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## A decision support system for the equipment selection of robotic manufacturing cells

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## **ABSTRACT**

### **A DECISION SUPPORT SYSTEM FOR THE EQUIPMENT SELECTION OF ROBOTIC MANUFACTURING CELLS**

**by  
Lars Johan Resare**

Considering the principles of concurrent engineering, a Decision Support System (DSS) is developed to aid in the equipment selection of robotic manufacturing cells. The objective is to synchronously and simultaneously select proper equipment for the cell to provide efficient performance, subject to operational and budgetary constraints.

The DSS consists of several modules, including a data base that houses the specifications of equipment available in the market place, a first cut selection module, and an optimization engine. In its development, the optimization scheme utilizes analytical models and algorithms that capture different sources of variability in production, such as tolerances, clearances and repeatability, encapsulating them into one index that calibrates the percentage of quality items yielded by the system. Based on the available resources, the cells' equipment are then selected to maximize this index. Although the system introduced here focuses on two of the major components in manufacturing cells, industrial robots, and machining centers, it can be easily extended to cover other devices such as conveyors or feeders.

In addition to the three case studies provided, where the DSS is utilized in various situations, a user's manual is appended to the thesis. Its purpose is to aid practitioners in an easily implementable step by step fashion to choose the proper components of the considered manufacturing cell.

**A DECISION SUPPORT SYSTEM FOR THE EQUIPMENT SELECTION  
OF ROBOTIC MANUFACTURING CELLS**

by  
**Lars Johan Resare**

**A Thesis  
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**October 1997**

**APPROVAL PAGE**

**A DECISION SUPPORT SYSTEM FOR THE EQUIPMENT SELECTION  
OF ROBOTIC MANUFACTURING CELLS**

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## ACRONYMS AND ABBREVIATIONS

<b>AGV</b>	Automated Guided Vehicles
<b>CARSP</b>	Computer-Aided Robot Selection Procedure
<b>CE</b>	Concurrent Engineering
<b>CM</b>	Cellular Manufacturing
<b>CNC</b>	Computerized Numerical Control
<b>DSS</b>	Decision Support System
<b>ESIR</b>	Expert System for Industrial Robot (selection)
<b>FMS</b>	Flexible Manufacturing System
<b>MADM</b>	Multi-Attribute Decision Making (models)
<b>MASR</b>	Maximum Allowable Size Ratio
<b>MCDM</b>	Multi-Criteria Decision Making (models)
<b>MODM</b>	Multi-Objective Decision Making (models)
<b>MS</b>	Microsoft
<b>NC</b>	Numerical Control
<b>PM</b>	Performance Measure
<b>PSA</b>	Probability of Successful Assembly
<b>RACT</b>	Robotic Assembly while Conveyor Tracking
<b>RALBP</b>	Robotic Assembly Line Balancing Problem
<b>ROI</b>	Return On Investment
<b>TCP</b>	Tool Center Point
<b>TOPSIS</b>	Technique for Order Preference by Similarity to Ideal Solution



# CHAPTER 1

## INTRODUCTION

In order to pursue the factors that influence expenses, and subsequently the efficiency of an organization in today's competitive market, it is necessary to thoroughly evaluate all types of decisions. To confirm or to optimize decisions and selections, in particular more extensive investments, tools are needed to support the decision makers in this endeavor, especially in the light of the increasing number of available types and models of machinery and production equipment. Also, when considering the fact that the aforementioned component alternatives are becoming more complex and sophisticated, the selection process requires extensive effort to distinguish and search for proper and efficient alternatives.

In the work presented here, a computerized decision support system has been developed for the selection of assembly and machining equipment. Though the system primarily focuses on the selection of these production devices in the form of industrial robots and CNC machining centers, it can be linked to include selection functions for other equipment such as conveyors and feeders.

An example of a typical production cell is shown in Figure 1.1. The machining center processes details that, together with standard components such as washers, fasteners etc., fed by a bowl feeder, are assembled by an industrial robot onto (or into) parts that are passing through the cell on a conveyor. A highly automated production cell, such as the one described here, often has a computerized cell control system that

### Linear Approximation of Device Accuracy Versus Cost

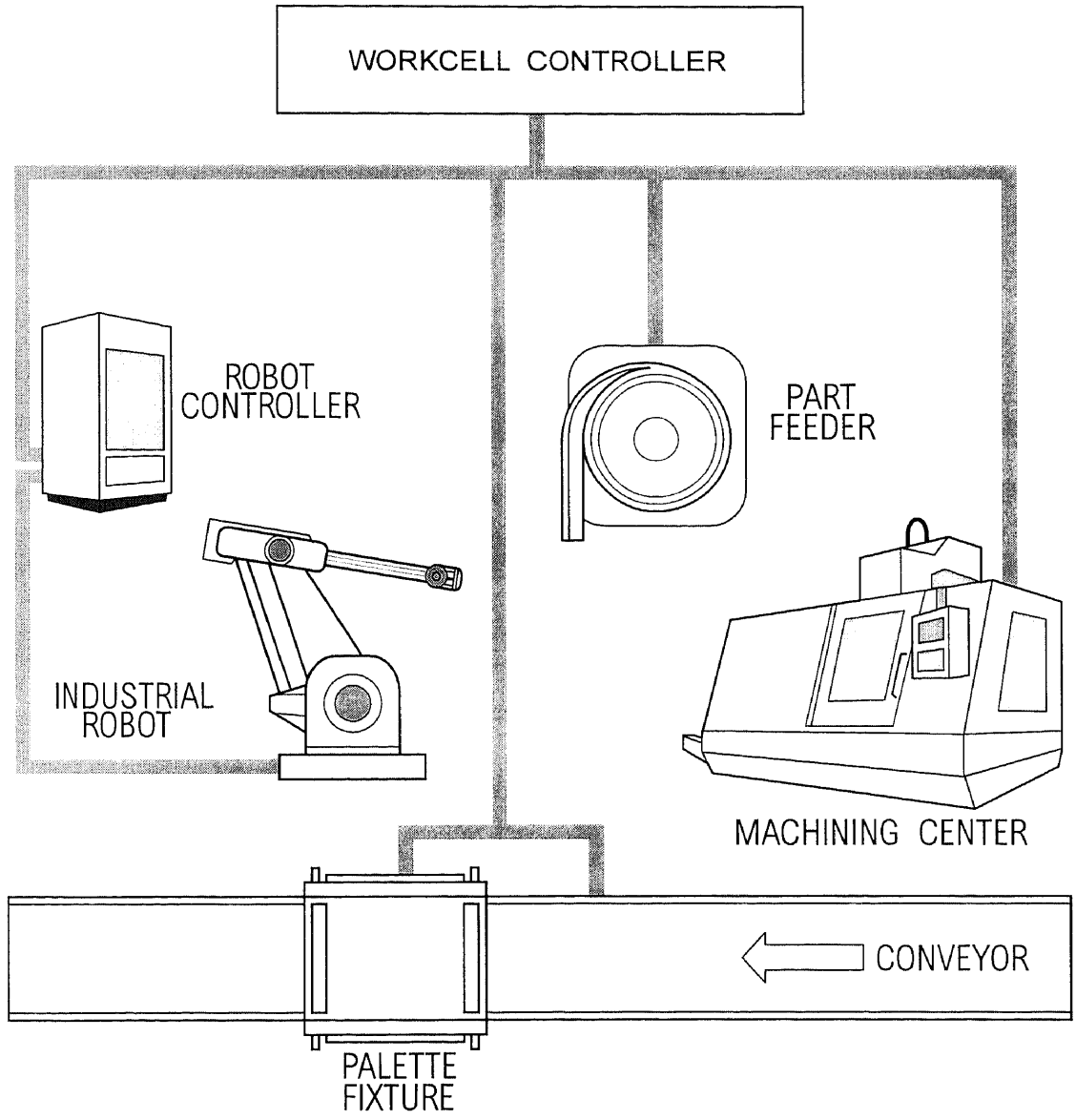


Figure 1.1 Flexible Production Cell

supervises the interaction between the cell components and their environment. However, all these components need to be carefully selected in order to guarantee a proper interaction and a high and steady level of production quality. Our approach here is in sync with the popular concept, often referred to as concurrent engineering philosophy.

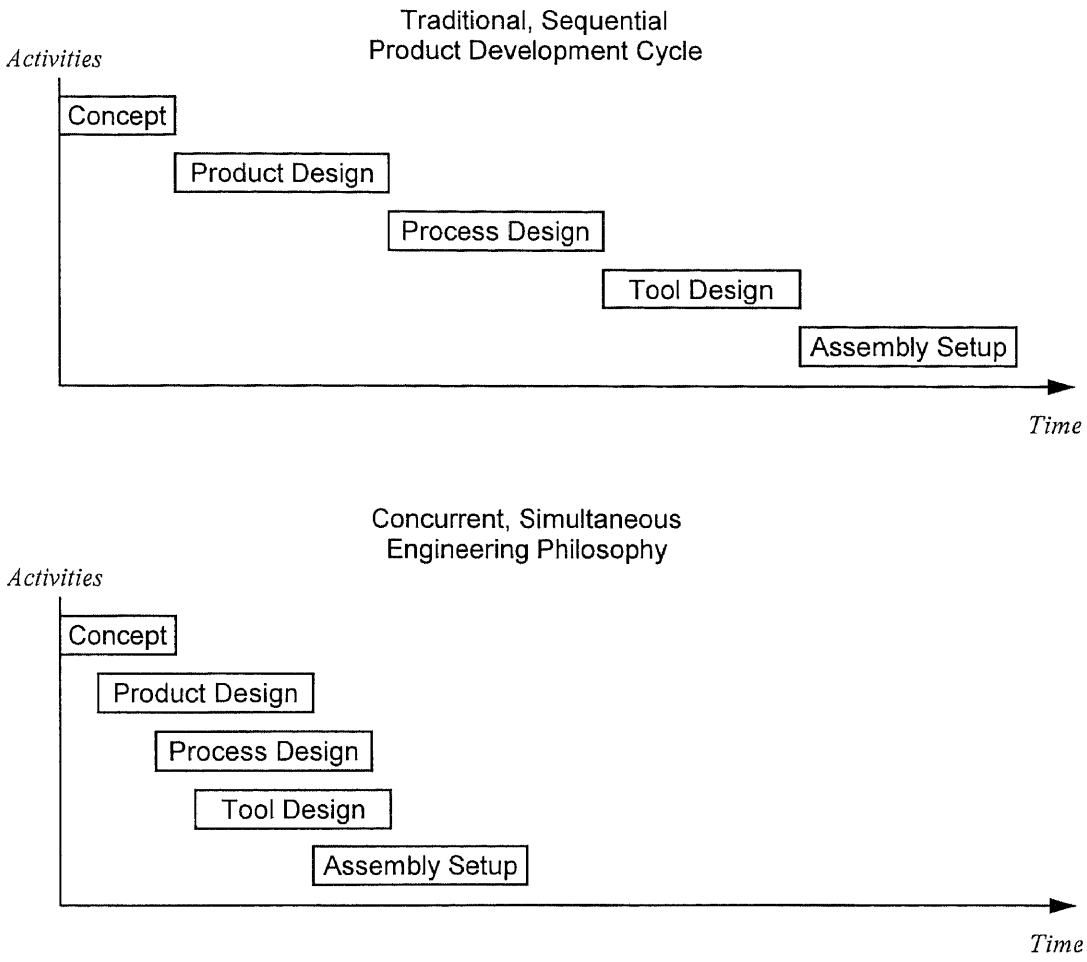
To give a more detailed picture of the need for this type of a decision support system, the following introductory sections discuss the importance and necessity for continuous development of supporting tools and methodologies. They include definitions of concurrent engineering and what is involved in equipment selection.

### **1.1 Concurrent Engineering Philosophy**

The concurrent engineering (CE) philosophy has emerged as a result from the increasing competition among industry and service enterprises during the past decades. The CE concept includes a variety of relatively new tools and methodologies developed to improve the productivity, quality, and efficiency of the market competitors. In order to choose among the wide selection of contemporary process and manufacturing equipment, to plan and design efficient facility configurations, and to successfully implement new machine and robot components, the CE concept is essential.

On a philosophical plane, the objective in CE is, rather than sequentially deal with each process one after another, to achieve the same results in a shorter time by simultaneously handling the various processes, as shown in Figure 1.2. As one can see, one of the most striking benefits of the CE approach is the drastically reduced cycle times, as shown here, in the case of a production development cycle. The idea is also that, in addition to the improved time efficiency, the overall performance will increase as the

different processes become more closely integrated with each other. The outcome will more likely be ‘right the first time’ and save the company time and money for correcting errors that are caused by poor communication.



**Figure 1.2** Conventional vs. CE Approach to Product Development

The term “flexible manufacturing” is an important concept in CE, and since the designation apparently also has a somewhat flexible meaning, we will try here to clarify the definition in the context of this thesis.

***Flexible manufacturing is the manufacturers’ ability to produce highly customized goods or products in a time and cost effective way.***

Representative of a flexible manufacturing system (FMS), such as the production cell in Figure 1.1, is the use of computer controlled machine equipment. Digital computers have made it possible to build re-programmable manufacturing systems that include CNC machining centers, industrial robots, and material handling systems such as Automated Guided Vehicles (AGVs), etc.

The flexible manufacturing and the popular quality management philosophies are an important foundation in CE. However, one should remember that the industrial evolution today is moving towards highly specialized organizations, where outsourcing, telemanufacturing, etc. place the company establishments in a new situation. Here, the structure is different from large and traditionally organized companies, and it is often impossible to achieve significant improvement potential provided by known CE methodologies. Therefore, the need for new tools and methods is by no means less today. Also, in order to properly select, optimize, and verify decisions in various aspects and situations in a company, new CE concepts are needed.

## **1.2 The Robot Selection Problem**

The use of industrial robots has been growing at a steady state of approximately 5,000 new robots per year during the past decade. Currently, it is estimated that 50,000 robots are used in American industry. The costs of a typical process robot usually vary from \$40,000 up to \$180,000. The money invested in a robot can be defined differently, depending on cost categorization philosophy. Nevertheless, an investment decision concerning robots will have a crucial affect on the whole process capacity for a relatively long period, as the robots often are used for significant time, typically up to six years.

Also, due to increasing complexity and a wider selection of available robot configurations and models, the problem of selecting the appropriate robot can have significant impacts on the whole company.

When looking into more detail, one can learn that according to Hoshizaki and Bopp [1990], there has been an evolution where every 5 to 6 years a new generation of robots and manufacturing systems has been introduced. How often an industry chose to replace their robots is dependent on the type of robot, the type of work application, and the utilization of the robot.

As the number of industrial robots available in the market today is quite extensive, and the amount of information on which the user needs to base the decision regarding when to invest in a new device is enormous. Therefore, there is a need for aiding tools and methods to help the decision maker to structure and process all this data in order to make an acceptable decision.

### **1.3 Machining Equipment**

As previously mentioned in the context of flexible manufacturing, the Numerically Controlled machines, NC, and the Computerized Numerical Controlled machines, CNC, are examples of devices that have improved the productivity, as well as the quality of processing. The term *machining centers* includes CNC milling machines, and sometimes CNC lathes. The latter is also referred to as *turning centers*.

One of the major advantages of CNC machining centers is the reduced processing time as compared to conventional machines. For example, a relatively complex part that may require six separate turning, milling, drilling, and tapping processes, can be

processed in the same machining center in only two setup operations, with a process time reduced with more than 50%. The computerized control system also allows processing of complex shapes and geometries that earlier were virtually impossible. Generally, machining centers are known to be especially suited for profile milling, pocket milling, surface contouring, and die sinking operations, in which two or three axes of the work piece must be simultaneously moving to achieve the required cutter path. A typical 3 or 4 axis machining center can have a tool turret with 20 tools, of which several can be powered, such as drills or mills. To maximize the utilization, machining centers are often used with pallets, sometimes with various setup positions, that allows loading, reorienting, and unloading of parts while another pallet is processed by the machine. The cost of a machining center varies from some \$50,000 up to \$300,000.

Other FMS equipment includes material handling systems such as the earlier mentioned AGVs, part feeders, and conveyors that feed and move material and parts between different work cells.

#### **1.4 The Expert System**

The reason that we have focused on the design of the expert system primarily for the selection of industrial robots and machining centers is that there is a strong correlation between the two. Often, parts processed in a machining center are not only handled by a robot, but also assembled by the same. If the user knows what s/he will produce in the machining center, and how these parts are to be handled by the robot, there is a better potential of obtaining a more optimized selection of the two. Furthermore, as in the robot selection problem, there is a similar dilemma when choosing proper machining

equipment, as the complexity and the wide selection of CNC devices is correspondingly overwhelming.

Like most expert systems, the one presented in this work is given in the form of a computer software. Accordingly, one of the intentions has been to provide an easy-to-use interface, engineered for any type of user that may need this. On the other hand, a very knowledgeable process engineer in charge of designing and selecting equipment devices for a new manufacturing cell, may use this system to broaden the approach, or to verify a already made decision.

### **1.5 Research Objective**

The research objective of this thesis is to design and build a functional software application that utilizes an analytical approach and a mathematical algorithm to aid in the selection of assembly robots and machining centers. The algorithm and model used here are developed to optimize the output performance of a assembly process with a separate robot, or the cell performance of combined robot and machining center. This part of the expert system can be described as a optimization module.

Furthermore, to design a new data base for industrial robots and machining center devices that can be used, either separately, or together with the optimization module. As these two components, or modules, together, represents a new decision support system (or expert system) for the selection of assembly and machining devices.



## **1.6 Organization of the Thesis**

The thesis consists of eight chapters that are organized as follows. After this introduction, the second chapter reviews the earlier work and the relevant literature to this project. The model and algorithm used in the expert system are described in chapter three. In chapter four, the design of the expert system is presented. Chapter five describes the data base part of the system, while the optimization module of the system is presented in chapter six. Applications by a set of three case studies are given in chapter seven. Finally, chapter eight contains the conclusion and directions for future research.

## CHAPTER 2

### LITERATURE RESEARCH AND EARLIER WORK

In this chapter we review the literature in the areas of equipment selection and expert systems design. Also, we review recent evaluation algorithms pertinent to the performance evaluation of manufacturing cells. It should be mentioned that most of the up-to-date work in equipment selection has focused on robot choice. A comprehensive review of the literature in this field is that found in Khouja and Offodile [1994], who categorized the robot selection models as follows:

- **Multi-Criteria Decision Making (MCDM) Models,**
- **Production System Performance Optimization Models,**
- **Computer-Assisted Models, Statistical Models, and**
- **Other Approaches.**

We will follow their classification model, as we begin this chapter by reviewing the literature on robot selection. Included here are also concepts of expert systems, algorithms, and data bases. Before concluding the chapter, the production cell selection and design is also considered.

#### 2.1 Multi-Criteria Decision Making (MCDM) Models

The Multi- or Multiple Criteria Decision Making (MCDM) methods refer to making decisions in the presence of multiple criteria. It is not unusual that the different criteria are conflicting each other's interests. A typical example is the speed and the repeatability or the payload and the repeatability of a robot. As the criteria can be classified either as

attributed, or as objectives, there are also two approaches within the MCDM class, the Multi-Attribute Decision Making (MADM) models, and the Multi-Objective Decision Making (MODM) models.

To help distinguish between the two categories, we refer here to Agrawal, Kohli and Gupta [1991], who present the following tabular comparison (Table 2.1).

**Table 2.1** Comparison of MADM and MODM

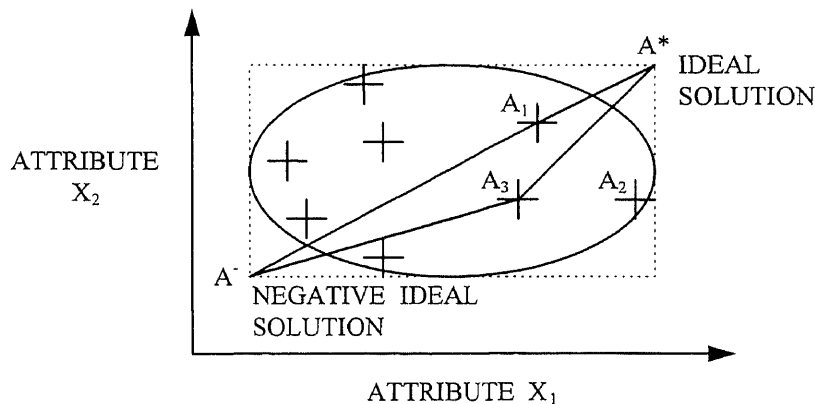
	<b>MADM</b>	<b>MODM</b>
Criteria	Attributes	Objectives
Objectives	Implicit	Explicit
Attribute	Explicit	Implicit
Constraint	Inactive (incorporated into attributes)	Active
Alternatives	Finite in number and discrete (prescribed)	Infinite in number and continuous (emerging)
Interaction with decision maker	Not Much	Mostly
Usage	Selection/evaluation	Design

Agrawal, Kohli and Gupta [1991] uses the multiple attribute decision making approach to motor a computer aided robot selection system. Their approach is to first let the expert system ask the user for information about the type of application for which the robot will be used. The system contains a list of different applications with their respective important key attributes. From the list of key attributes, a smaller number of pertinent attributes with the corresponding threshold values for the particular application is then assigned by the user. Information on the threshold values must be obtained by the

user, with some assistance from the expert system. These pertinent attributes, and the threshold values for each of them will present all the attributes that the expert system will focus and base the decision upon. Then, an elimination search through a data base of available robots will identify the feasible robot alternatives, based on the threshold values. Thereafter, a MADM method called TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is employed to rank the feasible alternatives. This method seeks the alternative that has the highest relative closeness,  $C^*_i$ , to the ideal solution  $A^*$ , according to:

$$C^*_i = \frac{S_i^-}{(S^*_i + S_i^-)}$$

where  $S_i^-$  is the distance between  $A_i$  and the negative ideal solution, and  $S^*_i$  is the distance between  $A_i$  and the ideal solution, as shown in Figure 2.1. The information on the feasible



**Figure 2.1** Ranking Feasible Alternatives by TOPSIS

alternatives is put into a decision matrix,  $A$ , where each column represents an attribute, and each row represents a feasible robot alternative. The user then has to specify the

relative importance of the pertinent attributes, by pair wise comparisons, that is stored in the 'D' matrix. In order to determine this  $D$  matrix, the Eigenvector method is used to modify the relative weights of all the attributes, so that the cumulative sum is equal to unity, and to obtain the weight matrix vector  $W$ . From decision matrix  $A$ , a normalized decision matrix  $R$  is then calculated. Having the matrices  $R$ ,  $A$ , and  $W$ , one determines the weighted normalized matrix  $V$ . From this matrix,  $V$ , one can determine the ideal ( $A^*$ ) and the negative ideal ( $A^-$ ) solutions. For each robot alternative one then calculates the relative closeness ( $C^*_1, C^*_2, \dots, C^*_n$ ) to the ideal solution, and ranks the alternatives ( $A_1, A_2, \dots, A_n$ , again, see Figure 2.1).

Another proposed Decision Support System for Robot Selection is described by Jones, Malmberg, and Agee [1985], where they present a more user friendly and easy-to-use decision support system. Here, as in the previously described approach, the user first determines which attributes that s/he wants to emphasize, and threshold values for each of them. The system has a clearly pre-defined list of 22 numerical attributes in two groups, and 7 discrete (for two options, ex. yes or no, 1 or 0, etc.) attributes in a third group. When utilizing the system, six different attributes should be specified to be accommodated simultaneously. Thereafter, the system searches the data base for feasible robot alternatives. A set of marginal value functions,  $V_i(X_i)$ , are used to convert the attribute values to scaled values between 0 and 1. The numeric attributes are then ranked according to relative importance. The importance of each attribute  $X_i$  is weighed with the importance value,  $\lambda_i$ . These scaling constants must satisfy:

$$\sum_{i=1}^n \lambda_i = 1, \text{ and } \lambda_i > 0$$

The weight factors involves a number of trade-off decisions that have to be made by the user, for example, a preferred cost value, can be traded off for a decreased payload capacity. Once the preference values and scaling constants are determined, the total preference value for each robot model is calculated according to:

$$f(X') = \sum_{i=1}^n \lambda_i V_i(X_i')$$

The  $f(X')$  value will get a number between 0 and 1, where the highest one indicates the most desirable choice.

