components which are loosely based on the time of occurrence - capital costs, operating costs and alteration costs. The capital costs are those incurred at the outset, the operating costs are incurred during the life of the system and the alteration costs

Table 4.1 Data Needed for the Methodology

- I. Product Information
    - a. Assembly Procedure
        - i. Sequence Information
        - ii. Support Equipment Required
    - b. Physical Product Details
        - i. Part Name and Count
        - ii. Feedability and Unfeedability
        - iii. Physical Size and Mass Characteristics
- II. Assembly Equipment Information
    - a. Device Name and Count
    - b. Physical Size
- III. Production Information
    - a. Initial Production Schedule
    - b. Future Production Schedule
        - i. Product-Mix Changes
            - 1. Amount of Change
            - 2. Frequency of Change
        - ii. Product Design Change
            - 1. Number of feedable part types
            - 2. Number of unfeedable part types
            - 3. New product-mix information
            - 4. Frequency of change
            - 5. Number of parts of each type
- IV. Economic Information
    - a. Equipment Related
        - i. Cost of feeder
        - ii. Cost of a magazine
        - iii. Cost of bins
    - b. Financial factors
        - i. Growth rate
        - ii. Planning Horizon

occur when there are changes in the demands on the system.

The capital costs include all costs that are incurred in installing the system. This includes the equipment and the development costs. Items that would come into this category are the purchase of kits, magazines and material handlers. The operating costs are those that are incurred during the operation of the system when there is no change in the product design or mix. Items that are in this category are the costs resulting from energy, maintenance and labor. The alteration costs are the costs incurred when a new product is introduced or a design change occurs. This consists of costs associated with the alteration or purchase of kits, magazines, feeders, manpower and other resources. Specific installations will have items that have not been listed above. In such instances, the base definition is used in determining the cost category to which a particular cost item is to be assigned.

The cost components of each of the categories that are independent of the part presentation system need not be considered. The costs of the basic robot, peripheral equipment, physical space and fixtures are capital cost elements that effectively fall out. These decisions have to be made specifically in regard to the system that is being considered. Only pre-tax analysis without depreciation is to be performed. The approach to be taken is to determine the part presentation system that will minimize the hidden costs that will be incurred down the line as a result of the current decision.

4.5 Cost Elements

In this study, a composite product is used for evaluating the system. It is assumed to be the unit of production and its characteristics (part count, part types, number of parts per part type, etc.) are a composite of the products that comprise it. These characteristics are updated whenever there is a change in production. A change in product mix would involve a change in the characteristics determined by the new ratio. A change in the product design would require an estimation of the characteristics of the new product design. These characteristics are then incorporated into the characteristics of the composite product. All future references to a product will denote the composite product.

The product consists of N parts of which NFP and $NUFP$ are the number of feedable and unfeedable parts respectively. Therefore, we have:

$$N = NFP + NUFP$$

If NFP_k is the number of feedable parts that are presented to the robot via a kit, then:

$$\text{Kitting factor} = \frac{NFP_k}{NFP}$$

All the unfeedable part types are handled by kits, while a decision would need to be made about how many and which of the different feedable part types would be handled by kit. The number of parts of each feedable part type is known from the product information. It is assumed that all parts of a particular feedable part type will be handled by the same part presentation device. So, the kitting factor would be a discrete function.

a. Material Handling: The flow of the feedable part types can be analyzed in terms of four different flows: one, the flow of some feedable part types to the kitting area; two, the flow of these part types via kit to the assembly area;

three, the flow of the remaining feedable part types to the feeding area; and four, the flow of these remaining feedable part types via magazine to the assembly area. The material transfer function can be performed in a number of different ways and the handler chosen differs between systems. The costs associated with the material handler would consist of an equipment cost and an operating cost. In the case of human labor, it would consist solely of the operating cost that could be given in terms of the hours spent in the operation. Several factors such as flow volume, part mass and size characteristics, etc. would influence the costs.

b. Cost of Kits: It is necessary to consider only the costs resulting from the use of kits to transfer feedable part types. The costs depend on the quantity of feedable parts that are transported by kit. The cost could be assumed to be due to the space and the positive locationing necessary to transport the feedable parts. The minimum number of kits required would depend on the relative times for preparing the kit and assembling the product, and the amount of time that the system is expected to work unsupervised.

c. Cost of Magazines: The cost of magazines is dependent on the number of different feedable part types transported, the number of feedable parts per feedable part type, relative times for preparing the magazine and assembling the product, and the amount of time that the system is expected to work unsupervised.

d. Costs of Feeders: The number of feeders necessary would depend on the number of feedable part types that are to be handled and the volume of the parts. It is possible to use programmable feeders to allow the system to adjust to future changes in the feedable parts that are to be handled.

e. Cycle Time: Assuming that the resource utilization of the assembly cell is critical, the cycle time for assembling a product determines the rate at which the parts need to be supplied to the assembly area from the kit/magazine preparation area, and also the rate at which the magazines and kits have to be prepared in the kit/magazine preparation area. The cycle time is influenced by the change in product mix or product design. The change results from the redistribution of the flow of feedable part types in the system or the introduction of new feedable part types. The change in the cycle time has to be estimated based on the estimate of this redistribution.

4.6 Assumptions

The system is assumed to be driven by the assembly cell, so that the time taken to assemble a product is the predominant factor in the determination of the production rate of the system. Since the frequency of material shipments between the assembly area and the kit/magazine preparation area are dependent on the cycle time, it is necessary to estimate this factor.

It is assumed that the assembly cell is an independent manufacturing entity. It does not share its resources with any other activity on the factory floor. The other resources such as the material handler and the equipment and handlers in the kit/magazine preparation area are assumed to be shared. However, they are always available when required, without the possibility of the contention of resources with other areas on the factory floor. For a flexible assembly system that is of a cellular nature, with pockets of automation linked together by material handlers and staging areas, it is possible to break down the overall system into cells similar to the one in this study.

Other technical elements such as equipment malfunctions, jamming of part feeders, part quality, etc. are not considered. The cost influences of these factors may be incorporated into the basic cost elements. These costs must be estimated by the engineer.

4.7 Cost Relations

Each of the sections of the system will be dealt with in sequence to determine the contribution that they have to the costs in the system. The sequence will be dictated by the flow of the parts through the system.

4.7.1 Inventory and Handling Area

When the parts enter the system, they are stored in the inventory and then transported to the kit/magazine preparation area as required. The inventory costs result from holding the parts necessary for the assembly of the composite product. The costs associated with the inventory are dependent on the volume of production only. Kitting factor does not influence these costs.

Once the components are delivered to the kit/magazine preparation area, they are released into the bins and feeder bowls according to the requirements of the system. It will be assumed that human labor is used for this operation. Once again, the work content of this operation is dependent only on the production volume and not on the kitting factor. Therefore, it does not enter the analysis. For the same reasons, the capital costs and alteration costs for this part of the system are not relevant for this analysis.

4.7.2 Kit and Magazine Preparation Area

At the kit/magazine preparation area, the influence of the kitting factor is most prevalent. The equipment that is present and the work content is dependent on the flow of feedable parts in each area. In the event of a production change, both alteration costs and operation costs will result that are influenced by the kitting factor.

4.7.2.1 Capital Costs

A number of items that are needed in the kit/magazine preparation area result in capital expense at the outset of production. Each of these items (part bins, kits, programmable feeder bowls, magazines, material handlers and floor space) is dependent on the volume of flow in each area and therefore the kitting factor.

a. Part Bins: Parts that are brought to the kit/magazine preparation area to be kitted are placed in bins. It is assumed that the size of each bin is such that it can handle an ample number of parts and can cover fluctuations in the number of components of any part type - feedable or unfeedable. One bin is assumed to be enough for a part type. The cost incurred for bins is given by equation 1 in Table 4.2.

Table 4.2 Cost Equations

Equation #	Capital Costs	
	Item	Equation
1	Bins	$CB_c = CPB_c * NFPT_k$
2	Kits	$CKS_c = CPP_c * NFP_k * NOK$
3	Feeders	$CF_c = CPF_c * NOF$
4	Magazines	$CM_c = CPM_c * NOM$
5	Kit Handler	$CCK_c = 2 * ICPP_k * NFP_k * PV$
6	Magazine Handler	$CCF_c = 2 * ICPM_k * \sum_{i=1}^{NFP} (\frac{NFP_i * PV}{MC})$
Equation #	Operating Costs	
	Item	Equation
7	Kitting	$OC_k = CPP_o * NFP_k * PV$
8	Feeding	$OC_f = UOC_f * NFP_f * \frac{PV}{FC}$
9	Feeder Servicing	$OC_{fs} = LC * ST * PV$
10	Kit Transportation	$KT_o = PV * NFP_k * RT_k * HC_k$
11	Magazine Transportation	$MT_o = PV * NFP_f * RT_m * HC_m$
12	Robot Operation	$RC_o = (\alpha_f * NFP_k + \beta * NFP_f) * UROC$

b. Kits: The parts are removed from the part bins and arranged on kits in the kit/magazine preparation area. For an arbitrary kitting factor, the kit would transport a certain quantity of feedable parts in addition to the unfeedable parts. The capital cost is incurred in the form of an increase in the size of the kit to accomodate the feedable parts. This cost can be expressed by equation 2 in Table 4.2.

c. Feeders: The feedable parts that are to be handled via magazines are dropped into the bowls of the appropriate feeders. It is assumed that all the feeders are identical. So, the capital cost incurred on feeders is given by equation 3 in Table 4.2.

d. Magazines: Oriented parts that exit the bowl are handled by 'out-of-bowl' tooling and loaded into magazines. The magazines are assumed to be identical for all the part types. Therefore, the contribution to capital costs is given by equation 4 in Table 4.2.