The authors make a very good point of stressing that one should bare in mind that the ranked values,  $f(X')$ , are only useful for detecting order-of-magnitude differences in the preferability of the alternatives. Furthermore, the result of the decision model is directly based on the type of attributes that the user has selected.

To briefly summarize the philosophy of the multi-objective decision making models, one can conclude that MODM maximizes the objective function in a similar way to the MADM. According to Khouja and Offodile [1994], the MODM provides an advantage over MADM as the decision makers objectives are explicitly considered and evaluated when using the latter. However, as there is a somewhat confused distinction between the numerous objectives and attributes in the robot selection problem, the importance to having an extensive knowledge of all these aspects is crucial for the decision maker. The same need for a good understanding of the relationship between the robot engineering attributes and the desired performance of the production system is mentioned as Khouja and Offodile conclude that one of the major advantages of the MADM is their ability to consider a large number of robot attributes.

## 2.2 Production System Performance Optimization Models

These models are designed to optimize one or several system performance measures. The system could include only the robot itself, or a more complex set of both robots and other equipment comprehended in the production process.

Abdel-Malek and Boucher [1985, a] first introduces an algorithm for evaluating the trade-off between different producibility alternatives (robot models) and the product design in terms of the clearance settings between the assembly parts in a Peg-In-a-Hole assembly. The algorithm uses the robot repeatability and the tolerance and clearance settings of both of the assembly parts (the peg and the hole part) to determine the probability of a successful assembly (PSA). A successful assembly applied in the peg-in-a-hole case is when the peg is inserted in the hole without jamming. In this paper, the author uses the model to maximize the robot productivity rate,  $RP$ ;

$$RP = P(I) \left( \frac{1}{CT} \right)$$

where  $P(I) = P(\text{clearance} \geq \text{repeatability})$ , and  $CT$  is the cycle time. This means that for  $P(I)=1$ , the robot productivity rate per hour is given as  $1/CT$ .

In Abdel-Malek [1985, b], a method for optimizing the number of trials for an assembly robot to insert a peg-in-a-hole, in order to optimize production rate, is introduced. This means that when there is an unsuccessful assembly operation, the robot can either drop the assembly part and start the next assembly with a new part, or try again, and here, the issue is to optimize the number of times that the robot attempts to fix a failure with a new try. The number of attempts depends on the ratio between the cycle

time and the time for a new trial. These are a direct function of the robot velocity. The expected cycle time is here expressed as:

$$C = C_T + C_r P(I) q \frac{\partial}{\partial q} \sum_{i=1}^n q^{i-1}, \quad i = 1, 2, \dots, n$$

$$q = 1 - P(I)$$

where  $C$  is the total cycle time,  $C_T$  is the cycle time for a successful assembly operation,  $C_r$  is the time of retrying, and  $n$  is the number of trials. In order to maximize the production rate,  $K$ , it is assumed that:

$$\frac{\partial K}{\partial n} = 0$$

where  $n$  is an integer, and the  $F$  ratio becomes:

$$F = \frac{C_T}{C_r} = \frac{1}{(\ln q)} [1 - q^n] + n [1 - 2q^n]$$

The approach to maximize the PSA is further developed by Abdel-Malek[1986], where the method is applied to parts with more complex geometries than the peg-in-a-hole case. Here, as earlier, the robot repeatability is the most crucial issue. However, the definition of the robot repeatability is further developed. It is broken down into the repeatability that usually is specified by the manufacturer, and to the angular repeatability that is caused by the robots axes that will cause an angular displacement of the assembly part. When calculating the PSA, the function is divided into the PSA in the x and y directions:

$$P(I) = P(U_x \geq V_x) P(U_y \geq V_y)$$

where  $U_{x,y}$  is the clearance between the mating parts in x and y directions, and  $V_{x,y}$  is the displacement or the repeatability in the x and y directions. If there is more than one



component that is to be inserted in the same operation, the author refers to Hadley [1961] to express the general formula for calculating the  $\mu$  and  $\sigma$  values:

$$\mu_{ic(x,y)} = \frac{1}{2} \left[ \left( \mu_{i(x,y)_2} \right) - \left( \mu_{i(x,y)_1} \right) \right]$$

$$\sigma_{ic(x,y)}^2 = \left( \frac{1}{2} \right)^2 \left[ \left( \sigma_{i(x,y)_2}^2 \right) + \left( \sigma_{i(x,y)_1}^2 \right) \right]$$

where  $i$  is the number of insertion components on the part object. For each component,  $i$ , the mean and variance values are expressed in a two column matrix form, where the first column represents the insertion part dimension and the second column represents the hole part dimension. The algorithm is also generalized to include the robot angular repeatability.

Abdel-Malek [1987] also uses the PSA approach to maximize the process profit per unit time,  $K$ , where the robot operating cost per unit time,  $g(r)$ , also is taken into account. Regardless of the fact that the author here assumes that the robot has a uniformly distributed repeatability, the objective function becomes:

$$K = \frac{fP(I)}{C_T} - g(r)$$

where  $f$  is the profit per unit assembled, and  $C_T$  is the cycle time of the assembly. The operating cost for the robot  $g(r)$  is equal to the clearance divided by the robot repeatability. To optimize the repeatability value,  $R$ , a computer program was developed to utilize the Newton Raphson method to find the numerical solution for:

$$C_T \frac{C}{f} - \mu\Phi(R) + \Phi(R) \left[ (\mu_d - R^2) \left( 1 - \frac{1}{\sigma_d} \right) + \sigma_d \right] = 0$$

as  $\partial K / \partial R = 0$ .

The models utilizing the PSA concept are also used to evaluate the economic feasibility of Robotic Assembly While Conveyor Tracking (RACT) in Abdel-Malek [1989]. RACT, that is used to increase the throughput of the assembly process, means that a robot performs the assembly operation while the part is moving on a conveyor belt. This operation requires that the robot can synchronize the speed of the assembly part with the mating part on the conveyor, and simultaneously position the part to fit in its position. This approach assumes that all the assembly parts are within their tolerance ranges, and that the robot's and the conveyor's repeatability is normally distributed. The repeatability that is used to calculate the PSA is here also influenced by the conveyor according to:

$$\sigma_r^2 = \sigma_f^2 + \sigma_\Delta^2$$

where  $\sigma_f$  is associated with the robot repeatability, and

$$\sigma_\Delta^2 = \sigma_\varepsilon^2 + (\beta v)^2$$

where  $\sigma_\varepsilon$  is the conveyor's positional repeatability. However,  $\sigma_\varepsilon$  is 0 since this factor can be eliminated by positioning sensors.  $\beta$  is a known constant, and  $v$  is the velocity of the conveyor. The cycle time for an assembly operation is the larger of the robot cycle time,  $T_f$ , and the time between two successive assemblies,  $T_\Delta$ , in the case where the conveyor has to stop during the insertion. The production rate thus becomes:

$$RT = \frac{P(I)}{T_f}$$

or, when  $T_f < T_\Delta$ :

$$RT_t = \frac{P_t(I)}{T_\Delta}, \text{ and } T_\Delta = \frac{\pi}{v^*}$$

where  $\pi$  is the distance between successive works on the conveyor, and  $v^*$  is the optimum conveyor speed. By assuming that

$$\frac{\partial RT_t}{\partial v} = 0,$$

the optimum velocity can be obtained by:

$$v^* = \sqrt{\frac{\sigma_{z_t}^2 P(I)}{2\mu_c \beta^2 \Phi(\mu_{z_t} / \sigma_{z_t})}}$$

The implementation of RACT should be economical feasibly when  $RT_t > R_T$  and  $T_f \leq T_\Delta$ .

In the case where  $T_f > T_\Delta$ , the author suggests solutions for how to reduce the  $T_f$ , such as, using multiple number of robots overlapping two or more processes that are able to handle the assembly operation, as well as the previous or following operation.

Doydum and Perreira [1991] present a method for selecting dimensions, tolerances and precisions for alignment. Their theory follows a similar concept as the one introduced by Abdel-Malek and Boucher [1985] and Abdel-Malek [1985] and [1986], where a maximized probability of a successful assembly (PSA) is applied as the objective function. Here, the probability of successful alignment (also PSA) indicates the influence of the parts' size ratio, tolerance, and equipment precision. The Maximum Allowable Size Ratio (MASR) is defined for one and two dimensional alignment error models and verified with a Monte Carlo simulation. If equipment with known precision is used, and a

maximum allowable alignment failure rate is specified, the PSA concept can be used to determine the parts dimension ratio and tolerance.

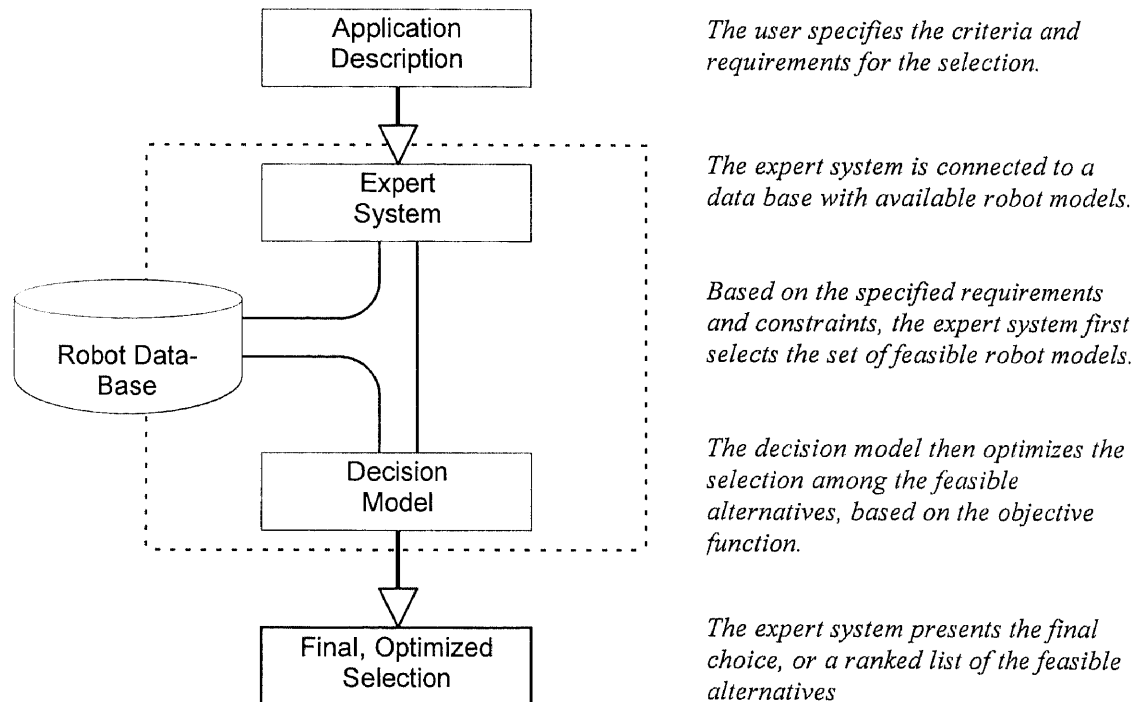
Abdel-Malek [1995] introduces the concept of evaluating and optimizing the robot selection problem by integrate the robot efficiency with the desire to achieve a more general, over-all optimized level of quality throughput. This is done by evaluating both the manufacturing and assembly (robot) capacities. The manufacturing perspective can be taken into account when examining a production process that includes a machine tool device that processes the assembly parts, and a robot that assembles these parts. The objective is to maximize the probability of a successful assembly, subject to constraints that include the total cost of investing in the robot and machine tool devices, as well as the design constraints of the product. An algorithm is introduced that gives the step by step approach for how to optimize the selection of the two devices with respect to their cost efficiency. The algorithm assumes that the accuracy of the machine tool and the repeatability of the robot are normally distributed, and that there is a linear relation ship between the cost and the accuracy/repeatability.

### **2.3 Computer-Assisted Models**

The computer aided models have achieved a increasing level of interest during the past years. Not only because of the increasing number of robots that are sold today, but also because of the wider selection of models and features, and the complexity of attributes. The computers' affordability and ability to efficiently store information of available models in data bases, together with their ability to combine these databases with

computerized decision support systems. One can describe the logic of a typical computer aided system as shown in Figure 2.2.

Among the first to develop a data base for industrial robots where McDermott [1984]. The data base provides a retrieval system that allows the user to specify threshold values of all the attributes that are specified in order to narrow down the selection. The data base contains 16 attributes and 9 different application functions. At the time, the data base contained some 220 robots that represented most of the available industrial robots in the US market.



**Figure 2.2** General Model of a Typical Computer Aided Decision Model

Offodile, Lamebert, and Dudek [1987] present the development of a Computer Aided Robot Selection Procedure (CARSP) that introduces the concept of standardized

storing of robot attributes into a database. CARSP utilizes an algorithm developed for selecting one or a number of feasible robot alternatives from the standardized data base. The development of CARSP included the selection of appropriate robot attributes or characteristics for the data base, the design of a coding and classification system (ROBOCODE) for the selected characteristics, the design of a grouping algorithm that classifies the robots to match the application requirements, and finally, applying an economical analysis to compare the costs of the feasible alternatives. The ROBOCODE is comprised of 40 digits that represents different classes, applications, and attributes, such as number of axes, work envelope, etc. The robot selection problem is captured in the objective function:

$$\text{Minimize } CT_r = \sum_{\delta=1}^{\Delta} CA_{\delta}$$

subject to:

$$f(X_i) \geq f(Y_j, Z_k)$$

$$X_i, Y_j, Z_k \geq 0$$

where  $CT_r$  is the total cost to install and use robot  $r$ ,  $CA_{\delta}$  is the cost of each component,  $\delta=1,2,\dots,\Delta$ .  $X_i$ ,  $Y_j$ , and  $Z_k$  is the robot model, the task, and the environmental variable. The first cost component is defined as the investment cost that identifies the unit cost, the installation and startup cost and the cost of related equipment such as special tooling etc. The second component, total overhead cost, is the maintenance, power supply, and robot operator education cost, etc. Finally, the production cost can be broken down to setup cost for the robot for each process and product, the actual production cost for running the robot of all expressed per unit time. Two different selection criterias are exemplified in the paper:

1. **A minimum total cost - the robot with the minimum total cost over a period of time of one year.**
2. **The minimum net present worth (NPW) amount - the most cost effective robot over a longer period of time, for example, the hypothetical present cost for operating the robot over a five year period.**

The authors also identifies the number of (and the type of) different tasks for the robot will influence on the most cost effective robot alternative.

Boubekri, Sahoui and Lakrik [1991] presents a development of a Expert System for Industrial Robot selection (ESIR). Similar to the earlier described computer aided robot selection system, ESIR contains a data base with the most common applications and attributes. The user is first asked to specify the application of the robot that will automatically assign certain performance parameters with respect to the application. For example, if the user is searching for a robot for spray painting, the system will automatically assign the minimum number of axes to three, vertical and horizontal robot motion capability, etc. The expert system has sets of questions related to each application that will ask additional questions for typical parameters. In the case where the user is looking for a spray painting robot, the system will ask what kind of environments the robot will operate in. An “unclean” environments will automatically assign the type of drive value to hydraulic. These sets of application related questions and their specific parameters are stored in the “fact base” of the data base. The user is then requested to provide values for the remaining factors or attributes. At any time, additional constraints and rules can be added to the search engine. For example, to fit a certain production need, such as in the example of the spray painting application, the rule that the speed needs to be ‘fast’ could be added. From these threshold values, acting as constraints, the system

searches through the data base for feasible alternatives. Depending on the outcome of the search, the user could either do a economical analysis to optimize the selection among the feasible alternatives, or change some attribute values to obtain a feasible alternative. In the case where the user wants to optimize the selection, the following payback period analysis is utilized:

$$P = \frac{I}{(L - E) + q * (L + Z)}$$

where  $P$  is the payback period,  $I$  is the total cost of investing in the robot,  $L$  is the labor cost,  $q$  is the difference in production rate between using the robot or using manual labor,  $Z$  is the annual depreciation cost of replaced equipment, and  $E$  is the maintenance cost of the robot. The user needs to know the values of the  $L$ ,  $q$ , and  $Z$  parameters, since they are not stored in the expert system.

Also, some of the earlier mentioned models can be arranged into this category. One example is the article by Jones, Malmborg, and Agee [1985] where they propose a computerized decision support system for robot selection.

## 2.4 Statistical Models

In the literature survey by Khouja and Offodile [1994], the authors mention three published works within this category. The purpose of these models is to optimize the tradeoff between robot engineering attributes. The robot engineering attributes are defined as the attributes strictly relating to the physical capacity of the robot, i.e. the robot's ability to perform a specific task.



## 2.5 Other Approaches of Robot Selection

Nnaji [1988] developed a mathematical model for evaluating and selecting robots by using three selection criteria:

1. **Critical measures.** These includes the return on investment (*ROI*), and whether or not the total budget is within its boundaries.
2. **Objective measures.** The objective factors,  $X_{1m}$ , are calculated from the payback period
3. **Subjective factor measure.** The subjective factors are the hardware/software,  $X_{2m}$ , vendor performance,  $X_{3m}$ , and the internal adaption,  $X_{4m}$ .

All of the above can be expressed as the total objective and subjective contribution to the performance measure,  $PM$ , as:

$$PM = (C_{1m} C_{2m}) [\Phi_1 X_{1m} + \Phi_2 X_{2m} + \Phi_3 X_{3m} + \Phi_4 X_{4m}]$$

where  $m$  is the robot model, the binary factors  $C_{1m} = 1$  if  $ROI \geq$  maximum  $ROI$  (equal to 0 otherwise), and  $C_{2m} = 1$  if budget ceiling is met (equal to 0 otherwise). The respective weight factors must satisfy:

$$\Phi_1 + \Phi_2 + \Phi_3 + \Phi_4 = 1$$

In order to first calculate the objective factor, the payback period is calculated by summarizing all the expenses and savings:

- **The Total Capital Investment Expenses,**
- **The Start-up Expenses,**
- **The Savings due to Wages and Benefits of Replaced Worker,**
- **The Savings due to Increased Accuracy,**
- **Earnings due to Increased Productivity,**
- **Maintenance Cost,**

- **Equipment Insurance Cost, and**
- **Energy Cost.**

Thereafter, a cash flow analysis is used to find the average savings over a number of years for a certain robot. The return on investment  $i_{Rm}$ , will correlate to the total initial cost. In the third step the payback period is calculated. From the payback period value, the objective values,  $X_{Im}$ , can be calculated. The subjective factors can be calculated either by using the authors suggested default values for each attribute, or by defining them individually. Finally, the over all performance measure for each robot alternative,  $m$ , is calculated, and the candidate that obtains the highest performance value is selected.

Kim and Park [1995] introduces a strong cutting plane algorithm to solve the problem of assigning an appropriate number of robots for an assembly line, here, defined as the robotic assembly line balancing problem (RALBP). The objective is to assign the work load to the various work stations in order to minimize the number of required work stations. An integer programming approach is used in a number of test problems, showing the considerable effect that an increased number of variables in the algorithm have on the processing time. The model assumes an unrestricted routing flexibility of the parts, and that the supply of parts is independent of the line balancing problem. The algorithm does, however, consider the precedence relationship between different work processes.

## **2.6 Production Cell Design and Equipment Selection**

In the concept of cellular manufacturing (CM), a heuristic method for cell formation and machine selection in the design of new manufacturing cells is presented by Beaulieu, Gharbi and Ait-Kadi [1997]. Rather than optimizing the physical design and layout of the

cell, the method attempts to choose the optimum number of machines, and select the best suited. The algorithm takes into account the machines and the material handling costs, the machine utilization and the different alternative routings of each operation. The method is divided into two different resolution phases, of which the first one formats independent cells using an aggression procedure, while the second seeks inter-cell movements to limit the number of machines required and attempts to increase the total utilization.

The mathematical model used expresses the objective function to minimize the sum of the fixed and variable costs for the machines selected. This method requires that the user specifies information, such as the product demand, the required process time of each operation for all the parts using the different machine alternatives, and also the expected rejection rate. In the first phase, each part is assigned to its own cell. Depending on the specified acceptable utilization rate, the second phase then attempts to eliminate all the machines that does not fulfill the aforementioned requirement.

Though the method does not guarantee the optimum solution, the main advantage is that it provides a feasible solution in a relatively short resolution time. Presumably the model does not apply to more complex problems with a larger number of parts and process operations, as the model neglects all physical aspects, such as geometrical layout and the various impacts of feasible routing options.

## **2.7 Summary of Literature Review**

Although there is a significant number of works addressing the robot selection problem and single process equipment optimization, one can conclude that there is insufficient attention given to the simultaneous selection of production equipment, such as industrial robots and machining centers. This has been one of the major motivations to undertake this study.

## CHAPTER 3

### THE MODEL

The algorithms and models used to optimize the equipment selection in RAMCOSS falls under the production system performance optimization approach, introduced in Chapter 2. To thoroughly explain the underlying logic of the models and the algorithm, we will first clarify the basic terms (described in Zeid [1991]) of tolerances, clearances. An introduction to the probability of successful assembly concept is included in the same section.

#### 3.1 Definitions

##### *Tolerances*

The *Basic Size* of a dimension which represents the nominal size, is in most cases is accompanied by a *Tolerance*. The tolerance can be either *unilateral* which means that variation from the theoretical size is allowed in only one direction, ex.  $25.0_{-0.0}^{+0.5}$ , or *bilateral* where the dimension permits a plus or a minus deviation, ex.  $25.0^{\pm 0.5}$  or  $25.0_{-0.1}^{+0.5}$ .

Although we only will be concerned with the tolerances describing the dimension accuracy of distances between certain positions, it is worth mentioning that there are other sets of other tolerances used to specify information regarding the remaining required dimensions. The latter are shown in Table 3.1.

**Table 3.1** Geometrical Tolerances

<b>Tolerance</b>	<b>Description</b>
Form	Straightness, Flatness, Circularity, Cylindricity
Profile	of a Line or a Surface
Orientation	Angularity, Perpendicularity, Parallelism
Location	Position, Concentricity
Surface	Roughness

Source: *CAD/CAM Theory and Practice* by Zeid, 1991.

Generally, there is a well known relationship between the tolerances and the manufacturing process cost. A more accurate tolerance will most likely result in increased processing cost when producing a particular part.

### *Allowance*

When dimensioning an assembly with two or more parts, the *Allowance* is the difference between the maximum material limits. A positive allowance will result in the minimum clearance, while a negative allowance corresponds to the maximum interference. Furthermore, parts that are assembled together can be designed either with a *Clearance* fit or a *Interference* fit. In the first case, the two parts are dimensioned so that there is always a certain clearance between the mating surfaces to allow a specific assembly method and/or to allow movement between the parts. In the other case, a prescribed interference between the parts will prevent them from moving in relation to each other.

### ***Repeatability***

For a robot, the repeatability indicates how precisely the robot can repeatedly return to a certain, taught point. Usually, this is also what the manufacturer specifies, rather than the accuracy, which gives a theoretical figure of the resolution. The accuracy or repeatability of a machining center is the specified, dimensional range in which the machine is guaranteed to perform.