4.7.2.2 Operating Costs

The operating costs prior to the kit/magazine preparation area do not enter the analysis for the reasons cited earlier. The operations at the kit/magazine preparation area that need to be considered are, the kitting operation; the feeding operation; the transportation of kits between the kit/magazine preparation area and assembly area; the transportation of magazines between the kit/magazine preparation area and assembly area; and the assembly process.

a. Kitting Operation: The kitting operation involves removing parts from bins and putting together the kit. The cost of this operation can be divided into two components, one each for the feedable parts and the unfeedable parts. The component due to the unfeedable parts is once again not important for this analysis. It is assumed that the operation cost is linear with respect to the number of feedable parts that are kitted. The operation cost is given by equation 7 in Table 4.2.

b. Feeding Operation: The operating costs associated with the feeder consist of the cost to operate the feeders and service them (i.e. replacing filled magazines with empty ones). Each of these operations is related to the production volume. The feeder operating cost is given by equation 8 in Table 4.2. Assuming the feeders are serviced by human labor, the cost of servicing the magazines is given by equation 9 in Table 4.2.

4.7.3 Kit and Magazine Handling Area

The kit and magazine handling area is responsible for taking populated kits and magazines to the assembly area to be assembled, and then returning the magazines and kits to the kit/magazine preparation area.

4.7.3.1 Capital Costs

The capital costs in the kit and magazine handling area consists of the cost of the handlers and the floor space that is used up.

a. Material Handlers: Each of the material handlers handling the kits and the feeders would need to be sized according to the volume of flow, and the weight capacity. Decisions regarding the relative merits of alternative handlers are assumed to have been resolved. Accordingly, the appropriate form of the equation is used. If an automated handler is adopted, the capital costs for the kit and magazine handlers are given by equations 5 and 6 in Table 4.2. If human labor is used for handling, the cost appears as an operating cost.

b. Floor Space: There are capital costs incurred from the floor space taken up by material handlers transporting kits and magazines between the kit/magazine preparation area and the assembly area. In addition there are costs incurred from the floor space taken up by buffer zones. The impact of the kitting factor is generally small and can be neglected.

4.7.3.2 Operating Costs

The amount of handling that takes place in the kit and magazine handling area is affected by the flow of kits and magazines and therefore, the kitting factor.

a. Kit Transportation: The operating costs for transporting the kits would be in the form of labor costs or material handler operating costs depending on the means adopted. The cost incurred is given by equation 10 in Table 4.2. This cost would be for labor or energy costs depending on whether human labor or a conveyor is used for the handling. The response time is the time it would take the handler to transport the kit between the kit/magazine preparation area and the assembly area. For a conveyor, it would be based on the conveyor speed and the distance between the source and the destination. A similar calculation with the corresponding quantities would be needed in the event human labor or another handler is used.

b. Magazine Transportation: The operating cost of the handler is given by equation 11 in Table 4.2. The observations related to the kit handler apply to the magazine handler also.

4.7.4 Assembly Area

The populated kits and magazines are inserted into the robot workspace and the proper setup procedures are initiated. The robot assembles the presented parts using peripheral devices such as end-effectors and fixtures to complete the composite product.

4.7.4.1 Capital Costs

It is assumed that the support devices that are required to perform succesful assembly are not affected by the manner in which the parts are presented to the robot.

4.7.4.2 Operating Costs

The assembly cell is assumed to consist of the robot and passive support devices. Therefore, the operating cost is due to the operation of the robot, and is given by equation 12 in Table 4.2.

4.7.4.3 Alteration Costs

It is assumed that production changes are such that there is no change in the peripheral equipment needs. The indirect cost that results is in the form of the cycle time change that affects the production volume. This item will be dealt with separately in the next section.

4.8 Cycle Time and Production Volume Calculation

The cycle time is important in order to calculate the production volume. A number of capital, operating and alteration costs are affected by the production volume. This section will deal with two items that are necessary to perform this study: one, the procedure to determine the cycle time from the information provided by layout design program, and two, the manner in which the cycle time is affected by the production change.

Assuming the operation runs eight hours a shift, two shifts a day and five days a week, the production volume during a production period can be obtained from the cycle time:

$$\text{Production Volume} = \frac{249600}{Cycle\ Time}$$

4.8.1 Cycle Time at Startup

The cycle time for assembling a composite product is the sum of the assembly time and the setup time. The setup time is assumed to be a constant and accounts for the time to introduce kits and magazines, and perform any calibration procedures. The assembly time is assumed to consist of the translation and operation components. The translation component results from the robot motion between stations, while the operation component results from actions such as grasping, insertion, release, etc, that are performed at these stations. The operation component is assumed to be a constant multiple of the translation component.

The translation component can be calculated from the robot speed and the translation distance. The layout design program provides the physical layout of the assembly cell and the translation distance for a specific kitting level. Instead of running the program for each kitting level, the translation distance and the cycle time are calculated from data for a base layout having an arbitrary kitting level, as shown in the succeeding pages.

4.8.2 Cycle Time After a Production Change

It is assumed that the assembly time is the sum of two components - one, due to the parts on the kits, and two, due to the parts on the magazine. These components are assumed to be related linearly to the number of parts handled by each of the part presentation device. So we have:

$$\text{Assembly Time} = \alpha_u * (d_u * NUFP) + \alpha_k * NFP_k + \beta * (d_m * NFP_f)$$

Each of the terms α_u , α_k , d_u , d_m and β need to be determined according to the system. Using the above equation, the cycle time can be calculated for either of the production changes (product design or product-mix) from information on the new distribution of parts between the magazines and kits.

4.9 Production Change Modelling

Production changes that are considered for this study are design changes and product-mix changes. These changes result in alteration costs, cycle time (therefore, the production volume) and a change in the characteristics of the composite product that affects the operating costs. The equations developed in the earlier sections can then be applied by using the new product information. Equations will be developed for each of these items in the following sections for each type of production change.

4.9.1 Occurrence of the Production Change

Production change events and event types are scheduled based on judgement or past experience. The events are assumed to occur at the end of an accounting period and that only one event type occurs at an event time.

4.9.2 Impact of the Production Change

The production change causes an immediate change in the product characteristics and the alteration costs. The ripple effects from the new product characteristics are felt in the cycle time (and the production volume) and the operating costs. The equations that have been developed in the earlier sections can be used with the appropriate parameters for the new production or accounting period.

4.9.2.1 Product-Mix Change

The composite product's characteristics are obtained from those of the constituent products using the product-mix information. The same operation is repeated to obtain the new composite product's characteristics. It is assumed that part types that were handled by a specific part presentation device continue to be handled by the same part presentation device after the product-mix change.

The alteration costs are in the form of unused capital resource, development costs and/or new acquisition. The former occurs when there is an unused capacity in the form of excess magazines, kit space and handling capacity. The latter occurs when there is the need for additional resources to supplement the existing resources, such as, new magazines, more feeders, etc. New acquisitions are treated as a one time cost.

4.9.2.2 Product Design Change

It is assumed that only one of the products in the product-mix has a design change. It is necessary to estimate the composition of the new design and relate it to the change in the composite product's characteristics. This is demonstrated in Chapter 5. The comments related to alteration costs for product-mix change apply here. The equations developed earlier for the operating costs at various points in the system change in accordance with the change in part flow in the system.

4.10 Evaluation Method

The problem is one where the costs and abilities of the system to adjust to changing production needs are affected by a current decision. It could, therefore, be considered a multi-staged decision problem and the object is to determine the optimal decision at the first stage. It is assumed that the feedable part type assignments are maintained after the production changes.

In the deterministic analysis, the cash flow diagram is drawn up based on the estimates of cash flows over the life of the system. The capital, operating and alteration costs are given in terms of the kitting factor. The cash flow over the life of the system is discounted to the present using a specified nominal growth rate. The net present worth and the total production volume are measures of the value of the system.

The equations for the system cost can be developed accordingly. The capital costs are incurred at the beginning of the project, while the operating costs occur at the end of each accounting period. The alteration costs occur at the end of the period in which changes were made to the system. Assuming no inflation, the net present worth of the system is given as:

$$\text{Net Present Worth} = C_c + \sum_{i=1}^{n_s} \frac{C_o^i}{(1+r)^i} + \sum_{i=1}^{n_c} \frac{C_a^i}{(1+r)^{p_i}}$$

The system cost measure is defined as the ratio of net present worth and the total production volume. The flexibility of the system is embedded in it.

4.11 Sensitivity Analysis

The uncertainities in the estimates of the nominal values for the various factors needed for the cost analysis must be studied in regard to their influence on the final decision. This is done by performing a sensitivity analysis on the objective function. The estimates that need further study depend on the specific application being considered and the availability of information from published literature or otherwise.