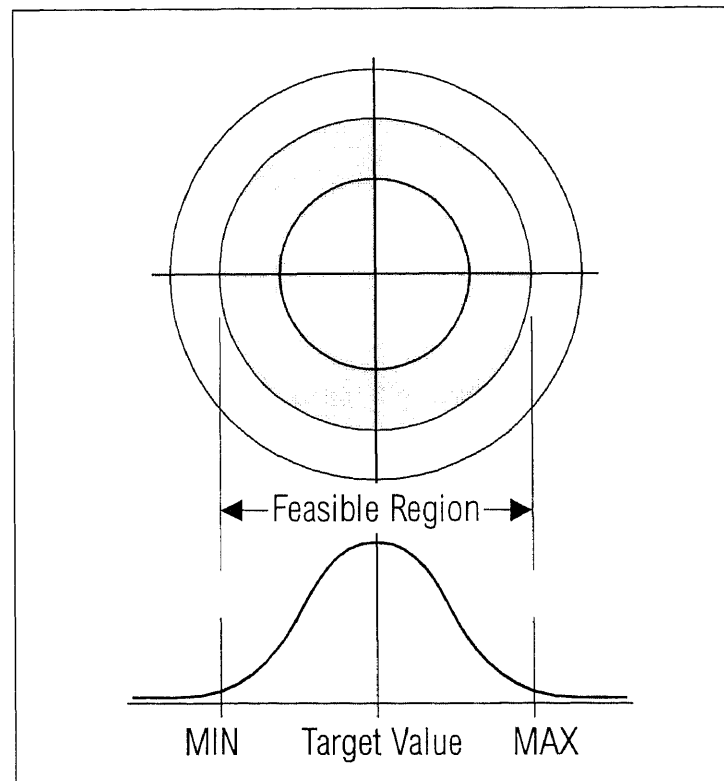
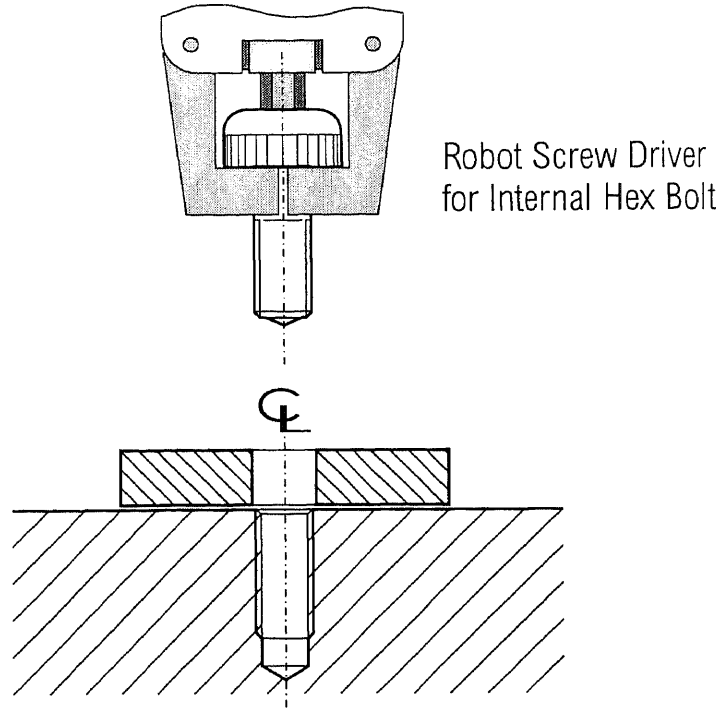
The robot repeatability is known to be normally distributed. For example, in Figure 3.1, where a robot with a screw driver tool positions a bolt over its corresponding hole and inserts it with a rotational movement. Also, shown in same picture, is a 2 dimensional target figure with the corresponding normal distribution function. The shaded area in the target picture is the feasible region, where in the robot has to return.

It is also reasonable to assume that the statistical outcome, the dimension wise a CNC machining center processes is normally distributed. A factor that makes this assumption valid, especially for CNC machines, is that most control systems have built-in tool wear out compensation.

### ***Angular Repeatability***

The angular repeatability is the inaccuracy around the robot vertical axis that will affect the robot performance. The robot gripper tool that holds the assembly part will therefore cause a certain angular displacement. (See also the Angular Displacement section, and Figure 3.4).

## Normally Distributed Angular Repeatability



**Figure 3.1** Robot Repeatability



### *Probability of Successful Assembly*

The probability of successful assembly (PSA) method is used as a performance measure of the output quality of a system by generating a percentage figure of the PSA, Abdel-Malek and Boucher [1985], Abdel-Malek [1985] and [1986]. In the most basic case this is done by only considering the assembly device itself: for example a robot.

Later, however, the PSA concept will be used to measure the overall output quality from a more complex production cell, also consisting of a machining center. Typically, an assembly process starts with the robot grasping the part that is to be placed or inserted, and there after place or insert the part onto or into what is defined as the mating “work” part. The *successful assembly* can be defined as follows:

**A successful assembly is when all the edges of the bottom surface of the part handled by the robot have been placed within the corresponding silhouette of the work part without interfering.**

In any other case, where in some section along the bottom surface there is an interference, the operation is considered as a *failure*.

### *Logic of the PSA*

The logic of the PSA is based on using the clearance and the robot repeatability to generate the percentage of successful assembly, according to:

$$PSA = \prod_{i=1}^n \int_{u=0}^{u_{\max}} \int_{v=0}^{v_{\max}} f_i(v) f(u) \, du \, dv$$

where  $v$  is the domain of the convolution of clearance, tolerance and effect of the part geometry;  $u$  is the domain of the robot repeatability;  $f(\cdot)$  is the associated probability density function; and  $n$  is the number of mating surfaces.

The following example of an insertion operation of a peg in a hole, shown in Figure 3.2, might be advantageous when illustrating further. The maximum displacement,  $T_p$ , is in this case (peg-in-a-hole), theoretically equal to exactly half of the clearance. The clearance between the hole diameter  $D_h$  and the peg diameter  $D_p$ , both assumed to be normally distributed,  $(\mu_h, \sigma_h^2)$  and  $(\mu_p, \sigma_p^2)$ , is here defined as  $2C = (D_h - D_p)$ .

When we define the clearance between the peg and the hole, the independent random variables becomes:

$$\mu_c = \frac{1}{2}(\mu_h - \mu_p) \quad \text{the mean clearance, and}$$

$$\sigma_c^2 = \left(\frac{1}{2}\right)^2 (\sigma_h^2 + \sigma_p^2) \quad \text{the variance of the clearance}$$

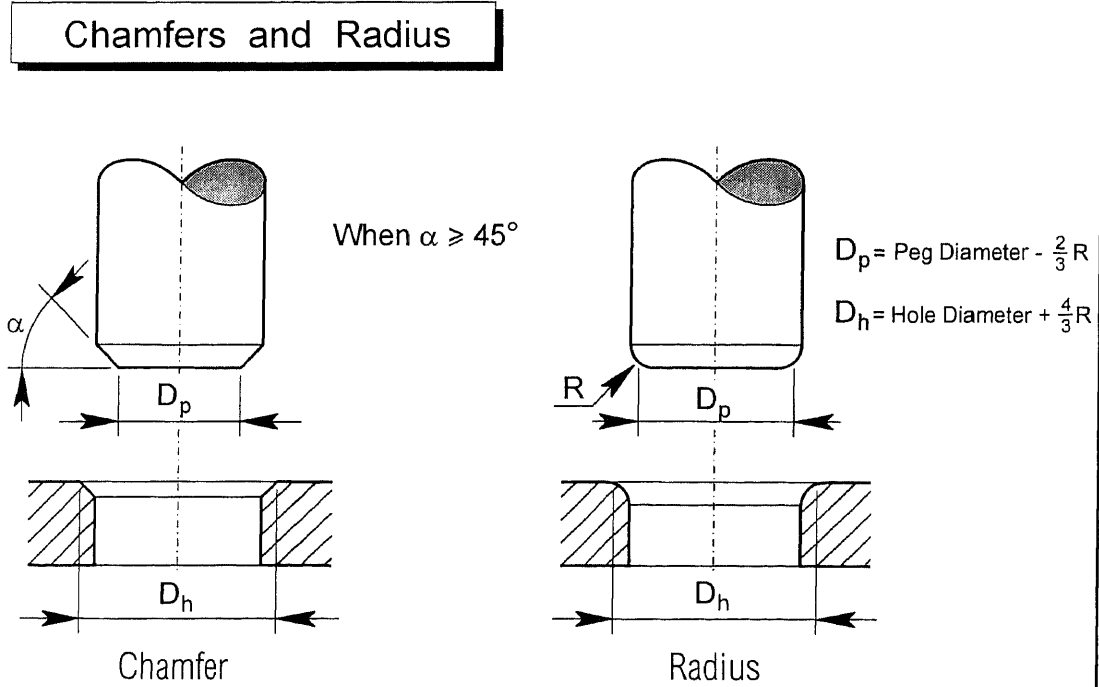
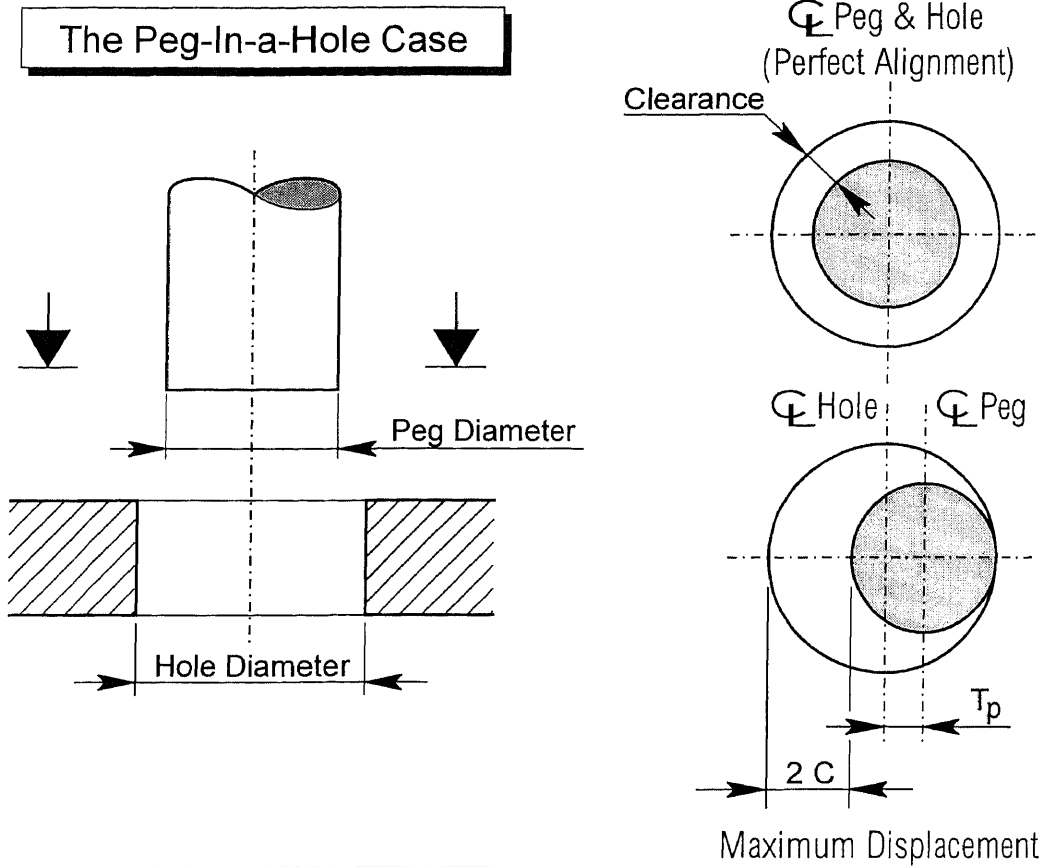
$$P(I) = P(c_1 \leq r \leq c_2)$$

$$P(c_1 \geq r) = P(z_1 \geq 0) = \Phi\left(\frac{\mu_{z_1} - 0}{\sigma_{z_1}}\right) = P(z_2 \geq 0)$$

$$P(r > c_1) = 1 - \Phi\left(\frac{\mu_{z_1} - 0}{\sigma_{z_1}}\right)$$

$$P(c_1 < r < c_2) = 2\Phi\left(\frac{\mu_z - 0}{\sigma_z}\right) - 1$$

From here on, we will use the following general expression for the probability of successful assembly function:



**Figure 3.2** The Peg-In-a-Hole Case

$$PSA = \prod_{i=1}^n \left[ 2\Phi\left(\frac{\mu_{z_i}}{\sigma_{z_i}}\right) - 1 \right]$$

For more thorough proof for the equation above, see Appendix A.

### *Angular Displacement*

When the PSA method is applied to an assembly where the parts have a non-circular, general shaped cross section geometry, the angular displacement will have yet another affect on the displacement caused by the robot. If we for example look at the part in Figure 3.4, the angular displacement,  $\theta$ , around the robot tool center point (TCP) will cause the corner on the furthest distance ( $R_{\max}$ ) from the TCP to result in the largest displacement. The displacement is defined in the x and y direction according to the following formulas:

$$d(x) = Y \sin \theta$$

$$d(y) = X \sin \theta$$

These two formulas, used in the algorithm, are somewhat simplified. The difference of the results using the formulas described above as compared to the exact ones, is negligible. See Appendix B.

## **3.2 The Model**

The driving motor of the expert system is the algorithm which maximizes the performance measure, the PSA, as introduced in the previous section. The algorithm has the following canonical form:

$$\text{Maximize: } PSA = \prod_{i=1}^n \left[ 2\Phi\left(\frac{\mu_{z_i}}{\sigma_{z_i}}\right) - 1 \right] \quad i = 1, 2, \dots, n$$

$$\text{so that } b_{l(j)} \leq g_j(x_m) \leq b_{u(j)} \quad m = 1, 2, \dots, M \text{ and } j = 1, 2, \dots, K$$

where  $[x_m]$  is the vector representing “ $M$ ” design attributes,  $g_j(\bullet)$  is the operator of  $j$ ’s constraint of these “ $K$ ” attributes’ lower and upper bounds,  $b_{l(j)}$  and  $b_{u(j)}$  respectively.

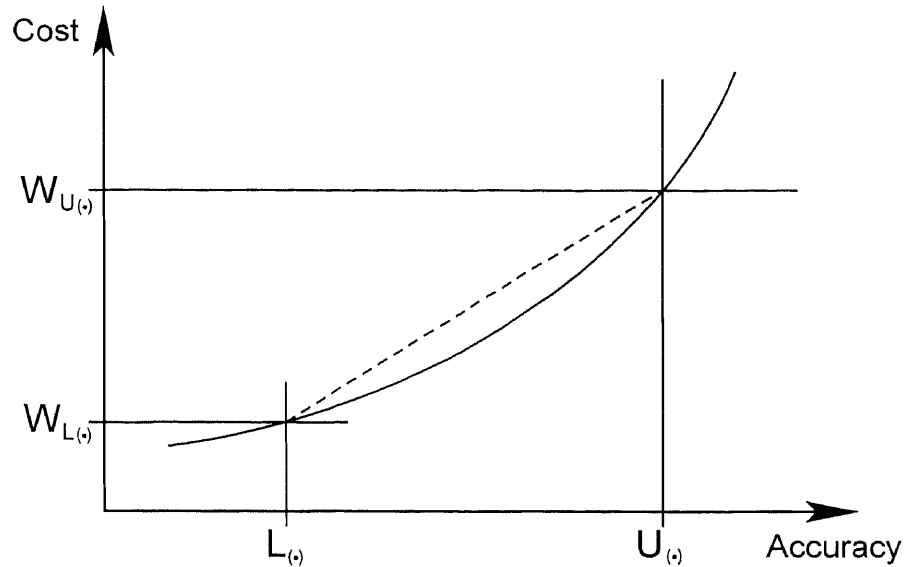
### ***Logic of the Algorithm***

The objective function will assume its maximum value when the numerator reaches its upper bound, or maximum value, at the same time as the denominator assumes the smallest possible value. Consequently, the maximum clearance between the mating assembly parts, and the combination of the most accurate assembly and machining devices, that does not violate the budget constraint, will result in a maximized objective function.

### ***Constraints***

The constraints used here are first, the budget constraint, defining the maximum available budget for purchasing the robot and the machining center equipment. Second, there is a set of geometrical constraints that will ensure the performance feasibility for the specified part and assembly situation. The most important is the clearance between the mating parts, specified for the x and y directions individually. Also, the geometrical limits can be countered into these constraints, as they have an impact on the angular displacement, caused by the robots angular repeatability.

### Linear Approximation of Device Accuracy Versus Cost



$$W_{M-C} = \frac{(W_{U_{M-C}} - W_{L_{M-C}})(\sigma_{M-C} - L_{M-C})}{U_{M-C} - L_{M-C}} + W_{L_{M-C}}$$

$$W_R = \frac{(W_{U_R} - W_{L_R})(\sigma_R - L_R)}{U_R - L_R} + W_{L_R}$$

#### Nomenclature:

- |     |     |                       |
|-----|-----|-----------------------|
| (•) | R   | Robot Device          |
|     | M-C | Machining Center      |
|     | U   | (Upper) More Accurate |
|     | L   | (Lower) Less Accurate |

**Figure 3.3** Linear Relationship

### *Assumptions*

Studies (Ostwald [1989] and Win & Elmaraghy [1988]) have shown that the purchasing cost of robots and machining centers can be approximated to have a linear relationship to their respective repeatability and accuracy. Figure 3.3 shows the function and its corresponding equations for the machining center ( $W_{M-C}$ ) and robot ( $W_R$ ).

### 3.3 Steps of The Algorithm

In the following, we will in more detail describe how to utilize the algorithm, applied to parts with general shapes.

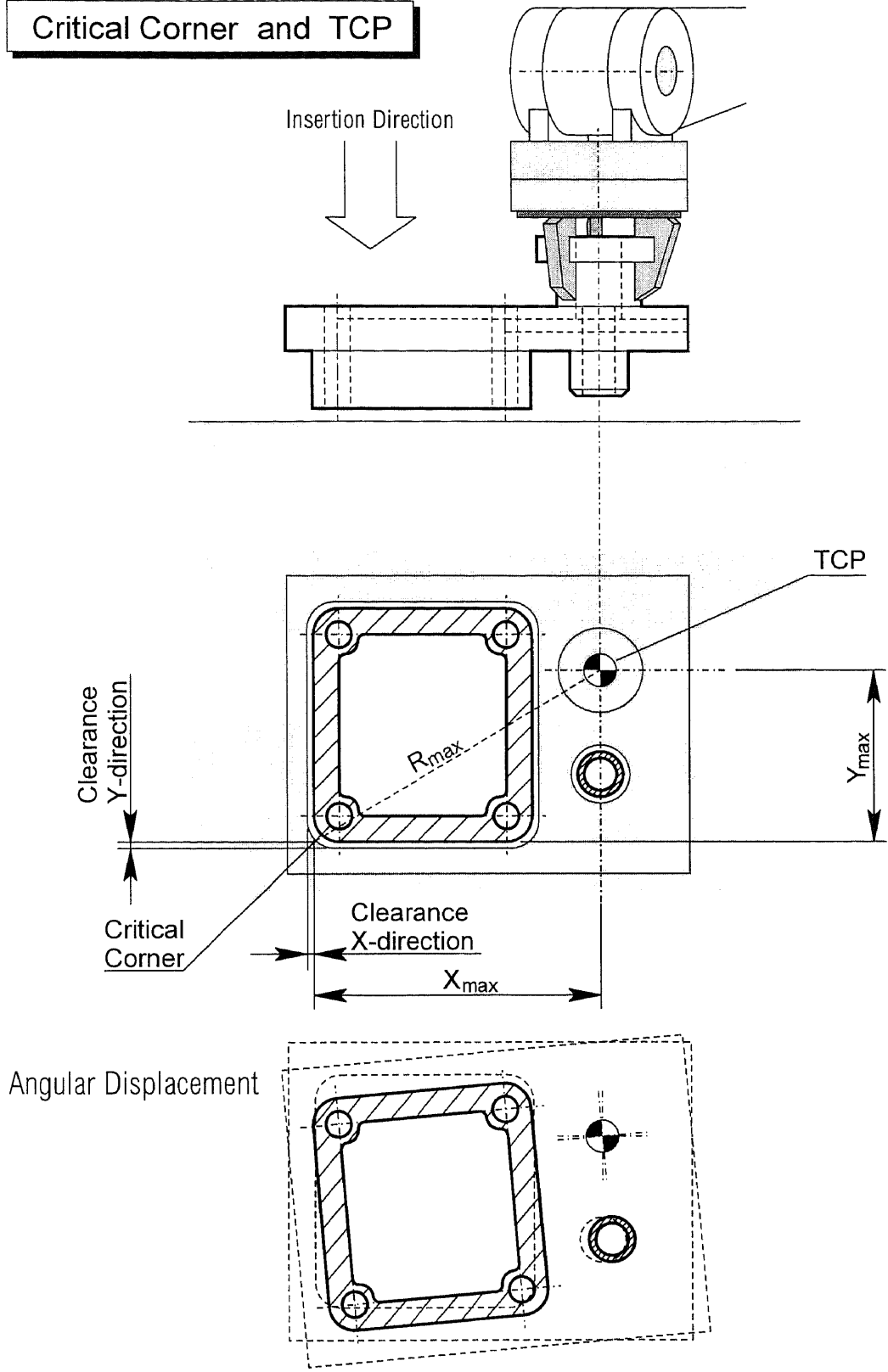
#### *Initialization*

Utilizing the algorithm, we first seek the most critical assembly situation that the equipment will be used for. That is:

**The assembly of parts that in a cross sectional view from above, has the largest dimensions and the tightest clearances, will represent the most critical, constraining situation.**

To start the algorithm, one needs to know the position of the TCP (robot's tool center point) versus the corner causing the largest displacement (see Figure 3.4). If the assembly part has a non-symmetric, general shape of the cross sectional silhouette that contains radius or chamfers, these are extrapolated to the closest, larger perpendicular shape. The corner that is at the longest distance from the TCP will be the critical corner. To clarify our definition for the cross sectional view, how to find the tool center point of the robot when gripping the part, and its relation to the critical corner, see Figure 3.4.

**Critical Corner and TCP**



**Figure 3.4** Initialization



Knowing these aforementioned data, one can calculate the maximum displacement that is caused by the robot in the x and y directions. Also, to initialize  $\sigma_R$ , it should be the maximum of:

$$\sigma_X = \sigma_{R,X} + Y \sin \theta$$

$$\sigma_Y = \sigma_{R,Y} + X \sin \theta$$

where  $X$ , and  $Y$  are the distances from the TCP to the critical corner;  $\sigma_{R,X}$  and  $\sigma_{R,Y}$  are the repeatability in the x- and y- directions; and  $\theta$  is the robots' angular repeatability. One should also compute the following:

$$\begin{aligned} W_t &= \frac{(WU_t - WL_t)(\sigma_t - L_t)}{U_t - L_t} + WL_t & W_R &= \frac{(WU_R - WL_R)(\sigma_R - L_R)}{U_R - L_R} + WL_R \\ C_1 &= \frac{WL_t - WU_t}{U_t - L_t} & C_2 &= \frac{WL_R - WU_R}{U_R - L_R} \\ A &= C_1 L_t + WL_t & B &= C_2 L_R + WL_R \\ W' &= A + B - W_{tot} \end{aligned}$$

where  $WU(\cdot)$  is the cost of the least accurate/least expensive device with  $U(\cdot)$  accuracy, and  $WL(\cdot)$  is the cost of the most accurate/most expensive device with repeatability  $L(\cdot)$ .

### Steps

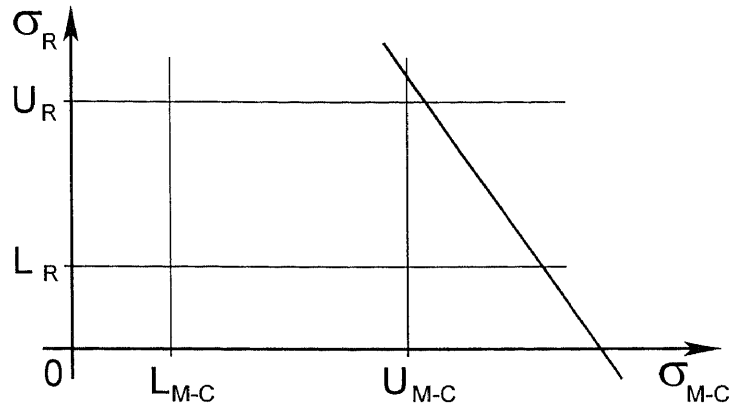
1. If  $C_1 U_{M-C} + C_2 U_R < W' \Rightarrow$  the problem is infeasible

(Figure 3.5.1, Step 1); otherwise go to step 2.

2. If  $C_1 L_{M-C} + C_2 L_R > W' \Rightarrow$  the optimal solution is

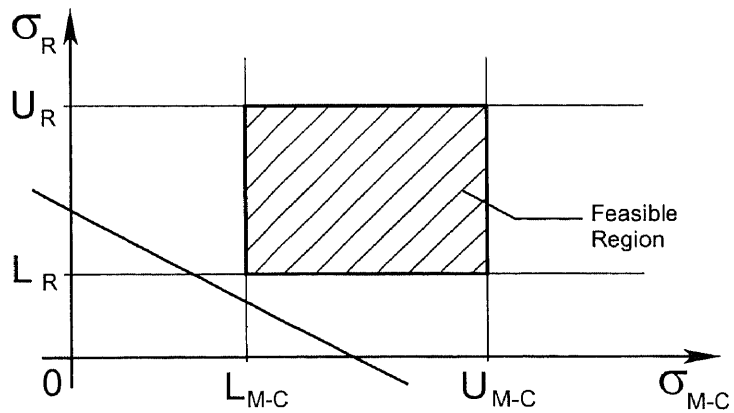
$\sigma_{M-C}^* = L_{M-C}$ ,  $\sigma_R^* = L_R$  (Figure 3.4.1, Step 2); otherwise go to step 3.

**STEP 1.**



$$C_1 U_{M-C} + C_2 U_R < W' \Rightarrow \text{INFEASIBLE}$$

**STEP 2.**



$$C_1 U_{M-C} + C_2 U_R \geq W' \Rightarrow \text{Optimal Solution: } (\sigma_{M-C}, \sigma_R) = (L_{M-C}, L_R)$$

**Figure 3.5.1** Steps of the Algorithm

3. Calculate the values of  $\theta$ ,  $\zeta_1$ ,  $\zeta_2$ ,  $\alpha$ ,  $\beta$ ,  $\eta_1$ , and  $\eta_2$ , where

$$\theta = \frac{C_1}{C_2}$$

$$\eta_1 = \text{Min} \left[ \frac{W' - C_1 L_{M-C}}{C_2}, U_R \right] = \text{Min} [\zeta_1, U_R]$$

$$\alpha = \frac{C_1 \eta_1}{W' - C_2 \eta_1}$$

$$\eta_2 = \text{Max} \left[ \frac{W' - C_1 U_{M-C}}{C_2}, L_R \right] = \text{Max} [\zeta_2, L_R]$$

$$\beta = \frac{C_1 \eta_2}{W' - C_2 \eta_2}$$

If  $\theta \geq \alpha$  go to Case 1, if  $\theta \leq \beta$  go to Case 2; otherwise go to Case 3.

**CASE 1:** If  $\zeta < U_R \Rightarrow$  the optimum solution is  $\sigma_{M-C}^* = L_{M-C}$ ,  $\sigma_R^* = \zeta_1$ ;

otherwise, the optimum solution is  $\sigma_{M-C}^* = \frac{W' - C_2 U_R}{C_1}$ ,  $\sigma_R^* = U_R$

(Figure 3.5.2)

**CASE 2:** If  $\zeta > L_R \Rightarrow$  the optimum solution is  $\sigma_{M-C}^* = U_{M-C}$ ,  $\sigma_R^* = \zeta_2$ ;

otherwise, the optimum solution is  $\sigma_{M-C}^* = \frac{W' - C_2 L_R}{C_1}$ ,  $\sigma_R^* = L_R$

(Figure 3.5.3)

**CASE 3:** Here, when  $\beta < \delta < \alpha$ ,  $\Rightarrow$

$\Rightarrow$  optimum solution is  $\sigma_{M-C}^* = \frac{C_1 W'}{C_1^2 + C_2^2}$ ,  $\sigma_R^* = \frac{C_2 W'}{C_1^2 + C_2^2}$

(Figure 3.5.4)

### STEP 3.

CASE 1:

$\theta \geq \alpha \Rightarrow$  Optimal Solution:  $(\sigma_{M-C}, \sigma_R) = [\eta_1/\alpha, \eta_1]$

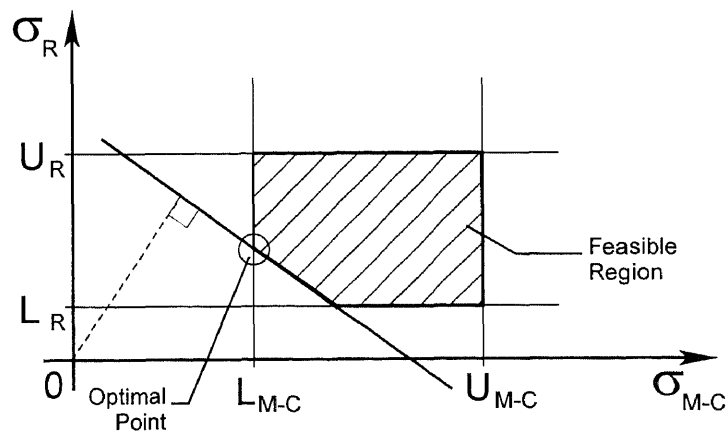
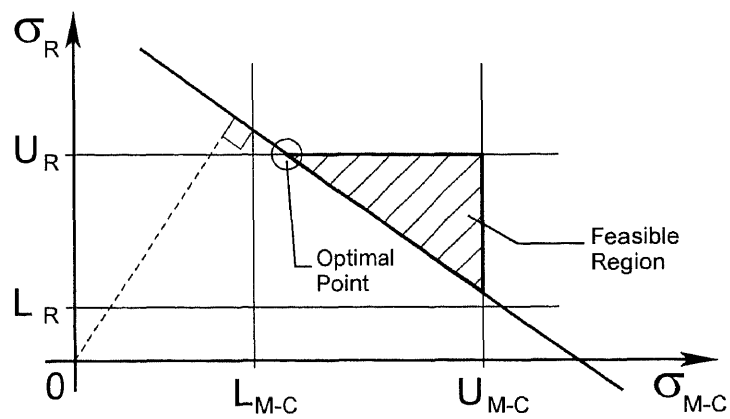


Figure 3.5.2 Steps of the Algorithm

**STEP 3.**

CASE 2:

$\theta \geq \beta \Rightarrow$  Optimal Solution:  $(\sigma_{M-C}, \sigma_R) = [\eta_2/\alpha, \eta_2]$

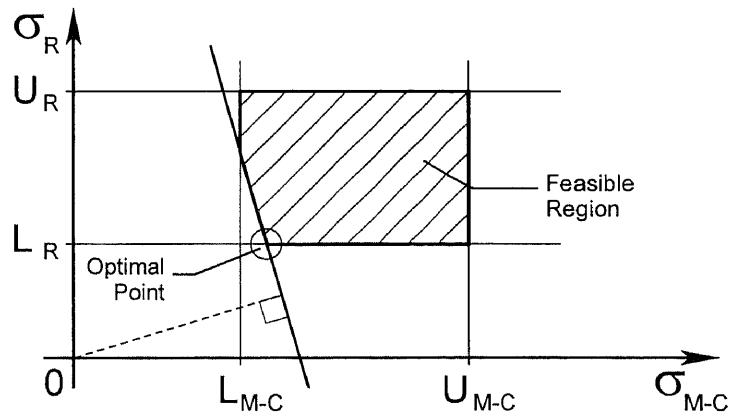
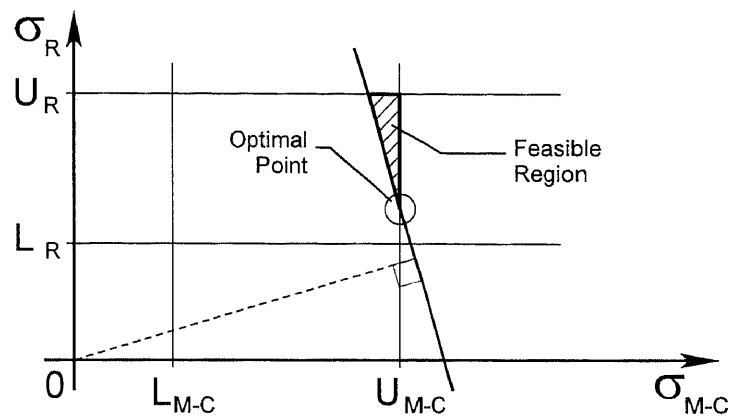


Figure 3.5.3 Steps of the Algorithm

### STEP 3.

CASE 3:

When neither Case 1, nor Case 2 is true, then

$$\text{Optimal Solution: } (\sigma_{M-C}, \sigma_R) = \left[ \frac{C_1' W'}{C_1'^2 + C_2'^2}, \frac{C_2' W'}{C_1'^2 + C_2'^2} \right]$$

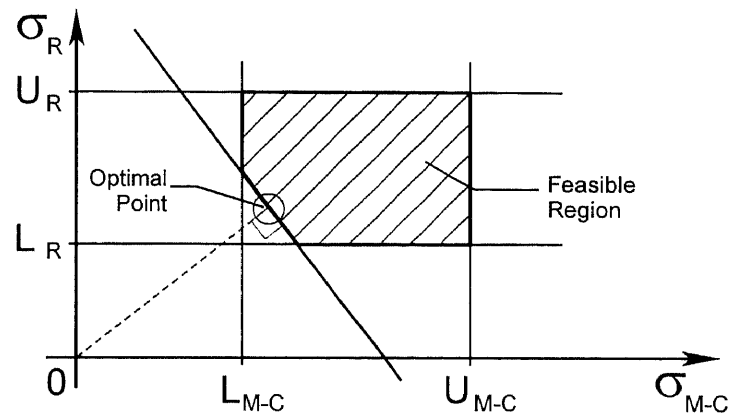


Figure 3.5.4 Steps of the Algorithm

## CHAPTER 4

### DESIGN OF THE EXPERT SYSTEM

As mentioned earlier in the introduction, the objective is to develop a software system that is based on the models introduced in the previous chapter. The models maximize the performance of production equipment. To do so, the next sections state the objectives and requirements more formally.

#### 4.1 Requirements

In order to develop an expert system to aid in the selection process of assembly and machining equipment, the following points have been considered.

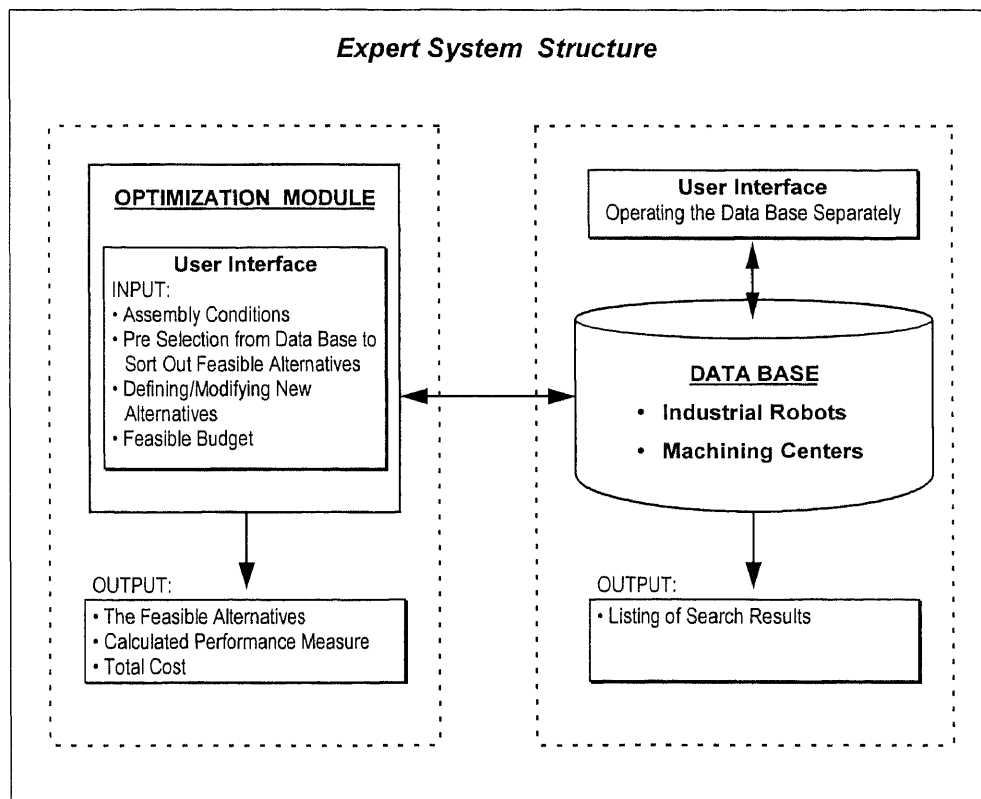
- **The system should give the user the option of selecting only a robot, or selecting a robot and a machining center simultaneously.**
- **A data base that can store available robots and machining centers existing in the market place should be included in the system. The data base should be expandable to include other types of devices.**
- **The system data base should have the capability of being used separately for searching alternatives by defining search criteria.**
- **Easy-to-use and ergonomically designed user interface and manual, that allows users with limited knowledge in the field to operate the system.**
- **The system should also permit the user to define new alternatives strictly for one particular situation, without utilizing the alternatives stored in the data base.**
- **The design should allow future expansion of the system to include functions for selecting feeders, conveyors, and other process equipment.**

From stating these requirements, the second design phase allows us to draw up the structure of the system.

## 4.2 Structure

The system has two components; a data base, that can be used separately, and a module that houses the algorithms and models to optimize the selection of robot and machining center equipment. We will designate this second component as the optimization module.

Figure 4.1 shows the structure of the system.



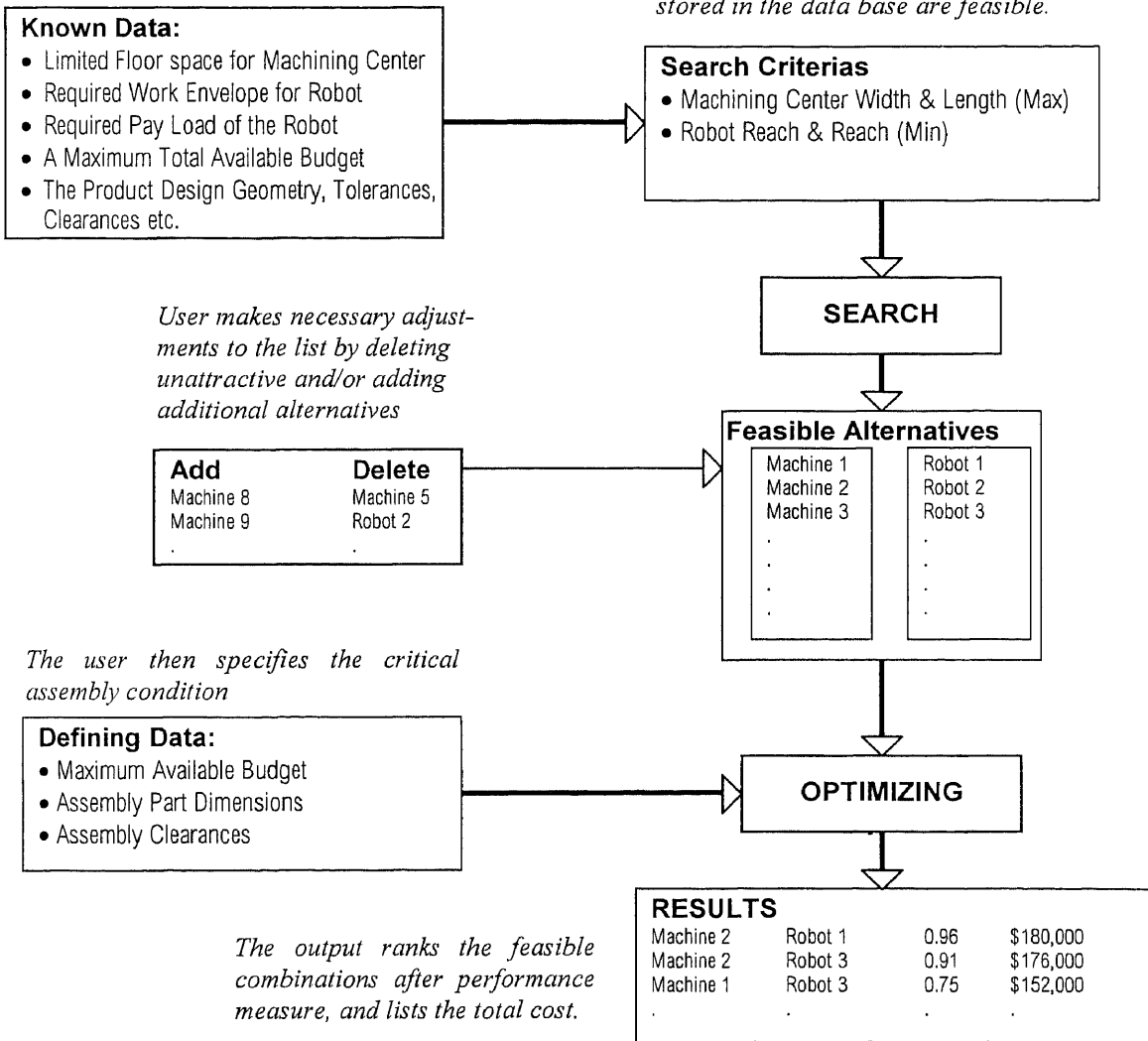
**Figure 4.1** The Expert System Structure



While the algorithms and models used in the optimization module main focus is the geometrical design of the assembly parts, and the repeatability and accuracy of the equipment devices. In order to efficiently sort out unfeasible alternatives with respect to other attributes, such as payload, work envelope, etc., the first cut selection provides ability to utilize a pre-search. The optimizing algorithm then generates the performance measure of the feasible component alternatives, (see Figure 4.2).

*User is about to choose a new assembly robot and a new machining center for a new production cell.*

*In the expert system pre-selection feature, the user defines the known requirements to find what alternatives stored in the data base are feasible.*



**Figure 4.2** Logic of the Expert System

In the example in Figure 4.2, the user has not only the ability to make a pre-selection to certify that the output results are feasible in all desirable aspects, but also the option to pre-screen the feasible alternatives and delete alternatives that for some reason do not apply, and/or add new alternatives that do not exist in the data base.

### **4.3 Design Procedures**

As the initial step, the pertinent attributes of industrial robots and machining centers are individually evaluated. Thereafter, the data base is created as the two robot and machining center sub data bases are designed. The two separate sub-data bases have two separate sets of entries. More details on the design of the data base and the attributes for respective sub data bases are described in Chapter 5.

After the data base is created and evaluated, the optimization module is constructed. Chapter 6 describes the design of the optimization module and the linking to the data base.

### **4.4 RAMCOSS**

During the work designing and building the new expert system, the work name RAMCOSS, which stands for Robot and Machining Center Optimization Selection System is used. Concluding the work presented in this thesis, the concept is presented under the RAMCOSS name. The User's Manual in Appendix C, and the case studies in Chapter 7, are referring to the system under the same name.

## CHAPTER 5

### THE RAMCOSS DATA BASE

The data base is one of the corner stones of the RAMCOSS system. The emphasis on this robot and machining center data base has been to create a pedagogic and easy-to-use design, rather than to search the market in an attempt to capture most of the equipment alternatives available today. To create the data base, Microsoft Access 7.0 have been used. MS Access is one of the more widely distributed data base softwares, as it has been included as a standard component in the MS Office package for MS Windows 95 and in MS Office 97. The trend also hints that MS Access in the future will merge together with FoxPro, one of the other major data base softwares. Supposedly, existing data bases, created in Access can then be automatically upgraded to the new standard.

It should be mentioned that the accuracy and reliability of a data base is a function of the information stored in it. It is therefore important and necessary to continuously upgrade the records of the data base. One should also verify the obtained data after a search before basing any decisions upon the information. This is especially crucial for the cost information, as this factor is known to change over time.

This chapter does not include instructions on how to operate the data base. Information and commands can be found in the User's Manual, Appendix C. Also, in the same User's Manual, an introduction to the industrial robot and machining center terminology is provided.

## 5.1 Structure

The data base has been built as two separate sub data bases that are operated from one central user interface. It has been designed to allow the user to easily access any of the following procedures:

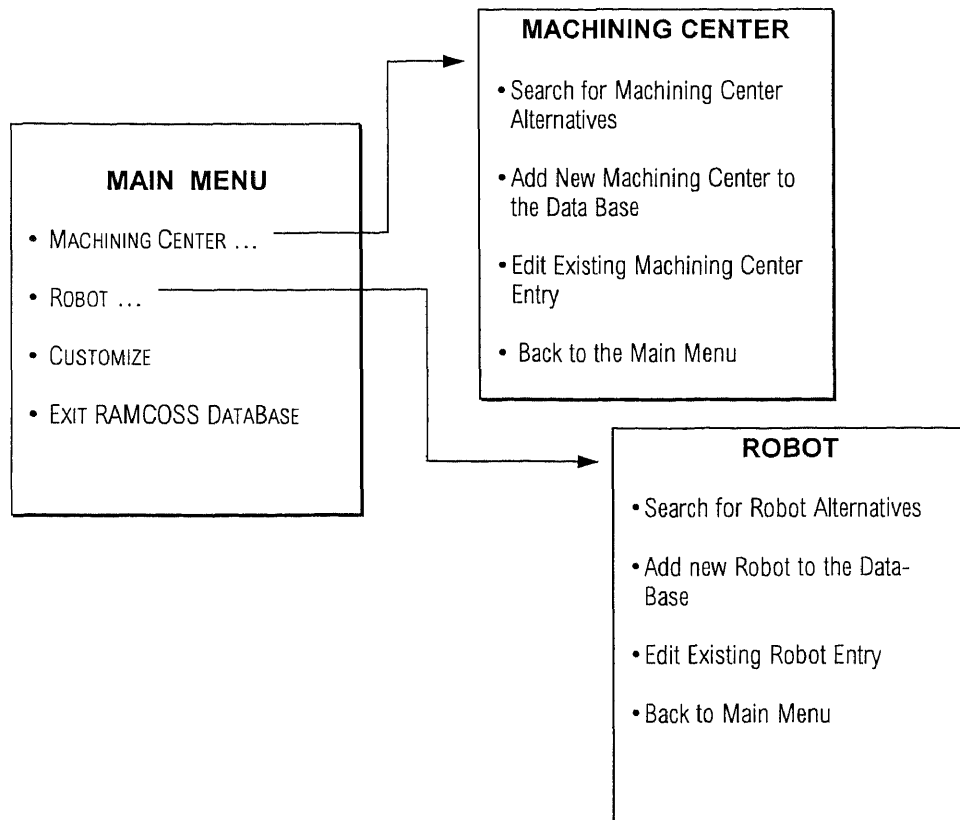
- **Searching for records by defining search criteria**
- **Adding a new record**
- **Edit an existing record**
- **Print out data records**

The data base user interface is designed as a main menu that gives the user the ability to enter any of these options for either the robot, or the machining center data base.

## 5.2 The Main Menu

To simplify the maneuvering of the data base, a main menu has been created that asks the user what feature s/he intends to use. Figure 5.1 shows the menu system that appears when the data base is opened.

From the main menu, the user chooses either the robot or the machining center data base. This will present the user the corresponding sub menu that gives the user the choice of either search the data base, add a new device, or edit an existing one for either the robot or the machining center data base respectively. In the main menu the user also has the possibility to customize the menu. This might come in handy if the user wishes to add new standard queries or report forms that easily can be accessed directly from the menu. The manual in Appendix C gives further information on how to use these features.



**Figure 5.1** Main Menu in the RAMCOSS Data Base

### 5.3 Attributes Relevant to the Data Base

Listed in Tables 5.1 and 5.2 are the data base attributes together with a brief discussion about their entries for the robot and the machining center data bases respectively. Some of them, such as the manufacturer, model name, and model description, are identical and displayed in the same fashion in the two data base's various forms. More extensive information regarding the attributes, such as default values, maximum number of characters in a field, etc., can be found in the RAMCOSS user's manual, displayed in Appendix C.