CHAPTER 5

THE FIGURE OF MERIT AND EXAMPLE

5.1 Overview

The methodology will be demonstrated using the control panel assembly presented in Chapter 3. The exploded view of the control panel assembly is given in Figure 3.14. The control panel assembly consists of a frame, shown in Figure 5.1, that has thirteen delivery/access points into which one of five different types of sub-assemblies described in Table 3.9 is inserted. A range of control panels is obtained by varying the mix of the different types of the sub-assemblies. The system is to produce two types of control panels denoted as Product A and Product B in equal quantities. The product information has been presented previously in Tables 3.8 through 3.12.

The system that is proposed for the assembly of the control panel assembly is shown in Figure 5.2. It consists of an assembly robot with associated control equipment that is served by a kit/magazine preparation area. The parts necessary for the manufacture of the products enter the system on demand. They are differentiated according to their feedability characteristics. The unfeedable parts and some of the feedable parts as determined by the methodology are moved to the kitting area and stored in individual bins. The remaining feedable parts are moved into the feeding area where they are released into programmable feeder bowls. At the kit/magazine preparation area, human labor is used to prepare the kits and service the feeders.

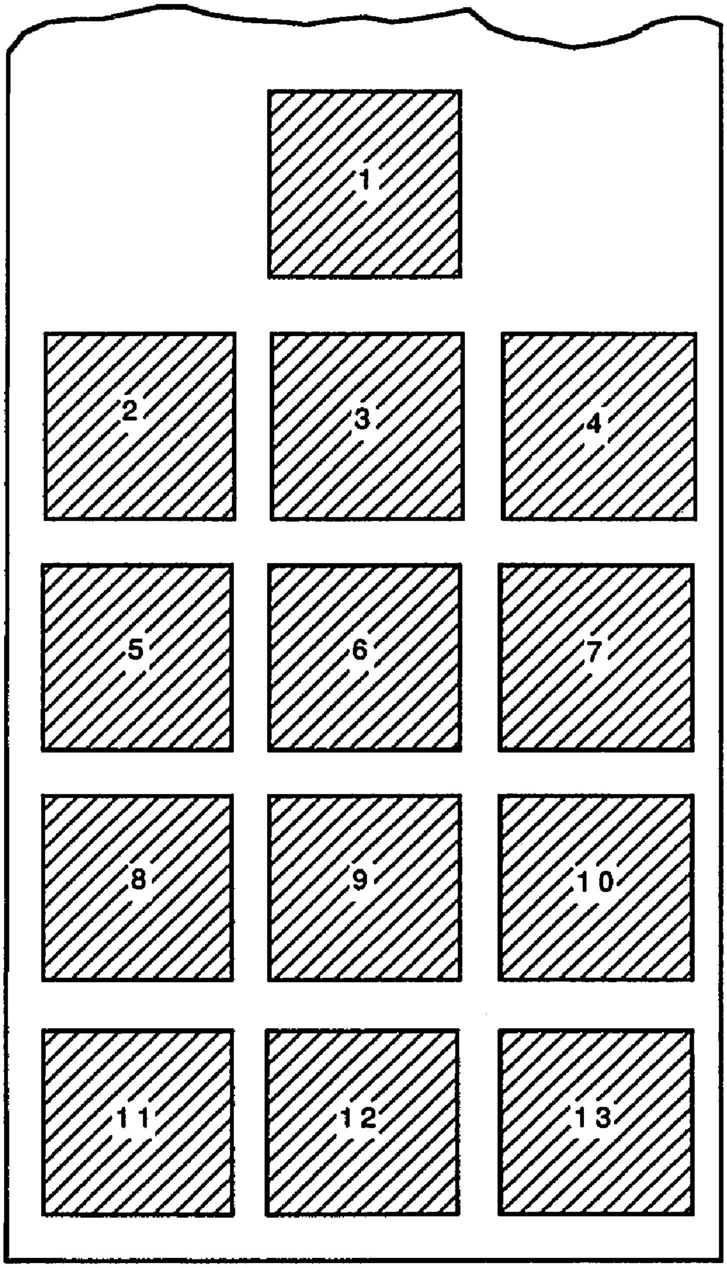

Figure 5.1 Delivery/Access Points on the Frame

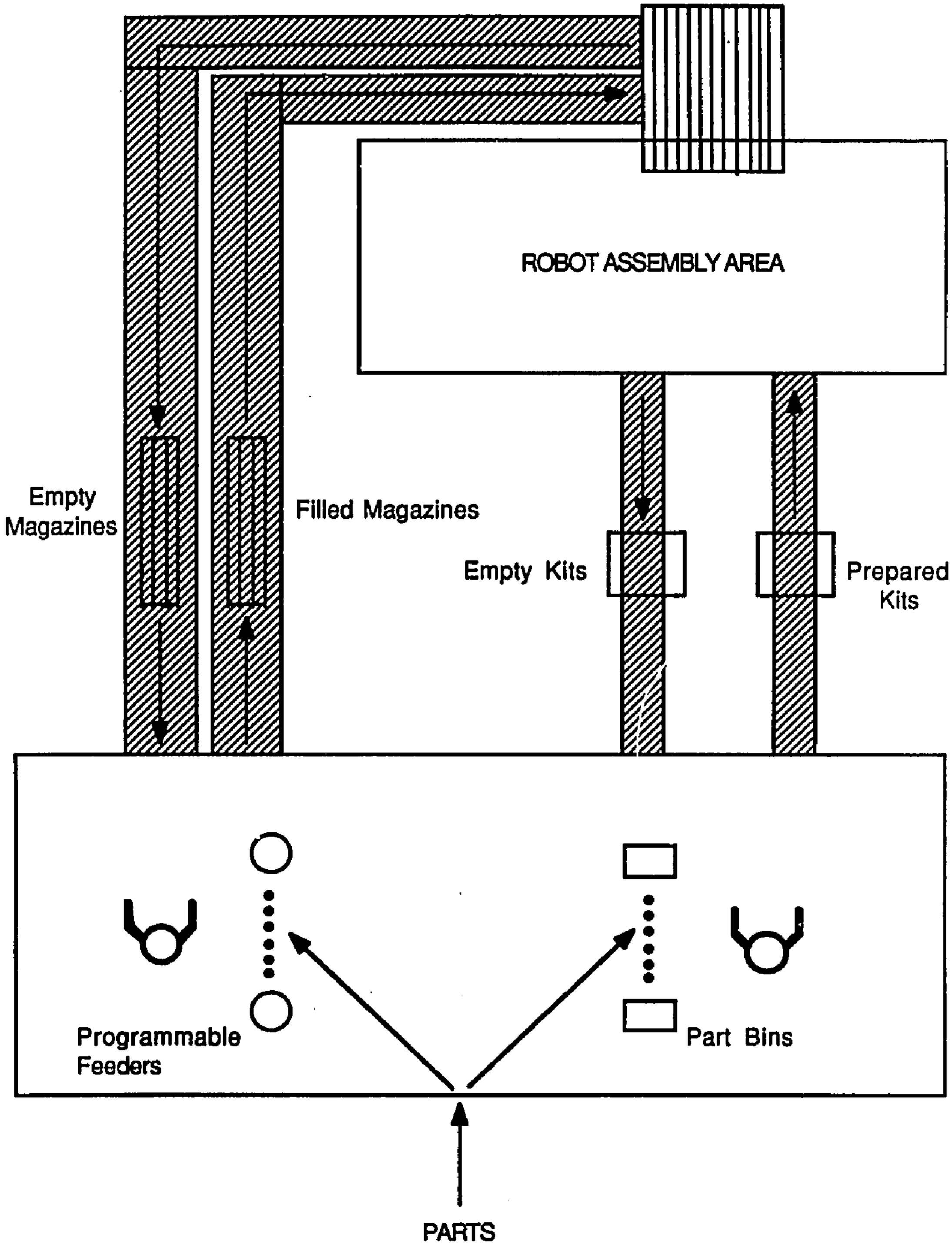

Figure 5.2 Schematic for the Assembly System
(Control Panel Assembly)

Kits prepared at the kit/magazine preparation area are inserted into the robot workspace. The robot performs the assembly using the parts from the kit and magazines. The final assembly is completed on a fixture provided on the kit. The kit and the assembled product is removed from the workspace, and is replaced with a fresh kit from the buffer. Empty magazines are replaced with fresh magazines periodically to ensure continuous supply of the feedable parts. The empty magazines, and kits with the assembled product are returned to the kit/magazine preparation area for recirculation. The handling of the kits and magazines between the kit/magazine preparation area and assembly area is done by conveyors.

5.2 Data Used and Assumptions

A number of assumptions relating to the configuration of the system, equipment, products, the nature of changes in the product and the impact on the system were made. These assumptions are grouped accordingly.

a. System Configuration and Equipment:
    i. The equipment choice is assumed to have been made from technical considerations.
    ii. The robot, its controller and associated equipment in the assembly area are dedicated to the manufacture of the products.
    iii. Human labor and the equipment in the kit/magazine preparation area are assumed to be shared resources. Demands made on them by the assembly area preempt all other demands from the factory floor.
    iv. Product defects, maintenance and breakdowns are not considered.

b. Products:
   i. The product is assembled on the kit.
   ii. The product has been redesigned for robotic assembly.
   iii. All the parts of a particular feedable part type are handled by the same part presentation device.

c. Production Changes:
   i. Production changes occur every six months.
   ii. The only production changes allowed are product-mix and product design changes.
   iii. New products belong to the same product family.
   iv. Changes in the product consist of an increase or decrease of the quantity of sub-assemblies of each type in a control panel assembly. It is assumed that the total number of sub-assemblies in a product remains the same.
   v. The changes in the product are assumed to be given as probabilities that a certain number of sub-assemblies of a particular type will be present.
   vi. The product design changes occur as frequently as the product-mix changes.

The constants presented in Chapter 4 are listed in Table 5.1. The values were obtained from industrial product data, or determined by judgement.

Table 5.1 Values of Constants Used in the Methodology

Symbol	Symbol Name	Value	Units
d_m	Difficulty factor for a feedable part on the magazine	2.0	-
d_u	Difficulty factor for a unfeedable part on the magazine	1.0	-
n	Number of periods	4	-
r	Growth rate	9.5	%
AT	Assembly time	120	sec/CP
CPB_c	Cost per bin	100	$/unit
CPF_c	Cost per feeder	800	$/unit
CPP_c	Cost of kit per feedable part	15	$/FP
CPM_c	Cost per magazine	100	$/mag
CPP_o	Operating cost per feedable part for kitting	0.05	$/hr
FC	Feeder capacity	50	ppm
HC_k	Kit handler operating cost	0.15	$/hr
HC_m	Magazine handler operating cost	0.15	$/hr
$ICPP_k$	Incremental cost of kit handler per feedable part per minute	425	$/FP/min
$ICPM_k$	Incremental cost of magazine handler per feedable part per minute	100	$/FP/min
LC	Labor cost (plus benefits)	20	$/hr
MC	Magazine capacity	25	-
NOK	Number of kits in the system	6	-
NOM	Number of magazines in the system	24	-
RT_k	Response time for kit handler	40	secs
RT_m	Response time for magazine handler	30	secs
ST	Service time (for feeders and magazines)	5	secs
SUT	Setup time	15	secs
UOC_f	Unit operating cost for feeder	0.01	$/hr
UROC	Unit robot operating cost	20.00	$/hr

5.3 System Cost Calculations

The life of the system is broken into production phases that are punctuated by production changes. The costs in each phase consist of a capital cost (one-time cost) and an operating cost (remains constant for the production phase). Capital/alteration costs are incurred at the beginning of the production phase while the operating costs are incurred at the end. At the beginning of each production phase, the product and production data are updated according to the products to be assembled in that phase. The data determine the capital/alteration and operating costs for the production phase. In this manner, the cash flow is built up over the life of the system.

The system cost measure is expressed in terms of two different factors - the net present worth and the total production volume. The discounted cash flow is determined from the cash flow diagram and the growth rate information. The number of units of composite products produced over this period is determined from the cycle time information.

Hand calculations for the system are shown on the following pages. Table 5.2 and 5.3 breakdown the products into the number of parts of each type that are in each sub-assembly. Table 5.4 lists the distribution of feedable part types between the kit and magazines. Table 5.5 shows the determination of the number of parts of each type in the composite product. Tables 5.6 and 5.7 show the detailed calculations for the various costs in the first production phase only. Similar calculations must be performed for each of the other production phases. To this end these calculations have been incorporated in a FORTRAN subroutine described later. The hand calculations demonstrate the use of pertinent equations and nominal values expected for each cost

Table 5.2 Composite Product Description

Sub-Assembly		Product Type		Composite
Type	Name	A	B	Product
a	Display Button	3	7	5.0
b	Push Button (Long)	4	1	2.5
c	Push Button (Short)	2	2	2.0
d	Toggle Switch (SPST)	3	2	2.5
e	Toggle Switch (SPDT)	1	1	1.0

Table 5.3 Sub-assembly Breakdown According to Part Type

Feedable Part Type Number	Feedable Part Type Name	Sub-Assembly Type				
		a	b	c	d	e
1	Display Button	1	-	-	-	-
2	Push Button	-	1	1	-	-
3	Long Plunger	-	1	-	-	-
4	Short Plunger	-	-	1	-	-
5	Lamp Holder	1	-	-	-	-
6	Display Housing	1	-	-	-	-
7	Toggle Housing	-	-	-	-	1
8	Switch Assembly	-	1	1	-	-
Unfeedable Part Type Number	Unfeedable Part Type Name	Sub-Assembly Type				
		a	b	c	d	e
1	Lamp	1	-	-	-	-
2	Spring	-	1	1	-	-
3	SPST Toggle	-	-	-	1	-
4	SPDT Toggle	-	-	-	-	1
5	Frame	-	-	-	-	-
6	Acoustic Material	-	-	-	-	-

Table 5.4 Kit/Magazine Assignment of Feedable Parts

Handled by Feeder	Handled by Kit
Display Button	Display Housing
Push Button	Toggle Housing
Long Plunger	Switch Assembly
Short Plunger	
Lamp Holder	

Table 5.5 Determination of Part Type Quantities in Composite Product

Sub-Assembly		Feedable Part Type #								Unfeedable Part Type #					
Type	# in Comp. Product	1	2	3	4	5	6	7	8	1	2	3	4	5	6
a	5.0	5.0	-	-	-	5.0	5.0	-	-	5.0	-	-	-	-	-
b	2.5	-	2.5	2.5	-	-	-	-	2.5	-	2.5	-	-	-	-
c	2.0	-	2.0	-	2.0	-	-	-	2.0	-	2.0	-	-	-	-
d	2.5	-	-	-	-	-	-	-	-	-	-	2.5	-	-	-
e	1.0	-	-	-	-	-	-	1.0	-	-	-	-	1.0	-	-
-	13.0	5.0	4.5	2.5	2.0	5.0	5.0	1.0	4.5	5.0	4.5	2.5	1.0	1.0	1.0

Table 5.6 Hand Calculations for the Capital Costs at t=0

Capital Item	Calculation	Eq.#	Cost ($)
Feeders	$CF_C = 10000 \text{ (\$/unit)} * (\frac{5*55467}{50(60*16*5*26)} + \frac{4.5*55467}{50(60*16*5*26)} + \frac{2.5*55467}{50(60*16*5*26)} + \frac{2*55467}{50(60*16*5*26)} + \frac{5*55467}{50(60*16*5*26)}) \text{ (units)}$	3	10000.00
Magazines	CM_C = 100 ($/unit) * 24 (units)	4	2400.00
Bins	CB_C = 100 ($/unit) * 3 (units)	1	300.00
Kits	CKS_C = 15 ($/FP.Kit) * 10.5 (FP) * 6 (kits)	2	945.00
Kit Handler	CCK_C = 2 * 425 ($/FP/Min) * 10.5 (FP/CP) * 0.4444 (CP/min)	5	3967.00
Magazine Handler	CCF_C = 2 * 100 ($/FP/min) * 0.4444 (CP/min) * 19 (FP/CP)	6	1689.00

Table 5.7 Hand Calculations for the Operating Costs in the First Period

Operation Item	Calculation	Eq.#	Cost ($)
Kitting	$OC_k = 0.01\ \text{(\$/FP)} * 10.5\ \text{(FPs/CP)} * 55467\ \text{(CP/Pd)}$	7	5824.00
Feeding	$OC_f = 0.01\ \text{(\$/hr)} * 19\ \text{(FPs/CP)} * \frac{55467\ \text{(CP/Pd)}}{50\ \text{(FP/min)} * 60\ \text{(min/hr)}}$	8	3.50
Feeder Servicing	$OC_{fs} = 20\ \text{(\$/hr)} * 5\ \text{(sec/mag)} * \frac{1}{3600}\ \text{(hr/sec)}$ $* (5 + 4.5 + 2.5 + 2 + 5)\ \text{(FPs/CP)} * \frac{55467\ \text{(CPs/Pd)}}{20\ \text{(FPs/mag)}}$	9	1464.00
Kit Handling	$KT_o = 55467\ \text{(CP/Pd)} * 10.5\ \text{(FP/CP)} * 40\ \text{(secs/kit)}$ $* 0.15\ \text{(\$/hr.FP)} * \frac{1}{3600}\ \text{(hr/sec)}$	10	971.00
Magazine Handling	$MT_o = 55467\ \text{(CP/Pd)} * 30\ \text{(secs/mag)} * 0.15\ \text{(\$/hr)}$ $* \frac{(5 + 4.5 + 2.5 + 2 + 5)\ \text{(FPs/CP)}}{25\ \text{(FPs/mag)}}$	11	53.00
Robot Operation	$RC_o = (1.89\ \text{(sec/FP)} * 10.5\ \text{(FP/CP)} + 3.78\ \text{(sec/FP)} * 19\ \text{(FP/CP)})$ $* 20\ \text{(\$/hr)} * 55467\ \text{(CPs/Pd)} * \frac{1}{3600}\ \text{(hr/sec)}$	12	28246.00

category. Some time and cost estimates are very conservative and may vary with application but the values shown are intended to demonstrate the methodology rather than model a very specific instance.