**Table 5.1** The Robot Data Base Entries

<b>Data Base Attribute</b>	<b>Entry</b>	<b>Unit</b>
ID Number	The number by which the data base is storing the robot	
Last Updated	The date when the record is previously updated or first entered. The date appears or updates automatically	
Manufacturer	Name of manufacturer	
Model Name	The model name/number	
Model Description	Field for distinguish abilities	
Robot Type	The robot configuration	
Degrees of Freedom	The basic robot's number of DoF	
Pay Load	The pay load as specified by the manufacturer	kg
Horizontal Reach	The maximum horizontal reach within the robots work envelope	mm
Vertical Reach	The maximum vertical reach within the robots work envelope	mm
Drive	The type of power of the robot	
Velocity	The robots velocity/speed as specified by the manufacturer	m/s
Repeatability	The robot repeatability as specified by the manufacturer	mm
Power Supply	The required power effect for running the robot	VAC
Program Steps	The maximum number of program steps that can be stored.	
Address	The number of bits used for addressing	bits
Memory Size	The available space for data storage in the system	Mb
Control System	The specific type, brand or model of data storage	
Robot Cost	The purchase cost for the robot in its basic configuration as specified from manufacturer or dealer	U.S. Dollars
Dealer	Address and additional information	

**Table 5.2** The Machining Center Data Base Entries

<b>Data Base Attribute</b>	<b>Entry</b>	<b>Unit</b>
ID Number	The number by which the data base is storing the robot	
Last Updated	The date when the record is previously updated or first entered. The date appears or updates automatically	
Manufacturer	Name of manufacturer	
Model Name	The model name/number	
Model Description	Field for distinguish abilities	
Table Load	The maximum work piece weight	kg
Travel X	The maximum table move in X -direction	mm
Travel Y	The maximum table move in Y -direction	mm
Travel Z	Maximum distance in Z-direction	mm
Accuracy	The smallest resolution	mm
Repeatability	As specified by manufacturer	mm
Feed Rate	The maximum feed rate	ipm
Cutting Rate	The maximum cutting rate	ipm
Spindel Feed	The maximum spindel feed	RPM
Spindel Effetc	The maximum spindel effect	W
Power Supply	Required power supply	kVA
Tool Capacity	The number of tool storage positions	
Machine Weight	The standard unit weight	kg
Length	Machine length (required to full stroke)	mm
Width	Machine width (required to full stroke)	mm
Height	Machine height (required to full stroke)	mm
Machine Cost	Purchase cost for standard configuration as specified by manufacturer or dealer	U.S. Dollars
CNC System	Type, brand or model name	
EIA/ISO	CNC standard (Yes/No)	
Pallet Shuttle	Feature option (Yes/No)	
Dealer	Address and additional information	

## 5.4 The Data Base Form Layout

Two separate form layouts have been created for the robot and the machining center databases respectively. One for the purpose of viewing and editing the existing records and adding new ones, and the second form, that has a somewhat more compressed layout, is designed for searching the data base. We will here only show the view/edit/add form for the robot (Figure 5.2) and machining center (Figure 5.3) data base.

**Microsoft Access - Robot**

File Edit View Insert Format Records Tools Window Help

**Industrial Robot DataBase** **RAMCOSS**

ID#: 1 Last Updated: 1/7/97 Model Description: Arc Welding

Manufacturer: ASEA

Model Name: IRB 1400

Robot Type: Vertical Articulated Drive: Electric Repeatability: 0.1 mm

DoF: 5 Velocity: 5 Power Supply: 240 VAC

Payload: 5 kg

*Work Envelope*

Horizontal Reach: 1280 mm

Vertical Reach: 1440 mm

*Data Storage*

PGM Steps: 0

Address: 0 bits

Memory Size: 0 Mb

Robot Cost: \$87,000.00

Control System: ASEA Dealer: ASEA

Information as supplied from the Manufacturers Catalogue

Record: 1 of 10

Form View NUM

**Figure 5.2** The Standard Robot Data Base Form Layout



Microsoft Access - MachiningCenter

File Edit View Insert Format Records Tools Window Help

**Machining Center DataBase** **RAMCOSS**

ID#:	1	Last Updated:	1/7/97	Model Description	FULL SLANT BED TURNING CENTERS
Manufacturer:	DOOSAN	Model Name:	DOOTURN 3		
Table Load:	0 kg	Feed Rate:	630 ipm	Tool Capacity:	12
Travel X:	579 mm	Cutting Rate:	0 ipm	Machine Weight:	4354 kg
Travel Y:	0 mm	Spindel Speed:	4000 RPM	Length:	2616 mm
Travel Z:	240 mm	Spindel Effect:	14914 W	Width:	1803 mm
Accuracy:	0 mm	Power Supply:	0 KVA	Height:	1905 mm
Repeatability:	0 mm			Machine Cost:	\$89,900.00
CNC System:	FANUC OTC	Dealer:	MCS Industry Supply Company 800 645-7270		
EIA/ISO:	<input checked="" type="checkbox"/>	Pallet Shuttle:	<input type="checkbox"/>		
Information as supplied from the Manufacturers Catalogue					

Record: 1 of 35

Form View

NUM

**Figure 5.3** The Standard Machining Center Data Base Form Layout

### 5.5 Instructions on Operating the RAMCOSS Data Base

The second section in the RAMCOSS User's manual in Appendix C describes in detail how to operate the data base. Also, the case studies in Chapter 7, give some guidance of some of the possibilities of the data base.

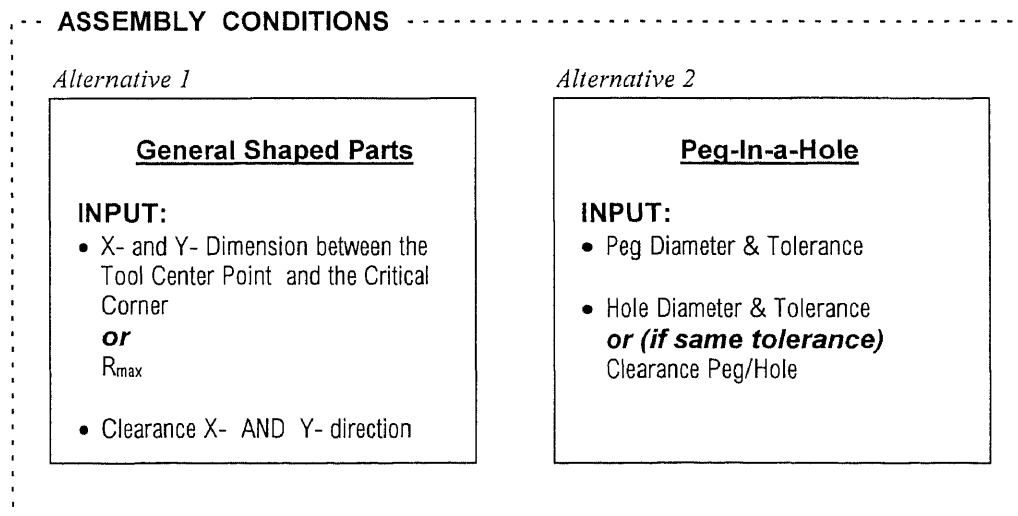
## CHAPTER 6

### THE OPTIMIZATION MODULE

The optimization module of RAMCOSS is created as an independent running software, created in MS Visual Basic 4.0. One of the reasons that MS Visual Basic is used to program the module, is its close relation to MS Access that made the linking of the optimization module and the data base convenient. The succeeding sections reviews the details of this module.

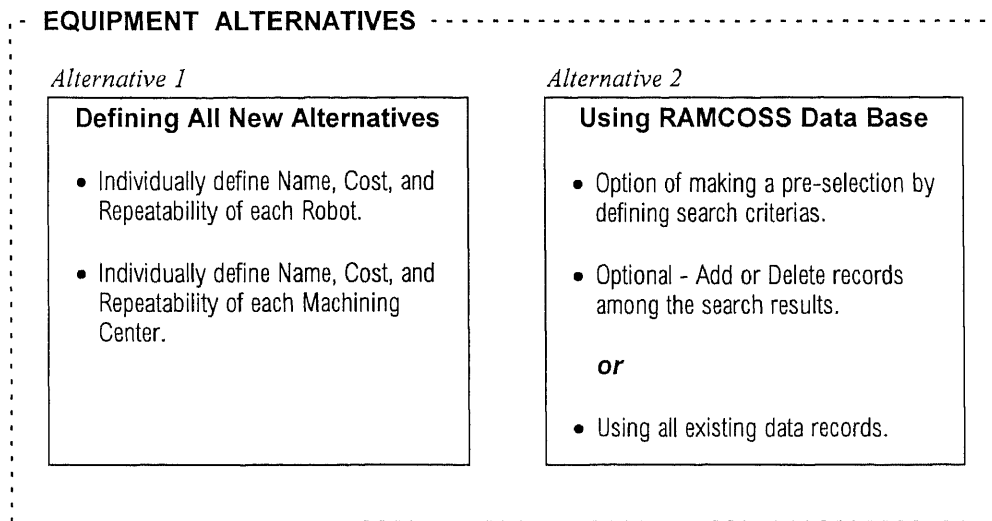
#### 6.1 Structure

The optimization module consists of two sub modules. Depending on the geometrical shape of the parts one of the modules should be applicable. The parts can either be of general shape, or of circular shape (peg-in-a-hole). Figure 6.1 shows the two options and the possibilities.



**Figure 6.1** The Assembly Conditions

There are also two different avenues of how to obtain the set of competing robot and machining center alternatives. The user can either define all the alternatives manually, or access the records in the data base. These can also be pre-selected by define the search criterias in a certain form. Before starting the optimizing algorithm, all the alternatives can be pre-screened, and the user can make final adjustments by adding, or deleting unnecessary records manually (see Figure 6.2).



**Figure 6.2** The Equipment Alternatives

## 6.2 Design of the Optimization Module

Like the RAMCOSS data base, the optimization module is built around a main menu screen. The menu has the following options that can be accessed at any time;

1. **Enter the general conditions for the assembly parts**
  - 1) **General Shaped parts**
  - 2) **Peg-In-a-Hole Case, only for robot selection.**
2. **Define Alternatives**
3. **Save**
4. **Exit RAMCOSS**

Define the equipment alternatives has a sub menu that can access all the features described earlier (Figure 6.2)

The save alternatives gives the opportunity to save a certain assembly condition, a set of feasible equipment alternatives, and the optimization results.

### 6.3 The Output Interface

Once the assembly conditions has been defined and the set of device alternatives has been approved, the optimization is started with a command button in the appropriate screen (see user's manual in Appendix C, and the examples in Chapter 7) the result screen displays the feasible alternatives. Figure 6.3 shows the design of the screen.

<b>RESULTS</b>					
Robot Alternative	Cost	Machining Center Alternative	Cost	Performance Measure	Total Cost
<b>Robot 2</b>	<b>78,000</b>	<b>Machine 1</b>	<b>34,000</b>	<b>0.93</b>	<b>112,000</b>
<b>Robot 5</b>	<b>62,000</b>	<b>Machine 3</b>	<b>78,900</b>	<b>0.86</b>	<b>140,900</b>
<b>Robot 9</b>	<b>52,800</b>	<b>Machine 2</b>	<b>46,000</b>	<b>0.72</b>	<b>98,800</b>
..	..	..	..	..	..
..	..	..	..	..	..
..	..	..	..	..	..

**Figure 6.3** The Output Screen

The feasible combinations (that does not exceed the total available budget) are ranked after decreasing performance measure. The robot and machining center model name, cost and total cost are listed.

## 6.4 The Optimization Module Logic

The logic of the RAMCOSS system, operated from the optimization module interface, is shown in Figure 6.3. Instructions on how to operate RAMCOSS from the module can be found in Appendix C.

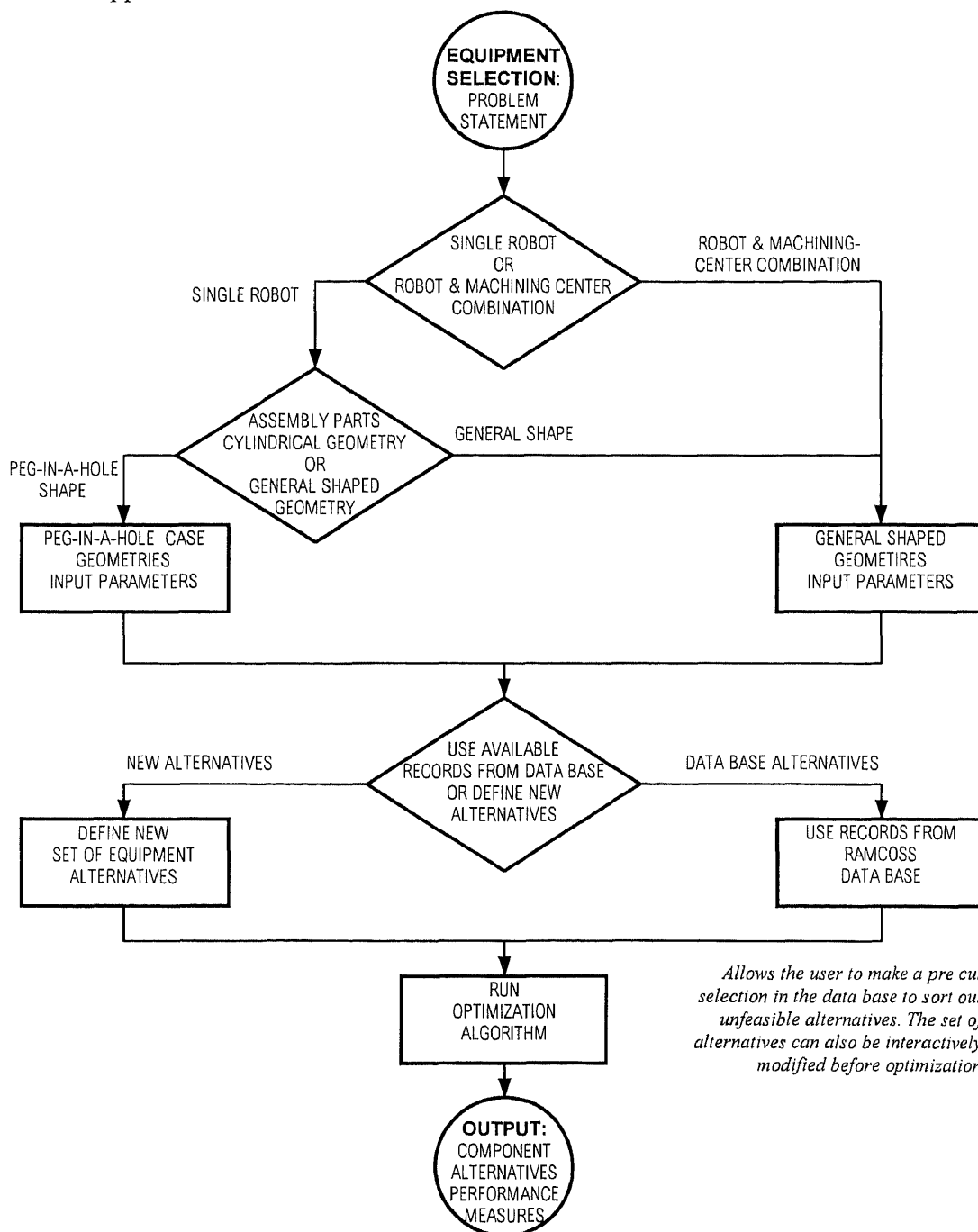


Figure 6.4 The Logic Utilizing RAMCOSS

## CHAPTER 7

### CASE STUDIES

The RAMCOSS system is here utilized in three different case studies, where we show some of the various approaches how RAMCOSS can be applied. The different steps are explained and can be followed by additional information on how to operate RAMCOSS in the User's Manual in Appendix C, and details on the products' design in Appendix D.

In the first case, the RAMCOSS optimization module is used to select an assembly robot for an existing product with out sourced part manufacturing. The robot data base is never used here as the company wishes to stay with their previous robot supplier. A set of feasible robot models from this supplier is manually entered into the optimization module.

The second example shows how to first utilize the RAMCOSS data base interface to obtain a set of feasible turning centers needed to produce a high volume product with tight tolerances. The turning center alternatives from the data base pre-search are then entered into the optimization module, while the robot alternatives for serving the machine are obtained directly from the data base.

In the last case study, equipment for a manufacturing cell of a product with high performance material properties and relatively tight tolerances is selected. The part is processed in a machining center which is served by a robot, which also assembles the machined part onto the corresponding parts. Both the machining center and the robot are here directly obtained from the RAMCOSS optimization module.

## 7.1 Case Study No. 1

In this first case study, we will use the RAMCOSS system to assist in selecting an assembly robot for an electrical pulse switch. As the switch is made essentially out of injection molded plastic parts, we will here use the module for selecting only the robot.

We first describe the design of the switch in detail. A paragraph also describes how the design has been modified in order to optimize the design for assembly. Thereafter, the assembly process is described together with the geometrical requirements. The most critical assembly step that will be used as input in the optimization module is identified. Robot alternatives are explored and defined, together with the assembly conditions in the RAMCOSS optimization module. Finally, we present the results.

### 7.1.1 Design of Assembly Parts

The electric pulse switch, shown in Figure 7.1 and Drawings No. A-10 101 and A-10 201 in Appendix D, is a fairly simple design that requires a one direction assembly, where all the parts are inserted into the housing. The conceptual design consists of the *housing*, that also serves as the case for all the components, which will also be the front panel facing the user once installed. The switch is assembled into the housing part with a snap fit function. The *control button* is the first part to be inserted into the housing. For the spring function that allows the control button to deflect, and to also returns the button to its rest position, a elastic *milyr dome* has been selected. On the center of the bottom surface, a metallic connector surface is applied, that serves as the connecting link when the switch is activated. Finally, the *base part* which is made as one cylinder where the two connectors are molded in position. When the switch is installed, the wiring is first

attached to the two connectors on the backside of the switch, which after the whole component is put into position, and is secured by the fasteners that go through the front panel.

### *Design Adjustments*

As can be seen in Figure 7.1, the final design has been somewhat modified from its original design to accommodate an efficient and straight forward assembly process. In the first design, the push button and the base part had a quadratic cross section, see also Drawings No. A-10 101 and A-10 102 in Appendix D. Without changing either the function or the reliability of the initial design, a few modifications will drastically improve the overall design efficiency, and allow a faster and less complex assembly.

Among the main advantages of the final design is the reduced number of parts. The connector pins are molded into the base part, and do not require a separate subassembly. Also, the connecting surface on the milyr dome, that earlier was an individual metal washer, has been replaced by a metal coating on the bottom center surface of the dome. Furthermore, all the assembly parts require orientation in only one direction, as the parts have a circular cross section. The final design proposal is shown in Drawings No. A-10 201 and A-10 202 in Appendix D.



### Case Study No. 1 - Design Proposals

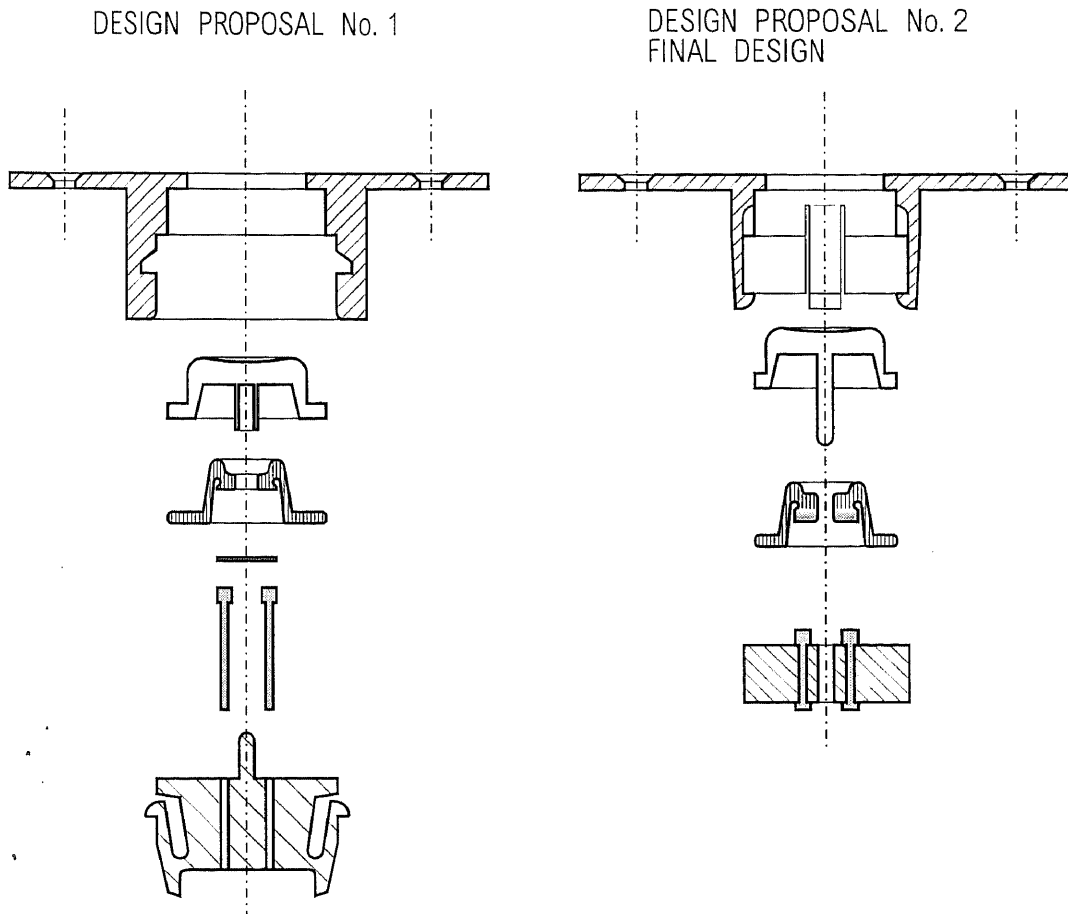


Figure 7.1 Design Proposals

### 7.1.2 Assembly Conditions

A robot has to be selected to assemble the above described electrical pulse switch. The following conditions, related to the assembly process, are known.

#### *Robot Gripper Tool*

A gripper has been developed which has the ability to grasp the control button by its center orientation pin, the milyr dome by a magnet that attaches to the connector surface, and the base part by the two connector pins.

#### *Assembly Process*

The assembly process looks as follows:

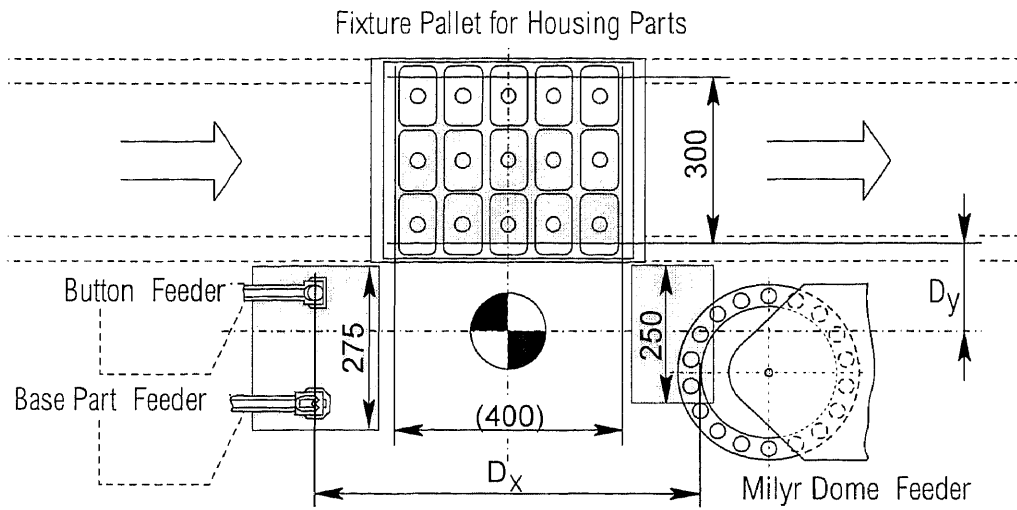
1. The milyr dome is picked up by the robot from its feeder,
2. It is mounted onto the orientation pin of the control button,
3. The robot picks up the button and the dome from the button part feeder,
4. The two parts are inserted into the housing part,
5. The robot picks up the base part,
6. The assembly is completed by the robot inserting the base part into its snap fit.