5.4 Computer Implementation

The evaluation of the system is based on production changes in the future that are of a stochastic nature. Therefore, in order to study a part presentation system it is necessary to simulate this stochastic nature. For each kitting factor, it is necessary to loop repeatedly through the same set of calculations for the entire life of the system. A single simulation run would consist of several loops through the calculations, where each loop involves building up the cash flow for the life of the system using production change information that is generated randomly. This mechanism has been written as a FORTRAN program.

In a simulation loop the cost equations for each production phase are based on information of the relative flow between the two part presentation device. This flow changes each time there is a production change. So it is necessary to have a mechanism to:

a. Identify the nature of the production change,
b. Relate the production change to the number of parts in the composite product, and
c. Determine the cycle time for the new composite product.

Each of these is described in the following sections. It has been assumed that a production change occurs every six months.

5.4.1 Nature of the Production Change

Since the production change is assumed to be either a product design change or a product-mix change with an even probability, a uniform (0,1) random number generator was used. The value of U, the random number determined the type of change as follows:

$0 < U < 0.5$ ==> Product Design Change
$0.5 \leq U < 1$ ==> Product-Mix Change

5.4.2 Relating the Production Change to the Number of Parts in Composite Product

The control panel assembly consists of 13 subassemblies of five different types whose composition is known in advance. The number of feedable parts, unfeedable parts, feedable part types, and unfeedable part types in each subassembly is assumed to stay constant. With the knowledge of the number of subassemblies of each type and the product-mix in each production period, the composite product can be determined. The part flow information can be derived from the composite product description as demonstrated in earlier sections. In the next sections the procedure to perform this transformation is described individually for each of the production change types.

5.4.2.1 Product-Mix Change

The alteration in the mix of Product A relative to Product B is modelled as a ten percent variation in the contribution of Product A to the composite product. Further product-mix changes cause a cumulative effect on the product-mix. The determination of whether this variation is a reduction or an increase is once again handled using a pseudo-random generator. If U is a random number, the change in the contribution of Product A to the composite product is given as:

$$0 < U < 0.5 \quad ==> \quad -10\%, \text{ and}$$

$$0.5 < U < 1 \quad ==> \quad +10\%$$

5.4.2.2 Product-Design Change

A product design change is assumed to be in the form of a change in the number of each sub-assembly type. It is also assumed that this results in the replacement of one of the existing products, with the product-mix being maintained the same as before the change. The total number of subassemblies must be thirteen. Since there are two products being assembled, it is necessary to first identify the product that is being replaced and then to construct the constitution of the new product. The product being replaced is done using the pseudo-random generator and follows the same pattern described for the product-mix change.

Two guidelines, dictated by engineering judgement, are assumed to be operative in determining the number of each type of subassembly in the new product.

a. The total number of single-pole single-throw and single-pole double-throw switch subassemblies is not greater than four.

b. The numbers of each of the other subassembly types is assumed to account for the remaining spaces in the control panel and they occur with uniform probability.

The number of each of the single-pole single-throw and single-pole double-throw subassemblies is determined from U_1 and U_2, two random numbers, as follows:

$$N_i = 2*U_i \text{ , where i=1,2}$$

Each of N_i, i={1,2}, represents the number of single-pole single-throw and single-pole double-throw subassemblies respectively, so the quantity on the right of the above equation is rounded to the nearest integer.

The number of each of the other subassemblies is determined from three random numbers, U_3, U_4 and U_5, as follows:

$$N_i = \frac{U_i}{U_3 + U_4 + U_5} * (13 - N_1 - N_2) \text{ , i=3,4}$$

$$N_5 = 13 - (N_1 + N_2 + N_3 + N_4)$$

Each of N_i , i={3,5}, represents the number of each of the other subassemblies.

5.4.3 Determination of the New Cycle Time

As mentioned in Section 4.9.2, the cycle time is assumed to be linearly related to the number of parts that are handled by each of the part presentation device. For the implementation of Equation 12 in Table 4.2, the following equations were used with the assembly time obtained from the layout design program to obtain α_u , α_k and β .

$$\alpha_u = \frac{AT*d_u}{NFP_k + d_u*NUFP + d_m*NFP_f} \text{ ,}$$

$$\alpha_k = \frac{AT}{NFP_k + d_u*NUFP + d_m*NFP_f}$$

$$\beta = \frac{AT*d_m}{NFP_k + d_u*NUFP + d_m*NFP_f}$$

The values d_m and d_u were estimated and are given in Table 5.1.

5.5 Calculation of the System Cost Measure

The FORTRAN program outlined so far was embedded in a loop to allow a Monte Carlo simulation of the system. Feedable part types were arbitrarily assigned to the kit and feeder respectively and the system cost measure was calculated. Since the kitting factor changes during the life of the system, the system cost measure is studied with respect to the initial kitting factor.

The system cost measure was given by the ratio of the net present worth and the total production volume over the life of the system. The system cost measure represents the incremental cost incurred per composite product in handling the feedable parts by specific part presentation devices. The average value for system cost measure during the simulation and the range of variation was monitored. Results obtained using this program are given in the subsequent sections.

5.6 Sensitivity of the System Cost Measure to the Initial Kitting Factor

The system worth is dependent on the relative flows through the kitting and feeding areas respectively through the life of the system. The choice of the initial kitting factor is therefore crucial. The FORTRAN program outlined in Section 5.4 was modified to study the system for the six different initial kitting factors. The results obtained from these runs are shown in Table 5.8. The choice of the feedable part types to move over from the kit to the feeder was done arbitrarily. The assignment of the part types to the kit or magazine for the simulation is shown in Table 5.9. The feedable part types listed in Table 5.9 are labelled according to the convention in

Table 5.8 Sensitivity of the System Cost Measure to the Initial Kitting Factor(IKF) and the Unit Robot Operating Cost(UROC)

IKF	UROC = $15/hr			UROC = $20/hr			UROC = $25/hr		
	Ave.	Min.	Max.	Ave.	Min.	Max.	Ave.	Min.	Max.
0.0000	0.5529	0.4747	0.6310	0.6949	0.5966	0.7950	0.8388	0.7186	0.9590
0.1525	0.5696	0.4857	0.6540	0.6950	0.5905	0.8042	0.8240	0.6976	0.9640
0.3559	0.5860	0.5054	0.6689	0.7035	0.6043	0.8056	0.8226	0.7031	0.9423
0.5932	0.6085	0.5215	0.6949	0.7103	0.6054	0.8210	0.8123	0.6853	0.9514
0.7458	0.6209	0.5354	0.7106	0.7089	0.6010	0.8169	0.7961	0.6680	0.9263
1.0000	0.6064	0.5229	0.6927	0.6782	0.5839	0.7747	0.7508	0.6449	0.8567

Table 5.9 Part Type Assignments for the System Cost Calculations

	Feedable Part Types on		Number of Feedable Parts on		IKF
	Kit	Magazine	Kit	Magazine	
1	-	1,2,3,4 5,6,7,8	0.0	29.5	0.0000
2	8	1,2,3, 4,5,6,7	4.5	25.0	0.1525
3	6,7,8	1,2,3,4,5	10.5	19.0	0.3559
4	4,5,6, 7,8	1,2,3	17.5	12.0	0.5932
5	2,4,5, 6,7,8	1,3	22.0	7.5	0.7458
6	1,2,3,4, 5,6,7,8	-	29.5	0.0	1.0000

Table 5.3. No attempt was made to find the optimum combination of feedable part types on the magazine that would result in the minimum system cost measure per composite product.

It may be seen that the optimal value of initial kitting factor for higher values of unit robot operating cost is zero. However, for lower values of unit robot operating cost, intermediate values of initial kitting factor become optimum. These results will be discussed in detail in subsequent sections.

As mentioned earlier, the kitting factor alone does not determine the optimum decision. The number of feedable part types handled by each part presentation device needs to also be taken into consideration. For the control panel assembly problem, when making a choice between different part presentation system with the same initial kitting factor, the one which handles the most feedable part types by the cheaper part presentation device works out to be the cheaper system, since the costs are keyed to the number of feedable part types handled by the part presentation device also.

5.7 Sensitivity of System Cost Measure to Other Factors

For the control panel assembly it was observed that the system cost measure was favorable to the feeders. It therefore, appears that all feedable part types should be handled by the feeders for a system with high unit robot operating cost. However, since the contribution to cycle time per feedable part on the magazine is larger than that due to a feedable part on the kit, a tradeoff point would appear as more feedable part types are moved over from the kit to the feeder. The higher cycle time causes an increase in the robot operating costs and a reduction in the production volume. The degree of the impact is dependent on two factors: one, the relative contributions to the cycle time of feedable parts on the kit and magazine; and two, the unit robot operating cost. Each of these influences is studied in the following sections while holding the other variables at nominal values.

5.7.1 Influence of Unit Robot Operating Cost

The simulations shown in Table 5.8 were made with very conservative estimates for the unit robot operating cost. When the maintenance, repair and downtime effects are included in unit robot operating cost, the value is several times that used in the earlier runs. Several runs with different values of unit robot operating cost were made to study its impact as shown in Figure 5.3.

The system cost measure varies linearly with unit robot operating cost. For a given initial kitting factor, the change in the system cost measure is directly proportional to the change in unit robot operating cost. The amount of this change is dependent on the initial kitting factor. It varies from 37% when initial kitting factor is zero, to 21% when it is one. This is to be expected since a change in unit robot operating cost only affects the numerator of the system cost measure, since the total production volume is not affected by a change in unit robot operating cost. The numerator itself is expressible as a linear function in unit robot operating cost if the other parameters are held at their nominal values. It can be shown that the percentage change in the system cost measure that results for a given initial kitting factor, is the fraction of the system cost measure that is due to the robot operating costs. So when

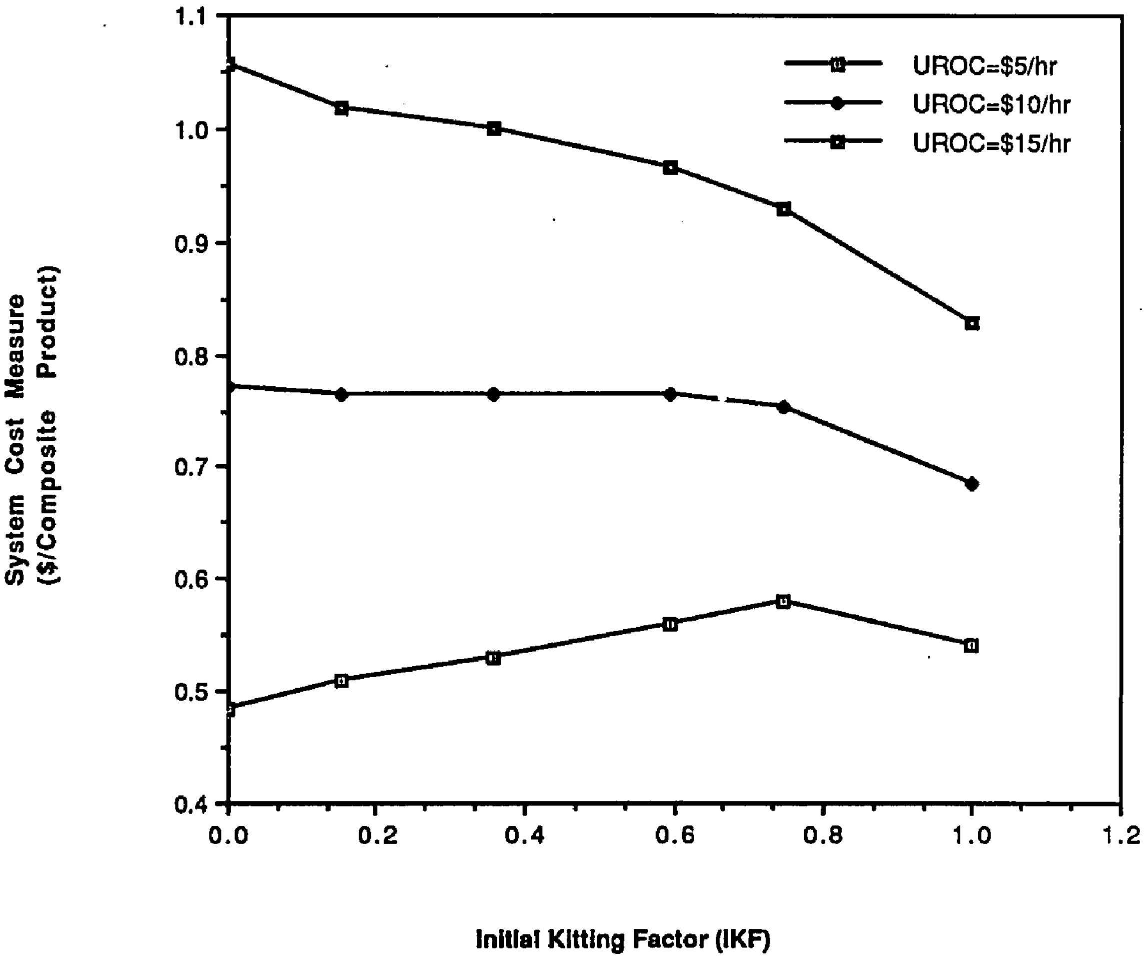

Figure 5.3 Sensitivity of the System Cost Measure to Unit Robot Operating Cost (UROC)

the unit robot operating cost is \$10/hr, the robot operating costs account for 37% of the system cost measure when the initial kitting factor is zero, and 21% when the initial kitting factor is one.

However the change in system cost measure over the range of initial kitting factor differs with the value of unit robot operating cost. The system cost measure changes by +12%, -11% and -22% over the initial kitting factor range when unit robot operating cost is \$5/hr, \$10/hr and \$15/hr respectively. The trend indicates that the system cost measure variation with initial kitting factor increase nonlinearly with unit robot operating cost. This is because an increase in unit robot operating cost causes an increase in the robot operating cost while the increase in the initial kitting factor causes an increase in the cycle time and therefore a reduction in the total production volume. The resulting opposite effects on the numerator and denominator of the system cost measure causes the nonlinearity. The sensitivity to this effect is dependent on the value of unit robot operating cost.

5.7.2 Influence of α_k and α_u

In Section 5.4.3 the method used to determine α_k and α_u was presented. It involved the estimation of d_m and d_u that represented the assembly time associated with a feedable part on the magazine relative to a feedable part on the kit and the assembly time associated with an unfeedable part relative to a feedable part on the kit. These factors influence the assembly time for a composite product and therefore the cycle time and the total production volume at a given initial kitting factor.

The impact of d_m and d_u on the system cost measure was studied. Each of the factors was altered by 10% about their nominal values while holding the other constant. The data from these runs are given in Tables 5.10 and 5.11 respectively. These were generated with unit robot operating cost set at $15/hr. The plots for these data are given in Figures 5.4 and 5.5 respectively.

The trend in the curvature of the plots for various d_m values shown in Figure 5.4 is to be expected. As the contribution of a feedable part on the magazine to the assembly time increases relative to that of feedable part on the kit, the system cost measure should shift in favor of the kits. The system has been unfavorable to kits in terms of the capital costs and operating costs, but its advantage lies in the fact that feedable parts presented by a kit require less time to assemble. The increase in d_m makes the choice of one as the optimal initial kitting factor more definite.

The system cost measure increases for smaller initial kitting factor and falls for higher initial kitting factor when d_m is increased. Since the robot operating costs are a product of unit robot operating cost and cycle time, the effect on the system cost measure would be compounded by an error in the estimate of unit robot operating cost and d_m in the same direction.

Though d_u alters the contribution of the unfeedable part in relation to the feedable parts presented by kit and feeder, it does not change the relative contribution to cycle time of the feedable parts on the kit and feeder. So the change in the number of feedable parts delivered by kit and feeders for a given initial kitting factor does not impact as heavily. More importantly, there is no shift in the optimal value of initial kitting factor. This can be seen in the plots on Figure 5.5. This observation is true

Table 5.10 Sensitivity of the System Cost Measure to d_m
(UROC=\$25/hr,d_u =1.0)

IKF	d_m=1.8			d_m=2.2		
	Ave.	Min.	Max.	Ave.	Min.	Max.
0.0000	0.8069	0.6913	0.9221	0.8658	0.7412	0.9918
0.1525	0.8034	0.6856	0.9318	0.8411	0.7082	0.9989
0.3559	0.8095	0.6944	0.9271	0.8335	0.7108	0.9557
0.5932	0.8129	0.6922	0.9447	0.8116	0.6792	0.9716
0.7458	0.8100	0.6865	0.9330	0.7837	0.6453	0.9203
1.0000	0.7741	0.6653	0.8842	0.7286	0.6267	0.8324

Table 5.11 Sensitivity of the System Cost Measure to d_u
(UROC=$25/hr, d_m=2.0)

IKF	d_u=0.9			d_u=1.1		
	Ave.	Min.	Max.	Ave.	Min.	Max.
0.0000	0.8541	0.7335	0.9795	0.8204	0.7043	0.9395
0.1525	0.8402	0.7100	0.9840	0.8069	0.6857	0.9480
0.3559	0.8374	0.7150	0.9593	0.8101	0.6917	0.9260
0.5932	0.8267	0.6947	0.9759	0.8001	0.6764	0.9358
0.7458	0.8070	0.6711	0.9399	0.7847	0.6536	0.9133
1.0000	0.7579	0.6521	0.8669	0.7412	0.6380	0.8471