#### *The Assembly Pallet*

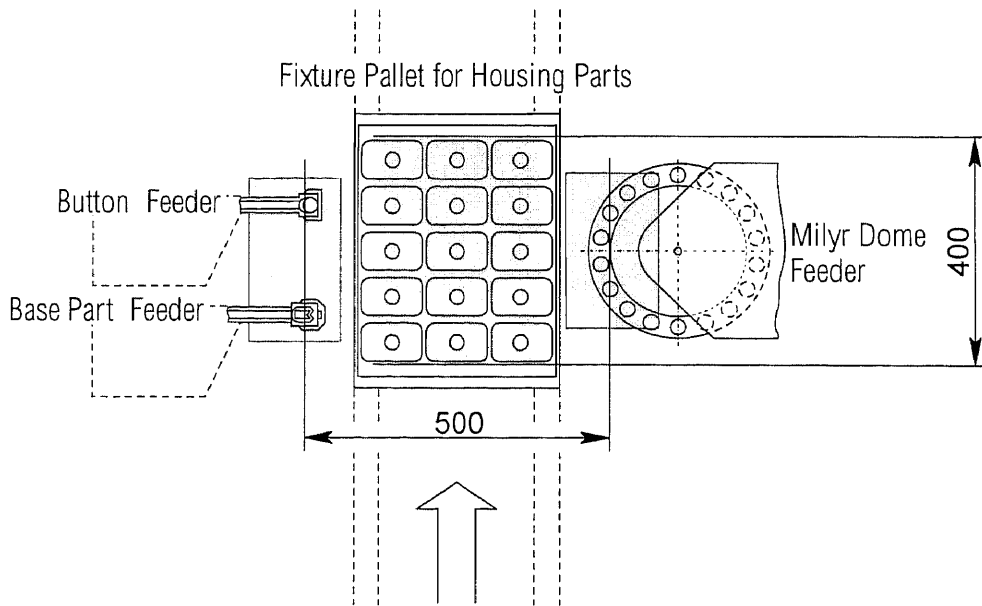
An already existing pallet will be used for the assembly. This pallet accommodates 15 switches. The housing parts are manually placed in these positions, and there after positioned on a conveyor that goes through the robot assembly cell. The requirement here is that the robot can reach all the assembly positions on the pallet at the same time as the feeders for the remaining parts. Figure 7.2 shows the required work envelope for two

**Case Study No. 1 - Required Work Envelope**

Robot Centered Cell;  
Cylindrical, Articulated, and Polar Configurations



Cartesian Robot Configuration Cell



**Figure 7.2** Required Work Envelope

different robot configuration categories. As the pallet is moving through the assembly cell on a conveyor (direction indicated by an arrow in Figure 7.2), the considerable dimension is the width of the pallet.

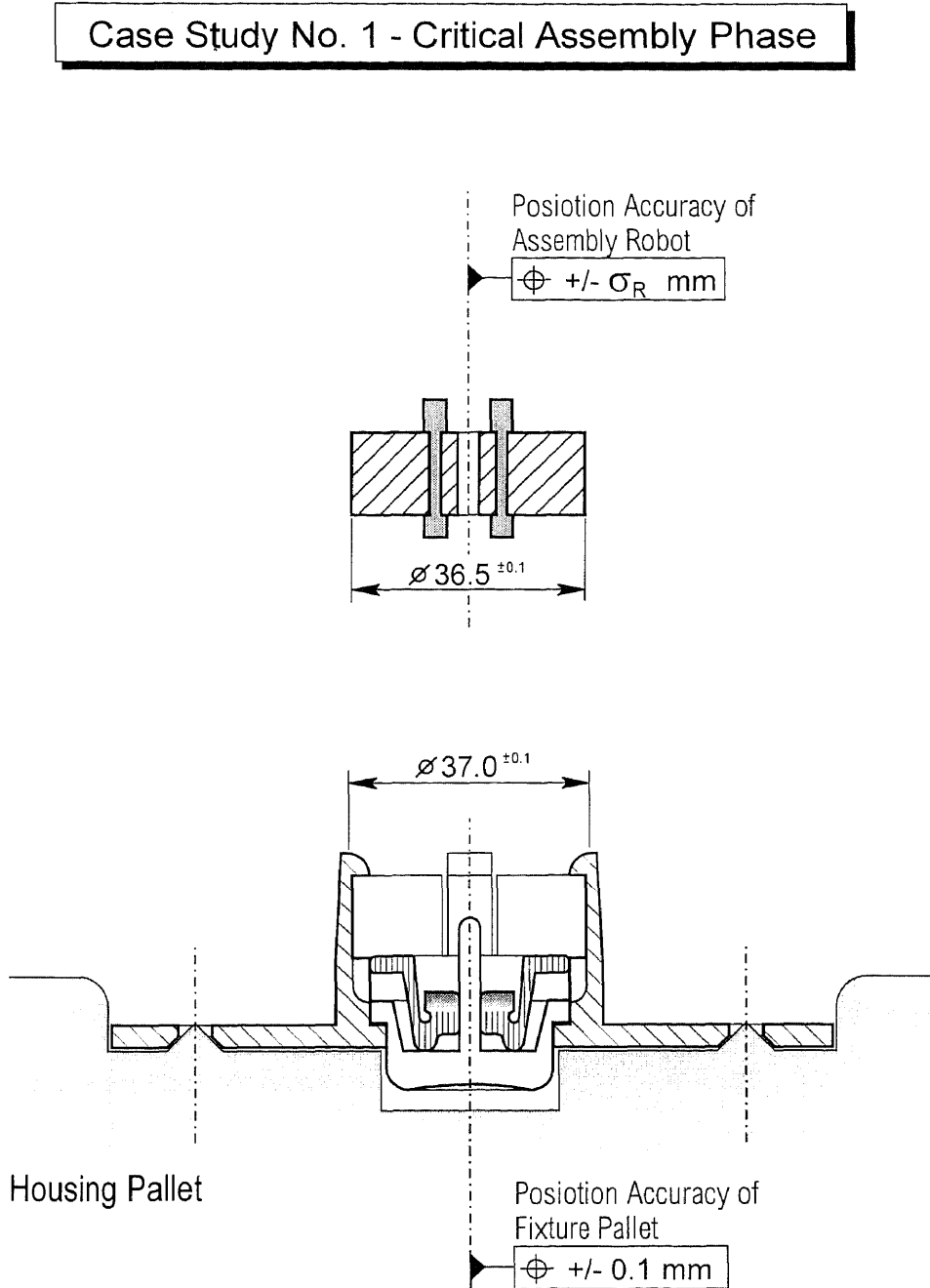
### **7.1.3 Identifying the Critical Assembly Process**

Looking at the assembly drawing of the final design (Drawing No. A-10 201 in Appendix D), one can identify that the final assembly step; inserting the base part into the housing, is the most critical step. Since the base part is secured by a snap fit function, the tolerances here are the tightest. More over, the base part can not be adjusted into position by the chamfers or radius on the housing part, as these will deflect due to their flexible snap fit function.

The optimization module will ask the user to specify the diameter and corresponding tolerances of the peg, in this case the base part, and the hole, which is represented by the housing. Figure 7.3 shows these required data.

### **7.1.4 Searching for Robot Alternatives**

The company that plans to start manufacture the light switch, has earlier bought all their industrial assembly robots from the same supplier. As the company has nothing but good experience and feel comfortable with the current service and support contract, the same robot supplier is preferred again. Furthermore, the already developed robot gripper tool has been designed with the same robot standard in mind.



**Figure 7.3** Critical Assembly Phase

From the robot supplier's product information on the world wide web, a number of models that fits the requirements regarding work envelope and tool connecting standard are identified. The feasible robot alternatives are listed in Table 7.1.1.

**Table 7.1.1 Feasible Robot Alternatives**

Robot Type	Model Name	Work Envelope	Repeatability	Cost
Cartesian	XM3064	600 x 400 mm XY	± 0.015 mm	\$ 30,000
	XM3106	1000 x 600 mm XY	± 0.015 mm	\$ 36,000
SCARA	TT8450-BN	450 mm Horizontal	± 0.02 mm	\$ 32,000
	TT8550-BN	550 mm Horizontal	± 0.02 mm	\$ 33,000
	TT8700-BL	700 mm Horizontal	± 0.025 mm	\$ 35,000
	TT8800-BL	800 mm Horizontal	± 0.025 mm	\$ 36,000
Cylindrical	RT3300	600 x 400 mm XY	± 0.015 mm	\$ 38,000

Information gathered at the Seiko Instruments USA Inc. WWW site; <http://www.seikorobots.com/products>  
All costs represent the basic robot in standard configuration. Driver, tool, and platform not included.

### 7.1.5 Utilizing RAMCOSS

When the RAMCOSS optimization module is started, the main menu first appears. There after, the following steps are followed;

1. The "Peg-In-a-Hole" option is selected.
2. In the general assembly conditions, the following data is entered

**Peg Diameter: 36.5 mm**  
**Peg Tolerance: 0.5 mm**  
**Hole Diameter: 37.0 mm**  
**Hole Tolerance: 0.1 mm**

3. Once all of the above are entered, the "Equipment Alternatives" option is selected.

4. In the Equipment Alternatives screen, “Add New Robot” is selected, where after the data in Table 7.1.1 is entered, one at the time.
5. After all the alternatives are entered, the “Optimize” control is selected.
6. The result screen appears.

### 7.1.6 Result

The result is given in the form of a list where the model name, the repeatability, the performance measure and cost is given as in Table 7.1.2.

**Table 7.1.2 Results**

<b>Model Name</b>	<b>Repeatability</b>	<b>Cost</b>	<b>Performance Measure</b>
XM3064	± 0.015 mm	\$ 30,000	0.97
XM3106	± 0.015 mm	\$ 36,000	0.97
TT8450-BN	± 0.02 mm	\$ 32,000	0.968
TT8550-BN	± 0.02 mm	\$ 33,000	0.968
TT8700-BL	± 0.025 mm	\$ 35,000	0.96
TT8800-BL	± 0.025 mm	\$ 36,000	0.96
RT3300	± 0.015 mm	\$ 38,000	0.97

The difference in performance is relatively small. Among the robot alternatives considered, the RAMCOSS system informs that the difference in repeatability has a negligent influence on the performance for the assembly of the electric switch. The final decision is to select the Cartesian XM3064 robot, that has a lower cost, but still ranks on top under the specified assembly conditions.

## 7.2 Case Study No. 2

In this second example, a new production cell is developed for a high volume product with tight tolerances. The crucial component here is the machining equipment, while the robot is mainly concerned with loading and unloading the machine. We will use RAMCOSS to assist in the selection of a sophisticated CNC turning center that can manage all the required machining operations on the product, which is a shaft for a tractor transmission.

### 7.2.1 Design of the Assembly Part

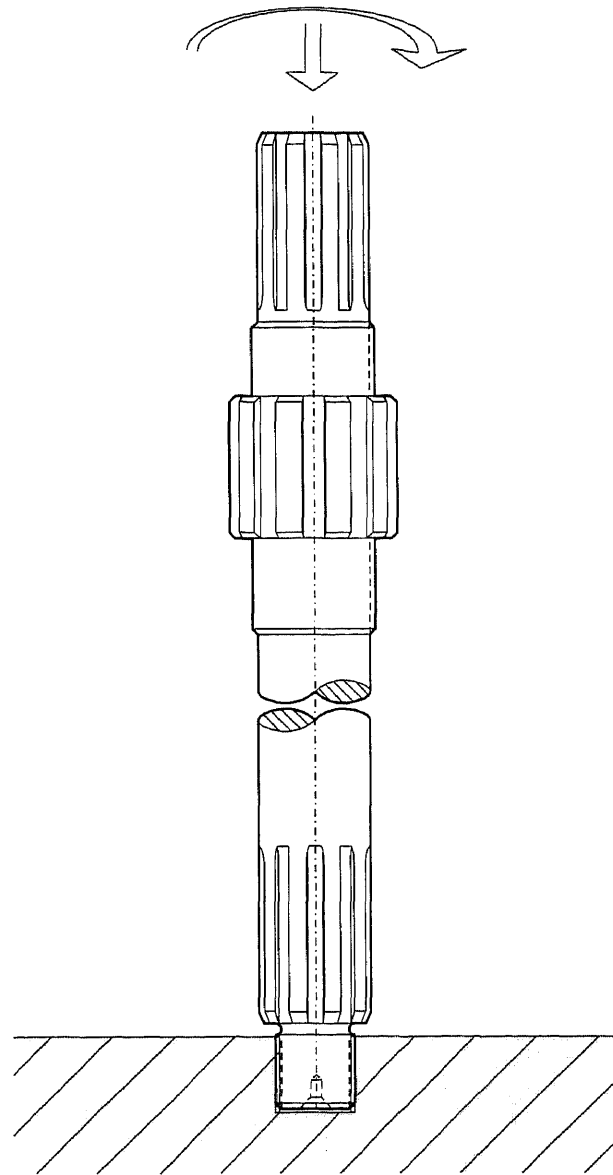
The component shown in Figure 7.4 has an established design that has been modified only few times in the past. The shaft has three sections with splines that requires high performance machining processing. With today's advanced CNC machining centers the whole shaft can be processed in one machine, a four, or five axes turning center, in no more than two setups. Once the shaft has been machined, it goes through a heating treatment process to obtain the required hardness. The shaft drawing is also shown in Drawing No. B-20 001, Appendix D.

### 7.2.2 Robot Requirements

The tasks for the robot are as follows;

1. **Pick up a new raw material work piece and load in into the turning center,**
2. **Switch the setup position of the shaft,**
3. **Unload the processed part from the machine,**
4. **Insert the shaft into the fixture pallet for the heat treatment procedure.**



**Case Study No. 2 - Position for Heat Treatment****Figure 7.4** Transmission Shaft in Fixture

Once the turning center has processed the first steps in setup position 1, the robot switches the shaft into position 2. After the shaft is completely processed in the machine, it is unloaded and put into the pallet for the heat treatment. The shaft mounted in the fixture pallet is shown in Figure 7.4. As the robot repeatability most likely will be more than sufficient, this requirement may not have any influence on the choice of robot. However, the all of the following requirements in Table 7.2.1 must be fulfilled, and will be entered in the RAMCOSS prescreening selection.

**Table 7.2.1** The Robot Requirements

<b>Data Base Attribute</b>	<b>Required Value</b>	<b>Unit</b>
Manufacturer	-	
Model Name	-	
Model Description	-	
Robot Type	articulated	
Degrees of Freedom	-	
Pay Load	>=2	kg
Horizontal Reach	>=500	mm
Vertical Reach	>=300	mm
Drive	electric	
Velocity	-	m/s
Repeatability	<=0.5	mm
Power Supply	-	VAC
Program Steps	-	
Address	-	bits
Memory Size	-	Mb
Control System	-	
Robot Cost	-	Dollars
Dealer	-	

The constraining requirements includes the configuration of the robot, the minimum payload, the minimum work envelope, and the minimum required repeatability for the robot to load, unload, and insert the shaft into the heat treatment fixture pallet. It is also preferable with an electrical robot drive. Worth noting is that no budget limit has been specified. One of the reasons for this is that some of the robot records in the RAMCOSS data base configuration that are used is based on several sources of information that is older than 2 years. Considering that especially the cost tends to fluctuate more than any other attribute, this requirement has not been specified here. See further section 7.2.4 (Utilizing RAMCOSS) for details.

### **7.2.3 Machining Center Requirements**

From the detail drawing of the shaft (Drawing No. B-20 001 in Appendix D), one can see that the tightest tolerance requirements on the part is  $\pm 0.01$  mm. Also the following requirements, shown in Table 7.2.2, are specified in the pre-screening selection of RAMCOSS. There is no option of specifying turning centers with more than 4 axes. Because of this, the feasible turning centers will be obtained by first search the RAMCOSS machining center data base for alternatives that fits the requirements. These feasible alternatives will thereafter be entered manually in the optimization module.

**Table 7.2.2** The Machining Center Requirements.

<b>Data Base Attribute</b>	<b>Required Value</b>	<b>Unit</b>
Manufacturer	-	
Model Name	-	
Model Description	turning center	
Table Load	-	kg
Travel X	>=400	mm
Travel Y	-	mm
Travel Z	-	mm
Accuracy	<=0.01	mm
Repeatability	<=0.01	mm
Feed Rate	-	ipm
Cutting Rate	-	ipm
Spindel Feed	-	RPM
Spindel Effetc	-	W
Power Supply	-	kVA
Tool Capacity	-	
Machine Weight	-	kg
Length	-	mm
Width	-	mm
Height	-	mm
Machine Cost	-	Dollars
CNC System	-	
EIA/ISO	-	
Pallet Shuttle	-	
Dealer	-	

#### 7.2.4 Utilizing RAMCOSS

Without having a made a definite decision on the maximum available total budget for the two equipment alternatives, the total figure of \$ 300,000 will be used. This figure is

actually a lot higher than anticipated, but gives a wider spectrum of feasible robot and machining center combinations in the optimization results.

First, the available turning center alternatives in the RAMCOSS machining center data base are identified as follows;

1. The RAMCOSS data base is opened.
2. From the main menu, the “Machining Center” option is selected.
3. In the machining center menu, the “Search data base” is activated.
4. The earlier definer requirements are specified in the respective entry box, using the query instructions (see further the User’s Manual in Appendix C).
5. The search results are printed out.

The search results with the RAMCOSS data base configuration used in this case study are shown in Table 7.2.3.

**Table 7.2.3** Feasible Turning Center Alternatives

<b>Model Name</b>	<b>Repeatability</b>	<b>Cost</b>
DOOTURN 4x	± 0.005 mm	\$ 144,785
DOOTURN 4	± 0.003 mm	\$ 98,950
HL-4	± 0.015 mm	\$ 79,900

Since the Peg-In-a-Hole option do not include the machining center optimization, the RAMCOSS optimization module is operated as follows;

1. The “General Shape” option is first selected.

2. The following general conditions are entered here in their respective entry boxes;

<b>R<sub>max</sub>:</b>	<b>14.0</b>	<b>mm</b>
<b>Clearance, X:</b>	<b>0.5</b>	<b>mm</b>
<b>Clearance, Y:</b>	<b>0.5</b>	<b>mm</b>

The R<sub>max</sub> value, 14.0 mm is equivalent to the threaded shaft radius. It is assumed that the shaft is hold by the robot gripper with the tool center point aligned along the shaft center line.

3. After these data are entered, the “Equipment Alternatives” is selected.
4. In the Competing Alternatives Screen, the “Alternatives” button is selected.
5. In the Competing Alternatives Screen, the Option 1 is selected by choosing the “RAMCOSS Machining Center DataBase”.
6. Here, all entries are cleared, where after “Select Machining Center Alternatives” is selected.
7. In the following Robot Pre-Selection screen, the requirements in Table 7.2.2 are entered where after the “Select Robot Alternatives” is selected.
8. Back in the Competing Alternatives Screen, the Maximum Total Budget is specified by entering **300,000** in the type in box.
9. All the machining center alternatives from the data base are cleared from the alternatives box by clicking “Clear All”.
10. From the data base search printout, the feasible turning center alternatives are added manually with the “Add New Machine” option. (The for the required information on feasible turning centers are shown in Table 7.2.3)
11. The “Optimize” button activates the optimizing algorithm, and the result screen shows the combinations.

### 7.2.5 Results

With the specified requirements and assembly conditions the performance of fesible robot and turning center combinations are listed as in Table 7.2.4.

**Table 7.2.4 Results**

	<b>Robot Alternative</b>	<b>Cost</b>	<b>Machine Alternative</b>	<b>Cost</b>	<b>Performance Measure</b>	<b>Total Cost</b>
1	IRB 1400	\$ 51,000*	DOOTURN 4x	\$ 144,785	0.9996	\$ 140,000
2	IRB 1400	\$ 51,000*	DOOTURN 4	\$ 98,950	0.9996	\$149,950
3	IRB 1400	\$ 51,000*	HL-4	\$ 79,900	0.9996	\$130,000
4	IRB 2400	\$ 68,000*	DOOTURN 4x	\$ 144,785	0.9996	\$ 212,785
5	IRB 2400	\$ 68,000*	DOOTURN 4	\$ 98,950	0.9996	\$ 166,950
6	IRB 2400	\$ 68,000*	HL-4	\$ 79,900	0.9996	\$ 147,900
7	IRB 4400	\$ 72,000*	DOOTURN 4x	\$ 144,785	0.9737	\$ 216,785
8	IRB 4400	\$ 72,000*	DOOTURN 4	\$ 98,950	0.9737	\$ 170,950
9	IRB 4400	\$ 72,000*	HL-4	\$ 79,900	0.9737	\$ 151,900
10	IRB 5000	\$ 82,000*	DOOTURN 4x	\$ 144,785	0.9234	\$ 226,785

\*Robot cost is an estimation, not verified with dealer.

As can be seen in Table 7.2.3 above, there are in the top ten combinations 9 feasible combinations that results in a higher performance measure than 95%. After verifying the cost, and performance data for the listed equipment alternatives, the final decision is made. Combination No. 3; the ABB IRB 1400 robot and the HAAS HL-4 turning center, which has a total cost of \$ 130,000\* is selected.

### 7.3 Case Study No.3

In this example, RAMCOSS is used to optimize the selection of a machining center and a robot. The equipment will be used in a completely automated production cell where a metal flange will be produced. The robot will be serving the machining center and also assemble the processed part onto its corresponding product part. The mating parts will be routed through the cell on an automatic conveyor.

The following paragraph, that describes the part design, also includes information on how and why the design was modified from its original proposal. The requirements are then identified, before RAMCOSS is utilized and the results presented.

#### 7.3.1 Design of the Assembly Part

The flange is a component that goes into a number of different product configurations which are produced for the chemical industry. The flange is designed to work as a standard connection for flexible, high pressure, hoses and has a certain bayonet pattern that corresponds with the hose connections. The products are often used in chemical, corrosive environments, which is the reason why the flange is made of stainless steel.

#### *Design Adjustments*

##### DESIGN PROPOSAL No. 1

Initially, the plan was to use an existing design of the flange that had previously been produced by individual milling and turning operations in smaller volumes. This design is showed in Figure 7.5 and in Drawings No. A-30 101 and A-30 102 in Appendix D. However, when using a relatively expensive material, this solution appears quite



unattractive as such a large part of the raw material is machined to scrap metal. Furthermore, the hole in the corresponding mating part requires a complex drilling operation with two diameters and a milling process for the O-ring. Another problem with this design is the assembly process where the O-ring has to be placed in its step, inside the hole, before the flange is assembled.

#### DESIGN PROPOSAL No. 2

Due to these, previously described concerns, a new design is proposed. The length of the flange is reduced with more than 50%. The corresponding hole is also simplified, as this design only requires one milling operation for the O-ring (Drawings No. A-30 201 and A-30 202 in Appendix D).

In order to test this design, a part is manufactured to carry out an experiment. One of the problems here is that nothing is holding the flange in position when the screws are inserted. Furthermore, the fact that when a force is applied on the flange, at the same time as the pressure is tested, this part has problems with leaking is not acceptable.

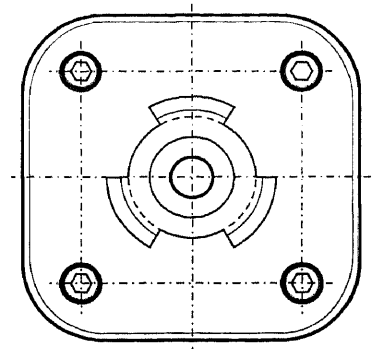
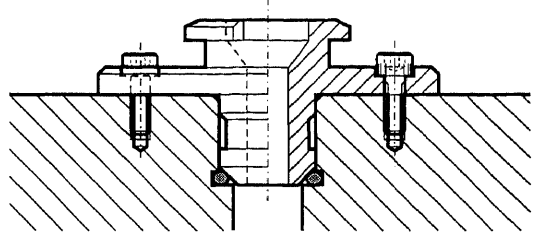
#### DESIGN PROPOSAL No. 3 - FINAL

In order to fix the position of the flange during the assembly procedure where the robot inserts the screws, the final design has the cylindrical feature from proposal No. 1. Also, to reduce the amount of scrap metal in the machining process, the raw material is here a round cylinder (diameter 75 mm), instead of the square cross section bar (72 x 72 mm). The final design is shown in Drawings No. A-30 301 and A-30 302 in Appendix D.

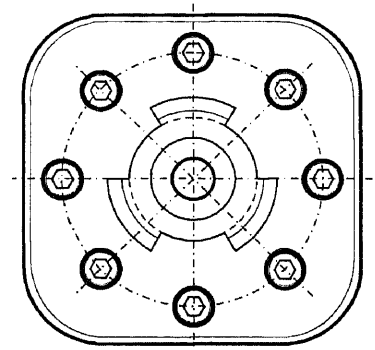
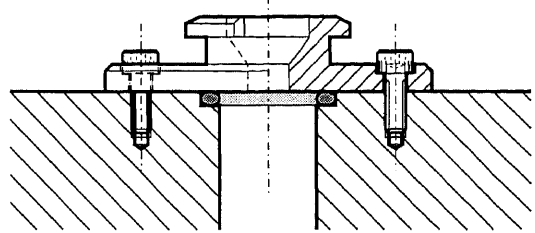
RAMCOSS - Master's Thesis - Industrial Engineering - NJIT

### Case Study No. 3 - Design Proposals

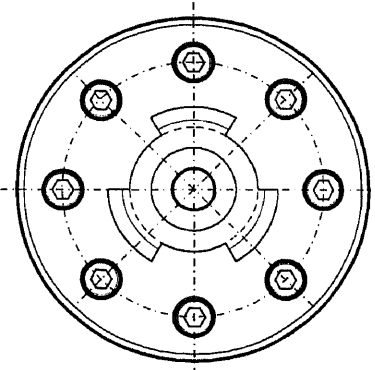
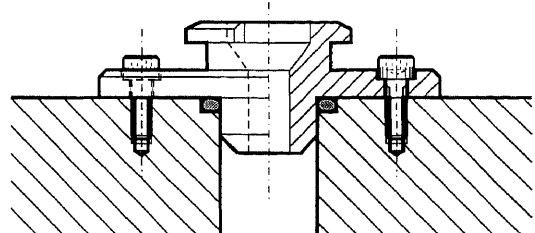
DESIGN PROPOSAL No. 1



DESIGN PROPOSAL No. 2



FINAL DESIGN



Lars Johan Resare 1997

Figure 7.5 Design Proposals

### 7.3.2 Machining Center Requirements

The machining of the flange is processed in two setup positions. Though the flange has a circular cross section, we will choose a vertical machining center since these have the capacity to process the part and also a lower cost than equivalent mill turn centers. The

**Table 7.3.1** The Machining Center Requirements.

Data Base Attribute	Required Value	Unit
Manufacturer	-	
Model Name	-	
Model Description	vertical machining center	
Table Load	-	kg
Travel X	-	mm
Travel Y	-	mm
Travel Z	-	mm
Accuracy	0.01	mm
Repeatability	0.01	mm
Feed Rate	-	ipm
Cutting Rate	-	ipm
Spindel Feed	-	RPM
Spindel Effetc	-	W
Power Supply	-	kVA
Tool Capacity	>=12	
Machine Weight	-	kg
Length	-	mm
Width	-	mm
Height	<=3,000	mm
Machine Cost	-	Dollars
CNC System	-	
EIA/ISO	-	
Pallet Shuttle	-	
Dealer	-	

machining center requirements are shown in Table 7.3.1. Included are a minimum tool capacity. The various processes requires 12 different tools that are used in the two set up positions shown in Figure 7.6. It should be mentioned that there is no requirements on the outer diameter ( $\varnothing 75$  mm) tolerance or surface finish. The raw material beam has the required diameter, and there will be no machining on this surface.

### 7.3.3 Robot Requirements

The robot requirements here includes a repeatability of at most  $\pm 0.1$  mm. Similar to the previous case study, the minimum required work envelope for an articulated robot configuration is specified as a horizontal reach of at least 500 mm, and a vertical reach of 300 mm or more. Table 7.3.2 shows all the robot requirements.

### 7.3.4 Utilizing RAMCOSS

In this case study, all the information required from the RAMCOSS robot and machining center data base can be accessed from the optimization module. The following steps describes the procedures:

1. In the RAMCOSS optimization module, “General Shape” option is first selected.
2. The following general conditions are entered here in their respective entry boxes:

<b>R<sub>max</sub>:</b>	<b>28.0</b>	<b>mm</b>
<b>Clearance, X:</b>	<b>0.05</b>	<b>mm</b>
<b>Clearance, Y:</b>	<b>0.05</b>	<b>mm</b>

The  $R_{\max}$  value here indicates the distance from the center line of the flange, aligned with the tool center point, to the critical corner. The latter will be the holes for the screws, that are distributed around a circular centerline with diameter 56 mm.

### Case Study No. 3 - Machining Processes

SETUP POSITION 1

SETUP POSITION 2

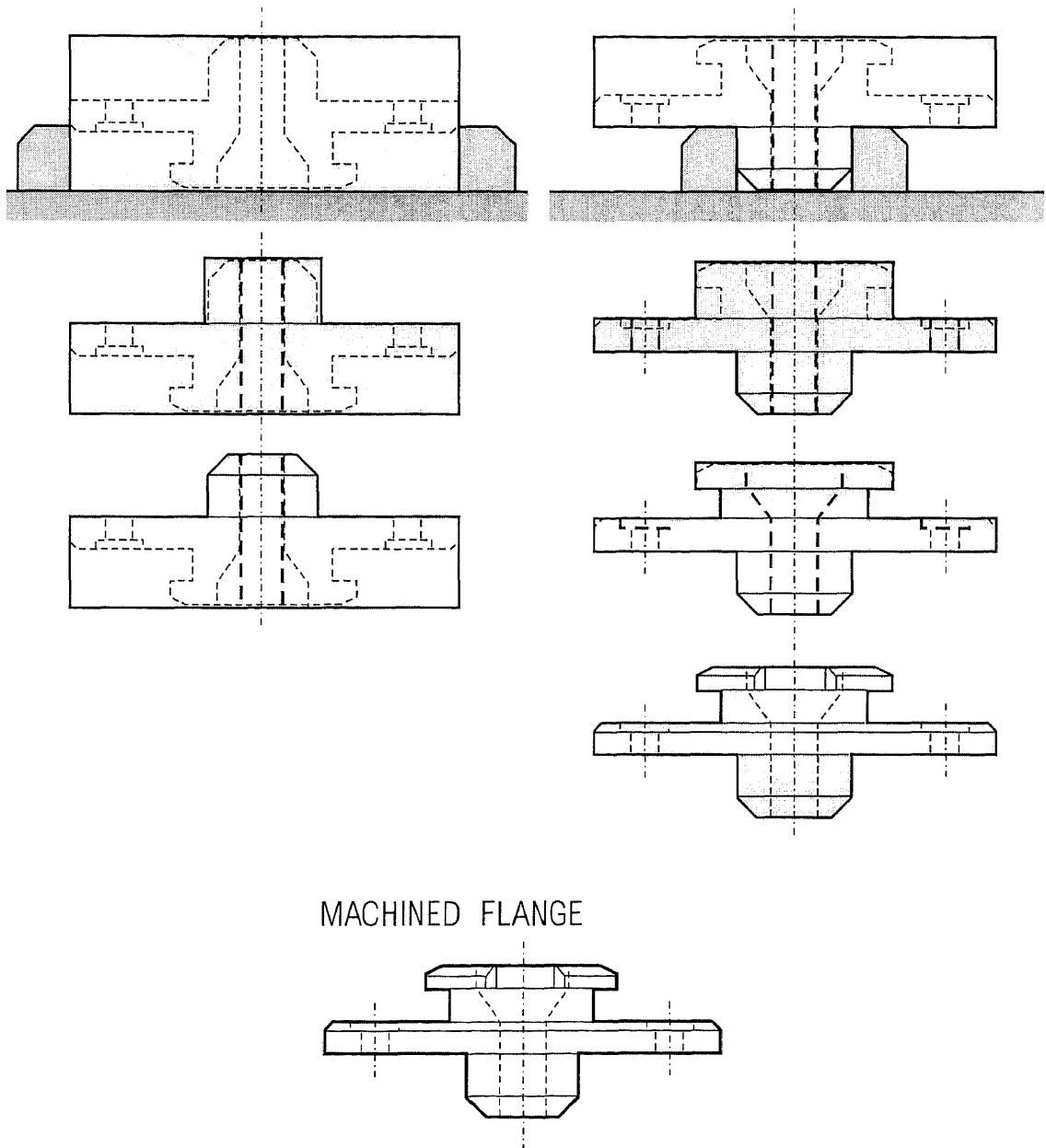


Figure 7.6 Machining Processes

**Table 7.3.2** The Robot Requirements

Data Base Attribute	Required Value	Unit
Manufacturer	-	
Model Name	-	
Model Description	-	
Robot Type	articulated	
Degrees of Freedom	-	
Pay Load	$\geq 2$	kg
Horizontal Reach	$\geq 500$	mm
Vertical Reach	$\geq 300$	mm
Drive	-	
Velocity	-	m/s
Repeatability	$\leq 0.05$	mm
Power Supply	-	VAC
Program Steps	-	
Address	-	bits
Memory Size	-	Mb
Control System	-	
Robot Cost	-	Dollars
Dealer	-	

3. After these data are entered, the "Equipment Alternatives" is selected.
4. In the Competing Alternatives Screen, the "Alternatives" button is selected.
5. Option 1 is selected by choosing the "RAMCOSS Machining Center DataBase".
6. Here, the earlier specified requirements (see Table 7.3.1) are entered, where after "Select Machining Center Alternatives" is selected.
7. In the following Robot Pre-Selection screen, the requirements in Table 7.3.2 is entered where after the "Select Robot Alternatives" is selected.

8. Back in the Competing Alternatives Screen, the Maximum Total Budget is specified by entering **500,000** in the type in box.
9. The “Optimize” button activates the optimizing algorithm, and the result screen shows the combinations.

### **7.3.5 Results**

Depending on the amount of data records stored in the data base, the processing time for the optimization may vary. Running the optimization with the initial data base records gives a fairly large number a feasible combinations that have a performance measure ranging from 64% up to 97%. No combination with a performance measure less than 90% is considered in this particular case, and the final decision is to choose the Cincinatti robot and the DOMAC vertical machining center that has a combined cost of \$ 230,000.

## CHAPTER 8

### SUMMARY AND FUTURE RESEARCH

Looking at earlier work in the field, numerous existing models, algorithms and methodologies have been developed that concern the selection and optimization approaches for robots and other process equipment individually. The contribution of this work is in further extending and customizing these algorithms to develop an optimization procedure in an expert system for the equipment selection in robotic manufacturing cells. The expert system simultaneously selects appropriate robot and machining center equipment for specified design parameters of the product parts. The following sections summarize the features of the expert system and propose future directions in the fields.

#### 8.1 Summary

The decision support system that has been developed and presented here is designed to aid in the selection and decision process when simultaneously choosing industrial robot and machining center equipment. The system can be used in several ways and also provide useful input in situations, such as;

- **A new production cell with machining center and industrial robots is planned and designed.**
- **A factory is planning for a new process layout and is assigning machining and robot equipment to new work cells for certain products.**
- **Cases where the user wishes to investigate how a set of robots will perform under given assembly conditions.**



- **A part's design in terms of geometrical dimensions, tolerances, and clearances need to be optimized for a certain set of robot and machining center equipment with known accuracy and repeatability.**
- **The user wants to learn about current available robot and machining equipment to get an estimated idea of requirements for planning a new production or assembly cell.**

The Robot and Machining Center Optimization Selection System, RAMCOSS, consists of two parts. A data base with two separate robot and machining center sub-databases, and second, an optimization module, that generates the performance measure for the different robots, or various robot and machining center combinations considered. The optimizing algorithm works with information given on the manufacturing and assembly parts' geometry, dimensions, tolerances and clearances between assembly parts.

A set of initialization procedures has been developed to identify the critical robot handling operation, especially in multiple product manufacturing cells, in order to specify these data variables in the optimization module. These procedures include guidelines for extrapolating non-perpendicular shaped assembly objects, compensating for chamfers and radius, etc..

The two parts are linked so that information stored in the data base can be accessed from the optimization module. The data base is designed so that it also can be used separately to obtain feasible robot and machining center candidates by specifying search criteria.

In a series of three case studies the new expert system has been used in different situations to choose equipment for assembly, machine serving, and machine processing purposes. Appended to this thesis is also the user's manual that has been developed to

instruct presumptive users on how to operate RAMCOSS. In the manual, the procedures for how to utilize the data base and the optimization module are given with illustrative instructions.

## **8.2 Future Directions**

The current data base records only include some 50 available industrial robot and CNC machining center models today. In order to include a more extensive and updated selection, a routine for how to obtain and maintain this information should be developed.

The model and algorithm used in the RAMCOSS system can also be extended to incorporate selection of other equipment. An interesting and advantageous future direction could be to further develop the concept to also include other equipment data bases, and a more developed optimization module interface.

## APPENDIX A

### PROOF OF NORMAL DISTRIBUTION FUNCTION EQUATION

For the normal distribution,

$$\begin{aligned}\bar{S}(R, T) &= \int_R^{\infty} (x - R)g(x, l + T)dx \\ &= \sigma\phi(z) - [(R - \mu)(1 - \Phi(z))]\end{aligned}$$

**Proof:**

$$\bar{S}(R, T) = \int_R^{\infty} (x - R) \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2}\left(\frac{x - \mu}{\sigma}\right)^2\right] dx$$

Let  $z = \frac{(x - \mu)}{\sigma}$ , and  $x = \mu + z\sigma$ ; then

$$\begin{aligned}\bar{S}(R, T) &= \int_{(R-\mu)/\sigma}^{\infty} (\mu + \sigma z - R)\phi(z) dz \\ &= \sigma \int_{(R-\mu)/\sigma}^{\infty} z\phi(z) dz + (\mu - R) \int_{(R-\mu)/\sigma}^{\infty} \phi(z) dz\end{aligned}$$

Evaluating the first term yields

$$\int_{(R-\mu)/\sigma}^{\infty} z\phi(z) dz = \frac{1}{\sqrt{2\pi}} \int_{(R-\mu)/\sigma}^{\infty} ze^{-z^2/2} dz$$

Let  $v = \frac{z^2}{2}$ ,  $dv = z dz$ ; then

$$\begin{aligned}\frac{1}{\sqrt{2\pi}} \int_{(R-\mu)/\sigma}^{\infty} ze^{-z^2/2} dz &= \frac{1}{\sqrt{2\pi}} \int_{(1/2)[(R-\mu)/\sigma]^2}^{\infty} e^{-v} dv \\ &= -\frac{1}{\sqrt{2\pi}} e^{-v} \Big|_{(1/2)[(R-\mu)/\sigma]^2}^{\infty} \\ &= \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{R - \mu}{\sigma}\right)^2\right] = \phi(z)\end{aligned}$$

Evaluating the second term yields

$$(\mu - R) \int_{(R-\mu)/\sigma}^{\infty} \phi(z) dz = (\mu - R)[1 - \Phi(z)]$$

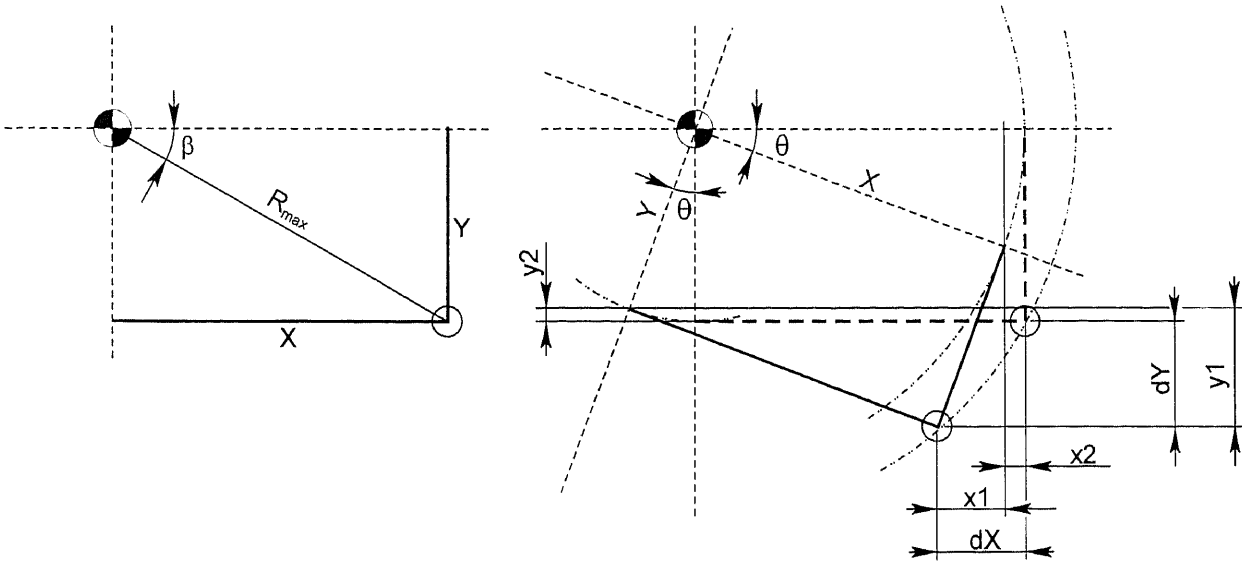
Therefore,

$$\bar{S}(R, T) = \sigma\phi(z) - (R - \mu)[1 - \Phi(z)]$$

Source: *Analysis and Control of Production Systems* by Elsayed and Boucher, 1994.

## APPENDIX B

### ANGULAR DISPLACEMENT THEORY



The exact displacement  $dX$ , and  $dY$ ;

$$\left. \begin{aligned}
 & X - \text{direction:} \\
 & dX = x_1 + x_2 \\
 & x_1 = Y \sin \theta \\
 & \cos \theta = \frac{X - x_2}{X} \Rightarrow x_2 = X(1 - \cos \theta)
 \end{aligned} \right\} \Rightarrow dX = Y \sin \theta + X(1 - \cos \theta)$$

$$\left. \begin{aligned}
 & Y - \text{direction:} \\
 & dY = y_1 - y_2 \\
 & y_1 = X \sin \theta \\
 & \cos \theta = \frac{Y - y_2}{Y} \Rightarrow y_2 = Y(1 - \cos \theta)
 \end{aligned} \right\} \Rightarrow dY = X \sin \theta - Y(1 - \cos \theta)$$

Proposed Approximation No. 1;

$$dX = R_{\max} (\theta \cos \beta)$$

$$dY = R_{\max} (\theta \sin \beta)$$

which requires that  $R_{\max}$  and  $\beta$  is known.

Proposed Approximation No. 2, (final);

$$dX = Y \sin \theta$$

$$dY = X \sin \theta$$

## Comparing Accuracy of Angular Displacement Approximation Methods

Angular	$\theta$	0.100	Old	0.100
Repeatability			$\beta$	0.245
Geometry	X	20.000		20.000
	Y	80.000		80.000
			R(max)	82.462
<b>X-direction</b>	x1	0.13962627		0.13962634
	x2	0.00003046		
EXACT VALUE	X	0.13965673		0.13965673
Error		0.00003046		0.00003039
<b>Y-direction</b>	y1	0.03490657		0.03490658
	y2	0.00012185		
EXACT VALUE	Y	-0.03478472		-0.03478472
Error		-0.06969129		-0.06969130

Angular	$\theta$	0.500		0.500
Repeatability			$\beta$	0.245
Geometry	X	20.000		20.000
	Y	80.000		80.000
			R(max)	82.462
<b>X-direction</b>	x1	0.69812283		0.69813169
	x2	0.00076154		
EXACT VALUE	X	0.69888437		0.69888437
Error		0.00076154		0.00075268
<b>Y-direction</b>	y1	0.17453071		0.17453292
	y2	0.00304615		
EXACT VALUE	Y	-0.17148455		-0.17148455
Error		-0.34601526		-0.34601748

APPENDIX C

THE RAMCOSS USER'S MANUAL

**RAMCOSS**

Robot And Machining Center Optimization Selection System

**User's Manual**

Version 1.0

Lars Johan Resare  
1997

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## About this User's Manual

In the introduction, a brief overview describes the basic structure of the system and some of its possibilities. Also, areas of application where RAMCOSS can be of great advantage are included.

Chapter two gives thorough instructions on how to operate the data base by presenting the menu options and the various commands for how to search the data base by defining own search criteria. It also informs on how to edit existing data records and how to add new robot and machining center devices into the data base.

In the third chapter, the optimization module of the RAMCOSS software is presented. The initialization procedures and assembly condition input alternatives are illustrated and explained.

To give additional information about the various aspects of assembly and machining processes, chapter 4 provides an introduction including definitions and crucial criteria of industrial robots and machining centers.



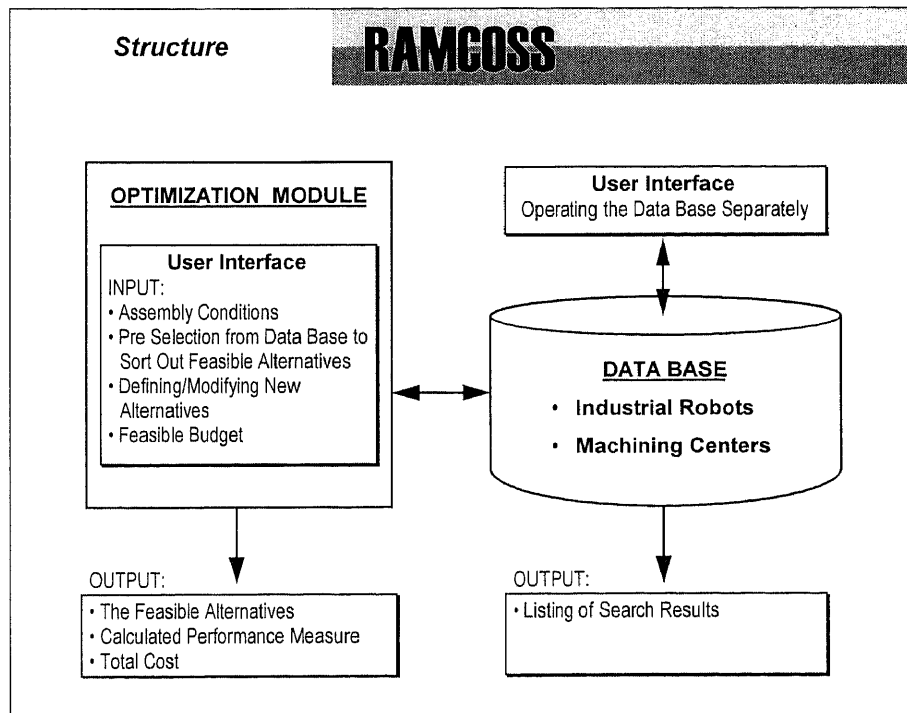
## 1 INTRODUCTION

The intention with the RAMCOSS system primarily focuses on an easy-to-use software. It includes a sophisticated analytical driving engine, while providing a high potential of generating useful and accurate input in the area of process planning and design adjustments.

### 1.1 The RAMCOSS System

This software, RAMCOSS (Robot And Machining Center Optimization Selection System), is a newly developed system to support the selection and the decision making process when designing new, or rearranging existing production cells. Figure 1 illustrates the basic structure of RAMCOSS.

The first of the two major components in RAMCOSS is the data base which consists of two separate sub data bases; one for industrial robots and one for machining centers. The second component is the optimization module. This module is designed to give the user an idea of how the different robot and machining center components will perform under certain, as specified by the user, conditions.

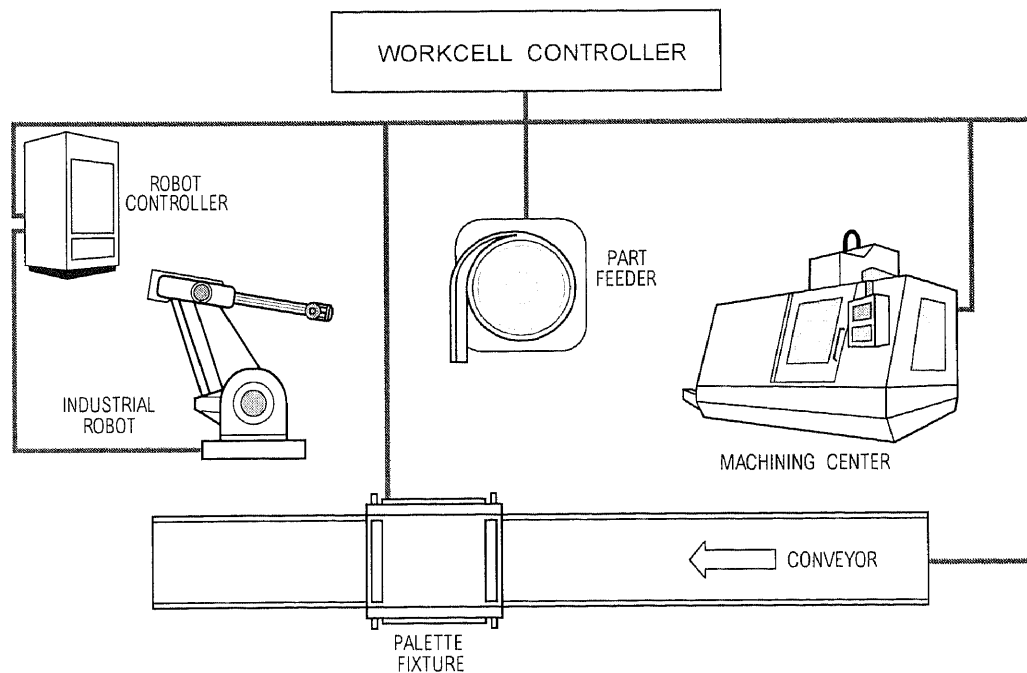


*Figure 1 The RAMCOSS System*

Looking at Figure 1 above, one can see that both the data base and the optimization module each have an individual user interface. This means that the data base can be used separately to search and obtain information about industrial robots and machining centers. The optimization module has a separate interface that enables the user to specify the governing factors for the selection criteria, while accessing all information stored in the data base.