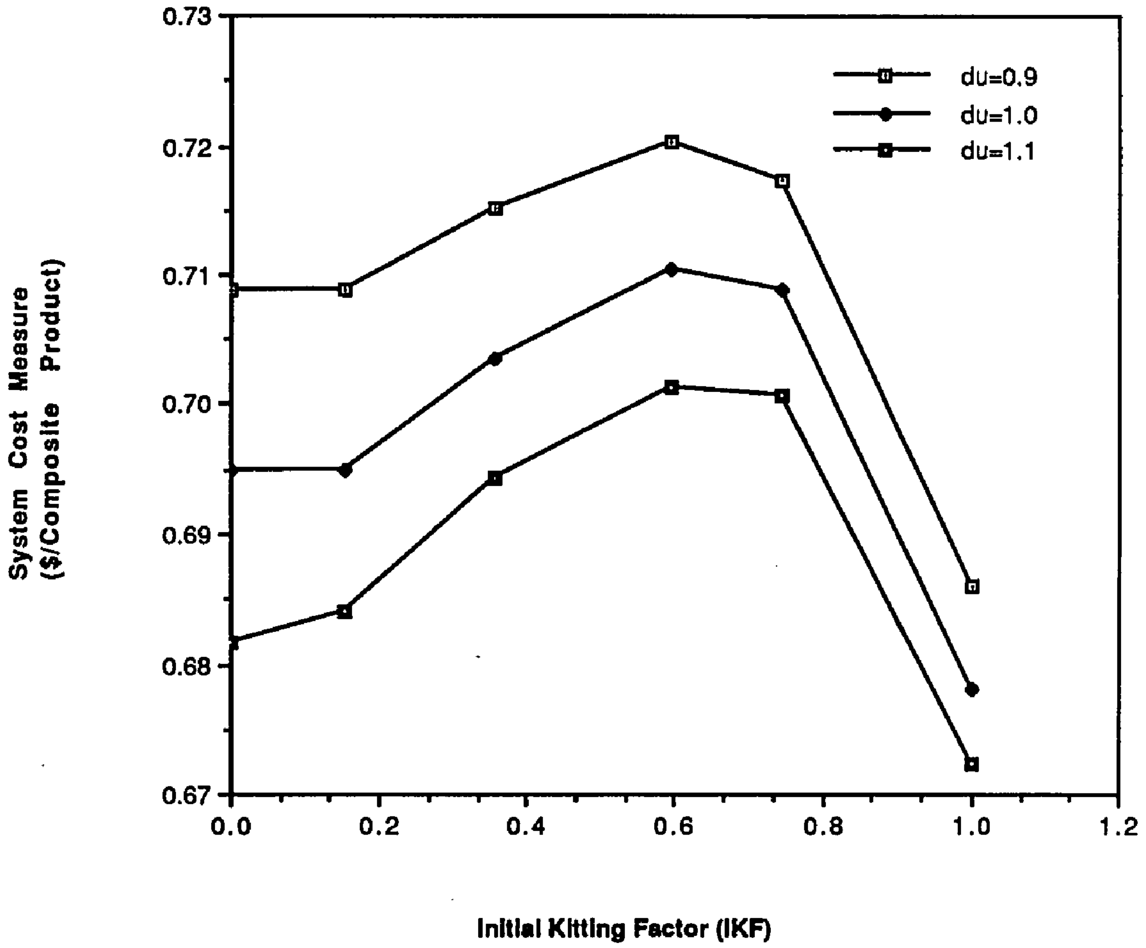

Figure 5.4 Sensitivity of the System Cost Measure to d_u

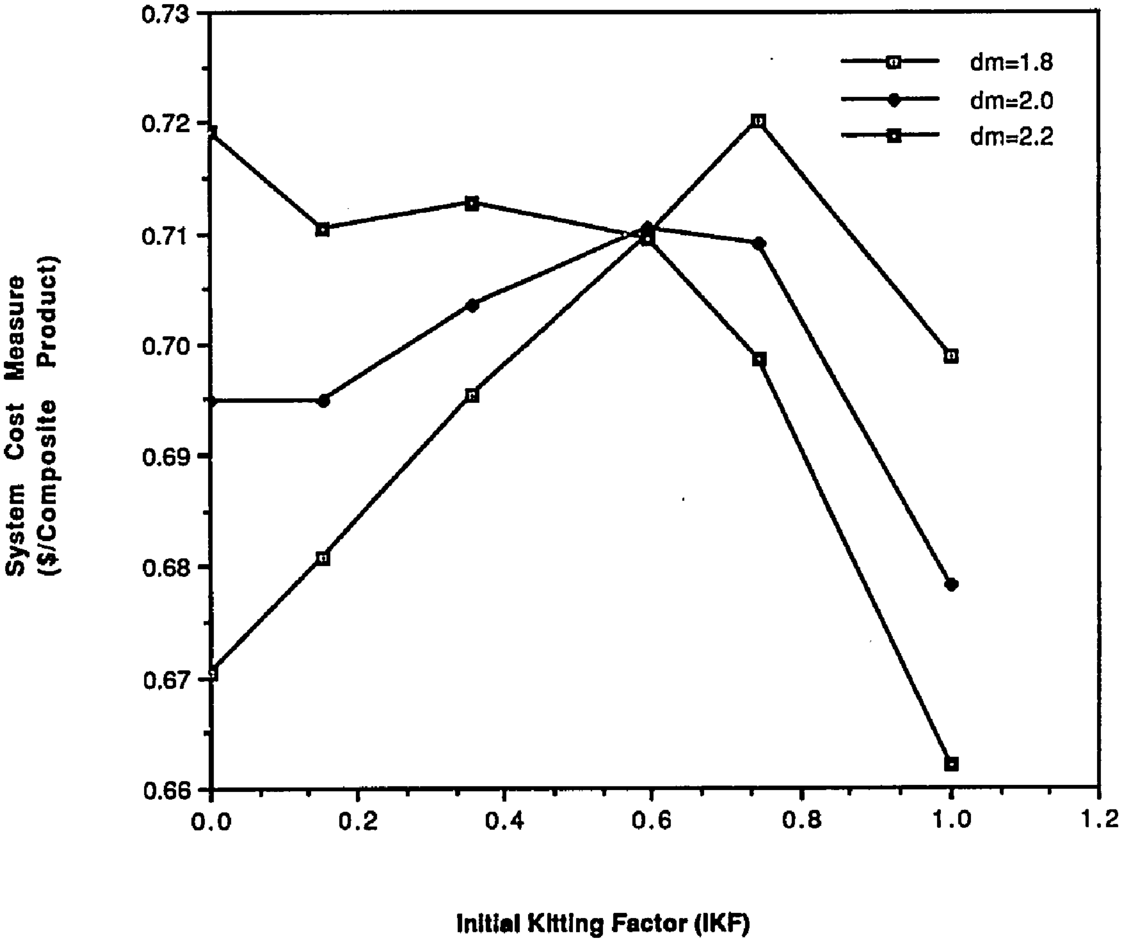

Figure 5.5 Sensitivity of the System Cost Measure to d_m

immaterial of the value of unit robot operating cost that is chosen.

5.7.3 Influence of the Assembly Time

Costs and therefore the system cost measure for this system are strongly influenced by the assembly time. Table 5.12 and Figure 5.6 give the results from the simulation of a +/- 10% error in the estimates of the assembly time. The plot indicates that this factor contributes heavily to the system cost measure. There is a significant change in the system cost measure, but there is no change in the location of the optimal value of the initial kitting factor. This is however dependent on the nominal values chosen for the other parameters, particularly the unit robot operating cost.

5.8 Conclusions

Application of the methodology to the control panel assembly problem indicates that careful study needs to be done to identify the value for unit robot operating cost. Since the effects of robot maintenance, repair and downtime over the life of the system can cause the value of unit robot operating cost to change drastically, the value of unit robot operating cost because an error of ten percent in the estimate of unit robot operating cost can affect the choice of initial kitting factor when unit robot operating cost is in the region of \$10/hr. The impact of variation in d_u does not change the optimal initial kitting factor value since the effect scales the relationship of system cost measure versus initial kitting factor. However, the impact of variation in d_m is important at unit robot operating cost values close to \$10/hr, since the nature of the curve changes. (See discussion in Section 5.6.2.) This results in different optimal

Table 5.12 Sensitivity of System Cost Measure to Assembly Time (AT)

IKF	AT = 108 secs			AT = 132 secs.		
	Ave.	Min.	Max.	Ave.	Min.	Max.
0.0000	0.7606	0.6519	0.8697	0.9172	0.7853	1.0483
0.1525	0.7537	0.6409	0.8766	0.8939	0.7543	1.0513
0.3559	0.7580	0.6483	0.8670	0.8860	0.7578	1.0175
0.5932	0.7551	0.6405	0.8869	0.8707	0.7301	1.0336
0.7458	0.7474	0.6283	0.8651	0.8463	0.6998	0.9874
1.0000	0.7121	0.6128	0.8136	0.7876	0.6770	0.8999

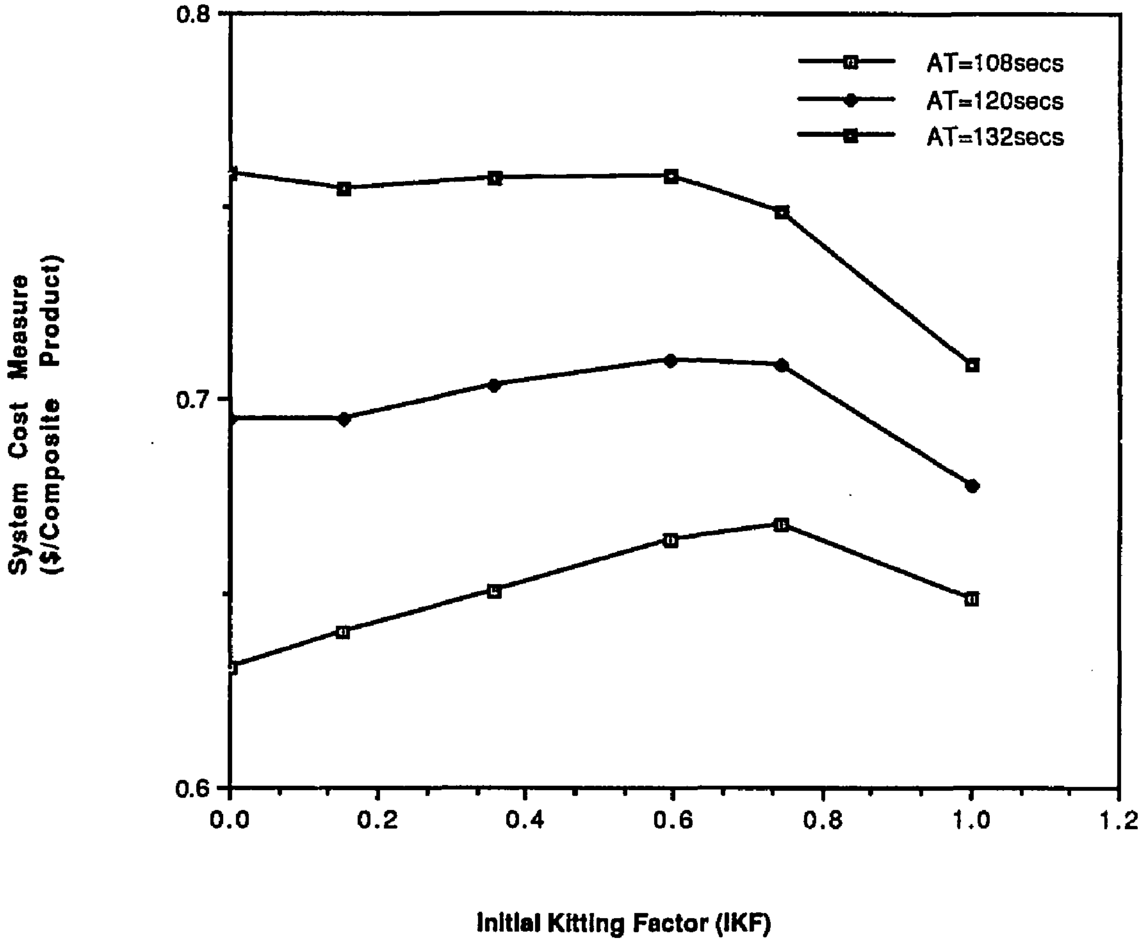

Figure 5.6 Sensitivity of the System Cost Measure to Assembly Time

values of initial kitting factor.

Because of the nature of the product, the alteration costs were ignored. For this problem, the alteration costs would have occurred in the purchase of capital items such as feeders, magazines, kits, bins and tooling; or in development costs. Both of these items do not enter the analysis. Given the high assembly time relative to magazine and kit preparation time, there is no need for additional feeders, magazines or kits. The system is assumed to be producing products of the same family and therefore the cost of tooling and bins does not arise. Finally, since there is little change in the kit/magazine preparation area, the development costs arise at the assembly area where the robot has to be reconfigured to perform the new assembly.

The analysis suggests that the system cost measure varies monotonously with the initial kitting factor for high unit robot operating cost. Therefore, for high unit robot operating cost, the optimal initial kitting factor will be one. However, for low values of unit robot operating cost, the optimal value of initial kitting factor becomes zero.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In automated systems, it is necessary to present components at a desired location and with a desired orientation for successful assembly. Devices based on feeder and kit concepts are the most common part presentation device employed. A large portion of the costs of assembly systems is related to peripheral equipment. So in a production environment characterized by large product mixes and short product life cycles, the ability of part presentation system to adjust, and its impact on the production costs takes on added significance.

While considerable work has been done on the evaluation of robots and hard automation very little work to date has addressed the evaluation of part presentation system. The methodology developed in this research presents a way to evaluate the flexibility of part presentation system in a changing environment.

Because the operation of a robotic assembly system is highly dependent on the robot cycle time, a layout optimization algorithm was developed to help minimize the cycle time by judicial arrangement of the devices used in the part presentation system. The layout optimization was demonstrated for three different robot assembly problems - a wire harness assembly, an office equipment assembly, and a control panel assembly.

An economic model was then developed that assumes that flexibility in the system is reflected in the costs incurred during the life of the system and in the production volume. A flexible system requires less changeover costs and operating costs during the life of the system, and is able to produce more units than a less flexible system. The methodology uses this fact to arrive at a system worth measure that reflects the relative worth of different part presentation system. The methodology breaks down the life of the system into production phases where each phase is separated from the next by a production change. The methodology uses product and production information to determine the capital (or alteration) costs, operating costs and the production volume for each of the production phases.

The production volume and the costs for the system life are then lumped into the total production volume and the net present worth respectively. The flexibility of the part presentation system is described by the ratio of the net present worth and the total production volume which translates to cost per composite product. This can be used to evaluate different part presentation system and to conduct sensitivity analyses.

The methodology provided a framework for the evaluating of candidate part presentation systems. It helped identify the critical parameters that influence the system cost measure. The approach incorporates the effects of system flexibility into standard capital investment evaluation procedures. It meets each of the four goals set in Section 1.2 and repeated below.

a. Develop a Methodology to Evaluate Alternative Part Presentation Systems: A systematic approach to the evaluation of such systems was developed. It allows the user to evaluate part presentation systems that are used for robotic assembly. Using the constructs outlined in item b. below, systems that are not constrained to the assembly of products from the same family can be studied.

b. Robot Cell Layout Design Package: A package was developed using super-shapes. This technique is a novel way of dealing with the physical design of robotic assembly cells. It has proved to be superior to other existing techniques for solving this problem. It combines the advantages of an efficient shape representation with the ability to define the objective function and the constraints in a simple form. It has been succesfully demonstrated for three different assembly cells. The promise of this technique lies in the ease with which it can be extended to three-dimensional problems and the ability to deal with non-rectangular workspaces, reserved areas, and fixed shapes.

c. Identify Suitable Constructs: Two constructs - composite product and kitting factor - were developed. Between the two of them are able to capture the information relating to the products being assembled and the part flow. Though the composite product was used to aggregate information on products belonging to the same product family, the same idea can be extended to products from different families. The kitting factor provides a convenient handle for the study of the part presentation systems and to perform the sensitivity analyses.

d. Incorporate Intangible Benefits: The flexibility of the system to production change is reflected in the production volume. A desirable characteristic for a candidate part presentation system is the low impact on production volume. The system cost measure captures this information. The net present worth for the study period accounts for the costs incurred in the system, while the total production volume accounts for the ability of the system to prevent loss in volume.

e. Demonstrate For a Practical Problem: The methodology was succesfully demonstrated for the assembly of a control panel. The system was studied for the impact of product design and product mix changes. It identified the penalty factor on feedable parts supplied by magazine and unit robot operating cost as critical parameters.

6.2 Recommendations

The super-shape approach has proved to be very useful for the design of the physical layout of robot assembly cells. Currently it represents devices by their two-dimensional footprints. A logical extension of this approach would be to implement a three-dimensional version which would not constrain the devices to the same plane.

Practical usefulness of the super-shape approach was enhanced by the use of the overlap and radius adjustment factors. Currently these factors are estimated by the user based on knowledge of the aspect ratios and symmetry of the devices that are to be located in the robot workspace. Formalizing the determination of these factors based on device information would be useful.

It was found that the unit robot operating cost and the penalty factor on the feedable parts supplied by magazines were important factors to be considered in the evaluation of part presentation systems. Extensive investigation of these economic constants would be very useful for the future implementation of this methodology.

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APPENDIX

ESTIMATION OF THE QUANTITY OF MAGAZINES NEEDED

The assembly of a composite control panel assembly consists of 87 motion segments (see the Overall Interaction/Weighting Matrix in Table 3.16). If it takes one second for each motion segment to complete, then

Cycle time (material transfer component) = 87 seconds

Assuming that the operation time (insertion, pickup, delivery, etc.) is approximately $1\frac{1}{2}$ times the material transfer component,

$$\text{Overall Assembly Cycle Time} = 87 + (1\tfrac{1}{2})87 = 217.5 \text{ seconds}$$

If it takes 15 seconds to setup the assembly cell to assemble the next product, then one unit is produced every 232.5 seconds. Therefore, $15\frac{1}{2}$ units of the composite product are assembled every hour.

Assuming that the stock of magazines provided at the cell is for a production time of $1\frac{1}{4}$ hour and the length of a magazine is 75 cms, the number of magazines required can be drawn up as shown in the table on the next page.

Item	Quantity Required	Size (cms)	Magazine Length	Number of Magazines
Display Button	$15.5 \times 1.25 \times 5 = 96.9$	3	290.7	$\frac{290.7}{75} \approx 4$
Push Button	$15.5 \times 1.25 \times 4.5 = 87.2$	3	261.6	$\frac{261.6}{75} \approx 4$
Short Plunger	$15.5 \times 1.25 \times 2 = 38.8$	1.5	58.1	$\frac{58.1}{75} \approx 1$
Long Plunger	$15.5 \times 1.25 \times 2.5 = 48.4$	1.5	72.6	$\frac{72.6}{75} \approx 1$
Lamp Holder	$15.5 \times 1.25 \times 5 = 96.9$	1.5	145.4	$\frac{145.4}{75} \approx 2$

VITA

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