## 1.2 Areas of Application

There are several ways in which this system can be utilized. First, it is developed to give useful information in the development of both new and existing, flexible production cells where industrial robots and/or machining centers are involved, such as the one in Figure 2. The data base alone, provides an extensive reference for the research of available equipment alternatives available in the market. The analytical optimization module simultaneously considers the performance measure of both the robot and the machining center, and generates a total performance output. This performance measure can be weighted with the cost of the particular work cell configuration. Furthermore, in the process of designing new components for automatic assembly, RAMCOSS will give an input of how the geometry of the assembly parts, and moreover, the tolerance and clearance settings of the two, will affect the producibility.



*Figure 2 Production Cell*

The RAMCOSS optimization module is developed originally from an assembly operation where the assembly parts' geometry and tolerances affects the total production output quality-wise. The robots' and machining centers' different capacities in terms of accuracy and repeatability, will result in an output parameter, indicating the cell configurations' performance.

Listed below are some of the more typical situations for which the RAMCOSS optimization module has been designed to assist.

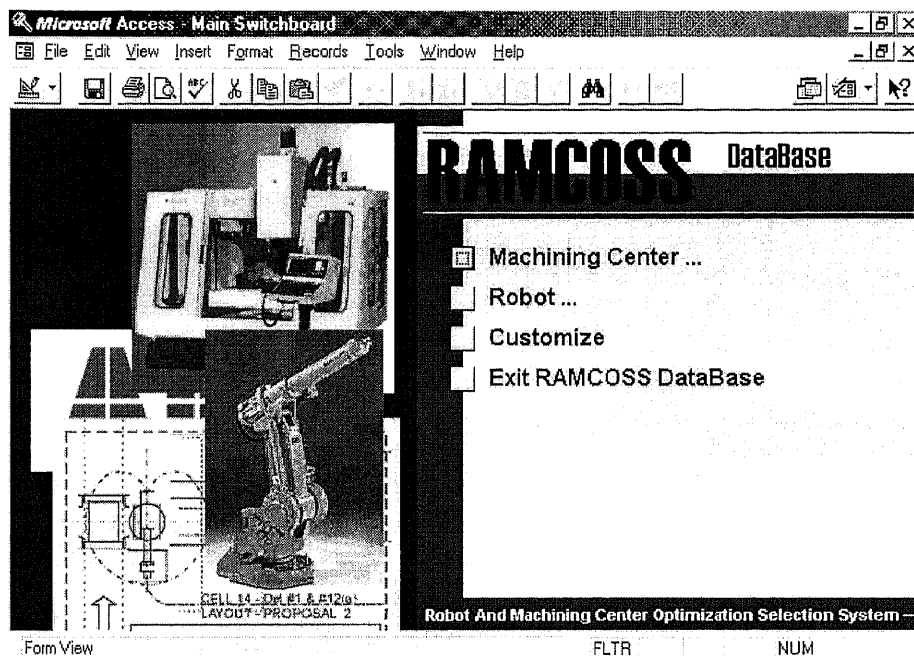
- **Design of a new production cell involving an industrial robot for assembly or material handling purposes, and/or a machining center for processing parts handled and/or assembled by the robot.**
- **Selection of an industrial robot for the purpose of handling or assembling parts with known geometry and tolerances.**
- **Investigation of the impact on the total production efficiency of different design solutions of parts that are automatically assembled, and/or processed by machine with known accuracy and repeatability.**

## 2 THE RAMCOSS DATA BASE

The data base user interface allows a number of options for operating the data base. The procedures on how to use these commands are described in the following.

### 2.1 Main Menu

When the RAMCOSS data base is started, the main menu, shown in Figure 3. first appears. From here, the user can choose any of the applications listed for any of the two sub-data bases.



*Figure 3 The RAMCOSS Main Menu*

Under the robot, and the machining center sub menus, the following feature options leads the user to the corresponding window.

- **Search the data base**
- **Edit Existing Information**
- **Add New Equipment Device to the Data Base**
- **Go Back to Main Menu**

The optimize option in the main menu refers to optimizing the menu itself. If the user chooses to design new queries or report forms, these can be incorporated into the menu system to be easy accessible.

## 2.2 Searching the Data Base

The search options in MS Access gives the user several alternatives for obtaining and displaying the search results. In the RAMCOSS configuration, a specialized form has been created for the search procedure. First, however, it should be mentioned that the most ergonomically designed form is the one used to edit existing and to add new devices.

### BROWSING THROUGH THE RECORDS

If the user wishes to view the stored data records, s/he could enter the robot or the machining center data base by selecting **Edit Existing Alternatives** from either of the sub menus.

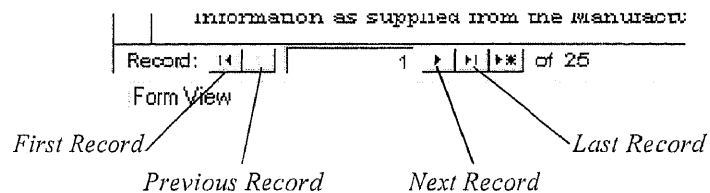
This will open up the corresponding edit form and also enable the possibility to change or delete data entries in the active record.

In order view records, the user can choose either of the following commands:

#### *Go to the Next (Following) Record*

Browse Records In the lower left corner of the screen where the Record field indicates the active record

- Click on the right single arrow on the right side of the field.



*Figure 4 Maneuvering Option*

- The **Page Down** button will move to the next record.
- From the **Edit** menu, select the **Go To** sub menu and chose **Next**.

***Go to the Previous Record***

- Pushing on the single left arrow will (if the current one is not number one) bring up the previous one. See Figure 4.
- The **Page Up** button will move back to the previous record.
- From the **E**dit menu, select the **G**o To sub menu and chose **P**revious.

Also, as shown in Figure 4, one can go directly to the first or last record. This can also be done by selecting **F**irst or **L**ast from the **E**dit and the **G**o To menu.

Searching the data base for robot and machining centers is made possible by using any of the built-in search or filter functions in MS Access. A special form has been designed for this purpose. The form contains exactly the same entries and information as the edit and add forms, but is slightly compressed in order to be more efficient if the user wishes to print out the search results.

Search

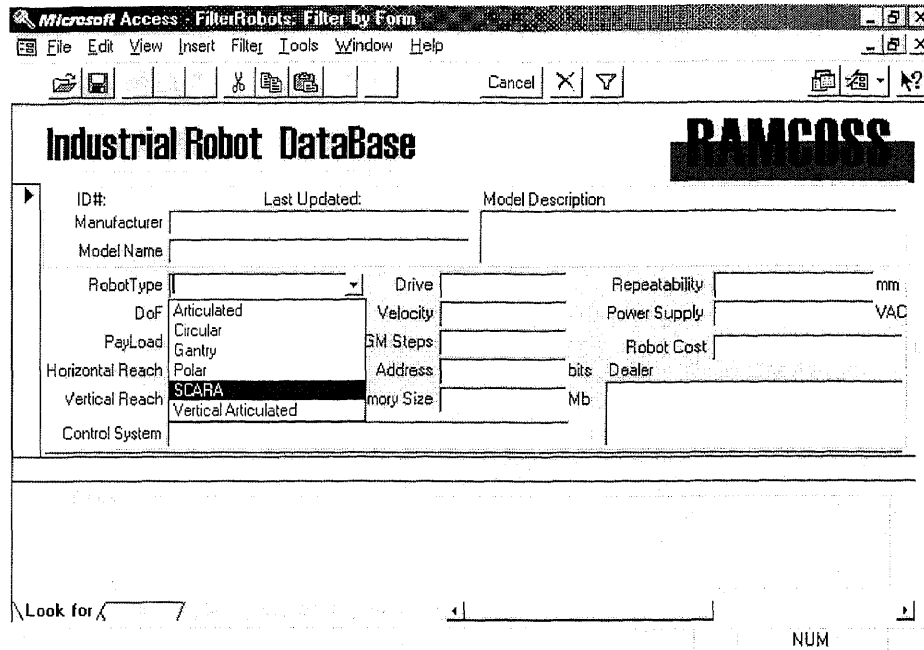
**SEARCHING FOR ALTERNATIVES**

The search form is opened by selecting **Search the Data Base** from one of the two sub menus. Here, the user can specify the search criteria in a number of different ways. The search criteria are defined by an expression.

Here, the user either starts the filter function by pushing on the **Filter By Form** tool button (the icon with a funnel and a form), or, from the **Records** menu and the **Filter** sub menu choose **Filter By Form**.

***Search for a particular Name, Model, or CNC System  
(Text Entries)***

If the user moves the pointer into any of the entry fields, an arrow down will appear at the right side of the field. When pushing on that arrow, a list box will display all the different entries in that field. See Figure 5.



*Figure 5 Selecting Among Existing Alternatives*

The same type of list boxes will appear when the user moves the pointer to any of the fields. This feature is most useful in any of the text entries to distinguish a particular Manufacturer, Model Name, Control System, Dealer, etc.. This is how one can define the expressions;

*Define Text Expression*

- Select one of the alternatives in the list box
- Type in the name on the key board

Wild Characters The \* (star) character can have any value and can, for example be used as in the following expressions;

**Model Name:** D\* Any Model Name starting with the letter "D"

**Model Name:** \*G Any Model Name ending with the letter "G"

After the expression is typed in a field and the user pushes **Enter**, the field will automatically change to "Like D\*" etc.

*Defining Multiple Criteria*

Worth noting from Figure 5 is also the lower left corner where the **Look for** tab is currently active. If the user wishes to search for either a certain manufacturer, perhaps with some other preferences that can be specified in the respective field, s/he may want to search for one other manufacturer. This is possible by doing either of the following:

- Or Criteria
- Fill in the various search criteria in the respective field. For the second alternative, first click on the **Or** tab, next to the **Look for** tab in the lower left corner of the screen. In the new, blank screen fill in the alternative criteria as usual.
  - In the particular field, type in the first criteria, then "Or", and thereafter the second criteria, and so forth.

**Manufacturer:** HAAS or Seiko or ...

It is possible to use more than two criteria with these commands. As a new one is added, a new **Or** tab will appear. Also more than two "Or" can be added in a field.

*Defining Numerical Expressions*

Many of the fields has numerical values. For these entries the user may want to specify a minimum or a maximum value. It is also possible to define a range between the two.

- Minimum
- A minimum value is expressed as ">=" (greater than or equal to), for example;

**Table Load:** >=100 Kg

- Maximum
- The maximum value is subsequently expressed as "<=" (smaller than or equal to), like;

**Robot Cost:** \$ <=130000

- Range
- Here, we need to use the "And" command, together with the minimum and maximum criteria, for example;

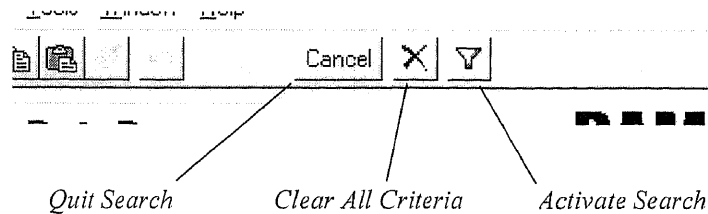
**Travel X:** >500 And <800 mm



Start Search

**Activating the Filter**

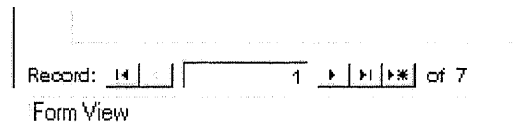
Once we have defined all the criteria with any of these expressions, the filter is activated by pushing on the Filter button in the tool bar at the top of the screen. This is the tool button with the funnel icon (Figure 6.). There is also the alternative to go to the **Filter** and choose **Apply Filter/Sort**.

**Figure 6** Filter Tool Bar

Search Results

**Other Useful Commands**

When the filter is applied, the number of feasible alternatives are shown in the lower left corner (Figure 7.). The results can be viewed by scrolling through the alternatives with any of the scroll commands.

**Figure 7** Number of Feasible Alternatives

Print Results

The search results can also be printed out by using any of the print Results commands (the Print icon, **Print** from the **File** menu, or **Ctrl+P**).

Clear Search Form

Before starting a new search, all the entry fields may be cleared, by using the **Clear** tool button. The button has the red X icon (see Figure 6.).

Cancel, and Main Menu

At any time, the user may cancel what s/he is doing by either pushing on the **Cancel** button in the tool bar (Figure 6), or by closing the active screen and going directly to the main menu.

### 2.3 Edit Existing Data

Eventually, the data may need to be upgraded, or perhaps corrected. This can only be done in the Edit form, that is activated from either of the two sub menus. Figure 8. shows the Robot Edit form.

Edit Data

The user simply moves the pointer to the particular field that s/he wishes to edit, and then inputs the new, desired value with the key board (**Enter** to confirm). Once the new value is entered and confirmed, it is automatically saved.

**Machining Center DataBase** **RAMCOSS**

ID#: 11      Last Updated: 1/7/97      Model Description: Vertical Machining Center

Manufacturer: HAAS

Model Name: VF-2

Table Load	1120 kg	Feed Rate	710 ipm	Tool Capacity	20
Travel X	762 mm	Cutting Rate	300 ipm	Machine Weight	3175 kg
Travel Y	408 mm	Spindel Speed	7500 RPM	Length	2235 mm
Travel Z	508 mm	Spindel Effect	7500 W	Width	2357 mm
Accuracy	0.005 mm	Power Supply	10 kVA	Height	2641 mm
Repeatability	0.0025 mm			Machine Cost	\$61,900.00

CNC System: HAAS Dual 32-bit 68030 CPU      Dealer: HAAS, 9601 Lurine Av  
 EIA/ISO       Pallet Shuttle       Chatsworth CA 91311  
 Information as supplied from the Manufacturers Catalouge      (818) 885 - 6050

Record: 11 of 95      Form View      NUM

Figure 8 The Robot Edit Form

## 2.4 ADD NEW DATA RECORD

Looking at either the robot or the machining center sub menus, one can see that there is an option for adding new devices. This form has exactly the same design as the edit form, but the existing records can not be accessed from here.

**Add New Record** To add a new robot or machining center, the corresponding Add form works exactly as the edit form. By moving the pointer to a field, the entry can be specified. As long as all the entries are not completed, one can go back to a previous field and change a value, if necessary.

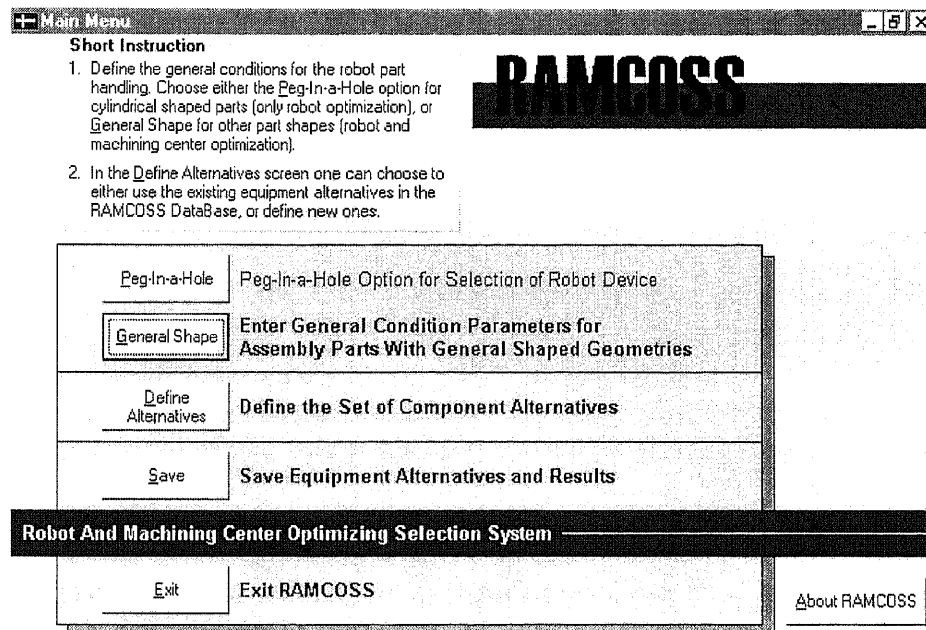
### 3 THE OPTIMIZATION MODULE

In this chapter, the optimization module is presented. In order to utilize this feature of RAMCOSS, one needs to specify the information regarding the conditions under which the robot will operate.

Before going into the instructions on how to operate this optimization, the initialization procedure and the two input alternatives will be introduced. To start, however, the main menu of the module is presented.

#### 3.1 The Main Menu

When starting the RAMCOSS optimization module, the main menu, shown in Figure 9, will first appear. All the module's features can be accessed from here.



*Figure 9 The Optimization Module Main Menu*

This main menu can also be accessed at any time from the different windows, by selecting the **Main Menu** button, which is always located at the lower left corner of the screen.

How to define the assembly conditions and how to operate all of these functions is described in the following sections.

### 3.2 Initialization Procedure

The purpose of this procedure is to identify the critical operation of the robot. This operation will be defined in a set of input parameters and used to obtain the performance measure in the optimization module. The performance measure can be generated either for a separate robot or for a combination of a robot and a machining center.

In most cases the “critical operation” is the procedure where the robot assembles two parts by inserting or placing a so called work part into (or onto) the mating part. It could also be the case where the robot moves the tool through a narrow passage. As the term implies, the critical operation is the process where the robot has to perform under the smallest allowable magnitude of repeatability.

#### *Some Definitions*

Tool Center Point	The Tool Center Point (TCP) is the axes around which the robot gripper tool rotates.
Critical Corner	The critical corner is the corner of the assembly part on the longest distance from the TCP.
$R_{\max}$	The $R_{\max}$ is the distance between the tool center point and the critical corner.

#### *Initialization Procedure*

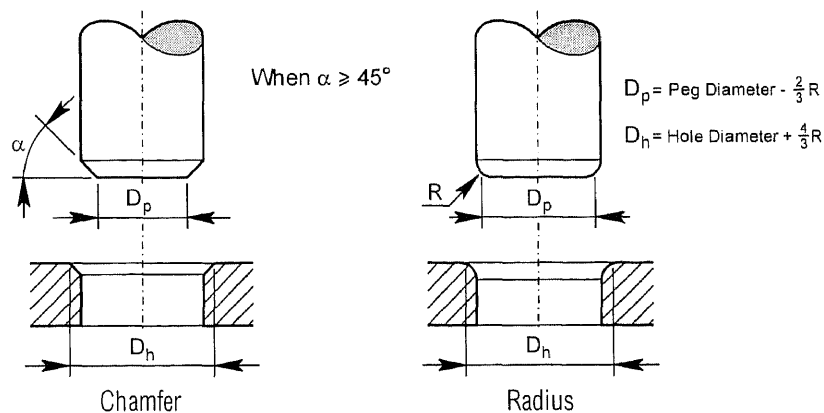
Initialization	<p>As mentioned above, the initialization step seeks the most delicate robot procedure. Generally, this is related to the step where the robot is placing a part.</p> <ul style="list-style-type: none"> <li>• If the robot handles numerous parts with different shapes and geometries, we seek to find the handling of a part that has the tightest placing, or assembly tolerance.</li> <li>• If a set of different parts has the same tolerances, the part with the <i>heaviest weight</i> and the <i>largest dimensions</i> will represent the “critical case”.</li> </ul>
----------------	---

Non-Perpendicular Shapes If the placement surface or the cross section of the insertion silhouette has a non-perpendicular shape, follow these guide lines:

- A radius, fillet or chamfer is extrapolated to the closest, larger perpendicular shape. This operation is only necessary for the critical corner. See also Figure 11.

Chamfer & Radius Sometimes, the insertion part has a chamfer, or radius feature to simplify the insertion process.

- Follow the simple guidelines in Figure 10. to generate the geometry measures. These guidelines can be used for any shape of insertion, as long as it applies to the edges of the bottom surface.



*Figure 10 Radius and Chamfer Adjustments*

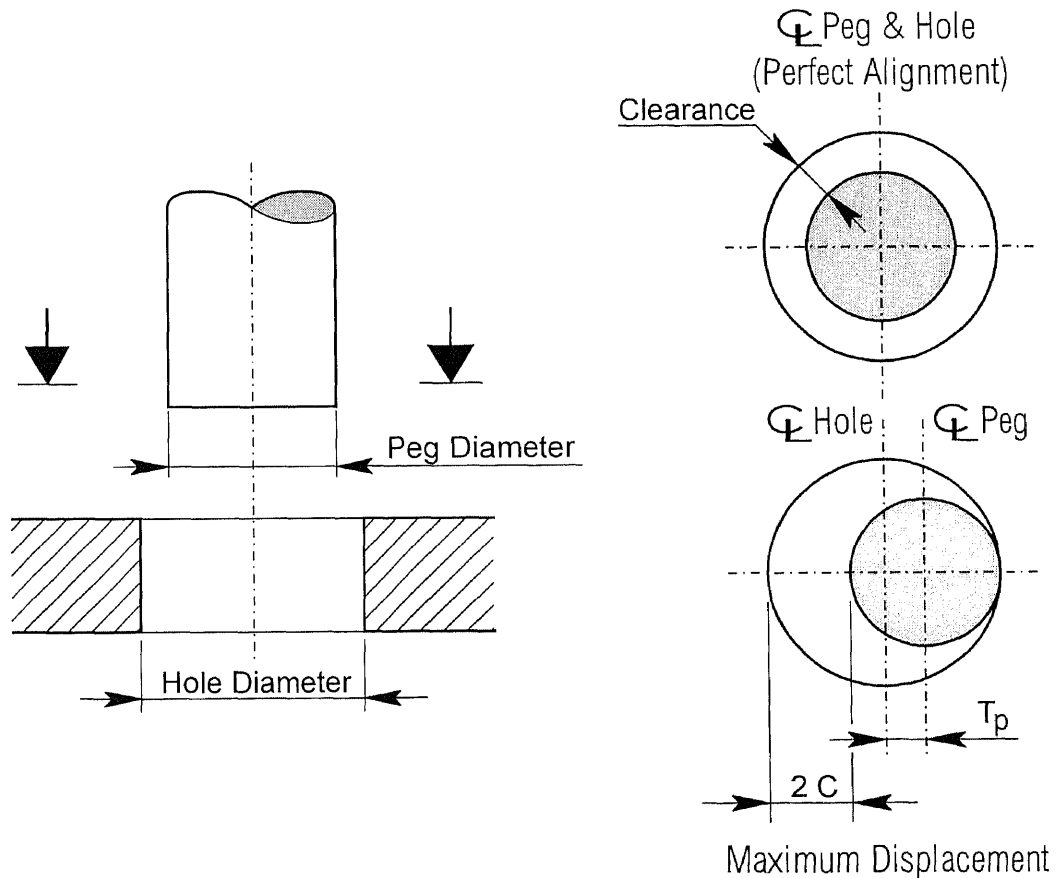
The RAMCOSS optimization module has two input alternatives. The reasons for having two alternatives is discussed in the following. What should be pointed out here are the different possibilities to select one robot device, or to choose a combination of a robot and machining center.

- 1. General Shaped Assembly Parts** Can be used to select a separate robot, or a combination of a robot and a machining center.
- 2. Peg-In-a-Hole Assembly Parts** with a circular cross sectional silhouette. Selects a separate robot.

In the following, the characteristics of the two alternatives are described with some illustrative figures on how to follow the initialization steps, described earlier. Please note that the chamfer and radius adjustments (Figure 10) are also applicable to the general shape alternative.

#### ALTERNATIVE 1 - PEG-IN-A-HOLE ASSEMBLY

This alternative applies when the user wishes to select a robot for assembly of cylindrical shaped parts. The “Peg-In-a-Hole” scenario is a well known and well documented case that applies to a large number of assembly situations. Figure 11 shows the relationship of the peg and the hole diameter, and the clearance.



*Figure 11 The Peg-In-a-Hole Case*

### ALTERNATIVE 2 - GENERAL SHAPED ASSEMBLY PARTS

The assembly part (or parts that are handled by the robot), seen in a cross sectional view from above, has two features that need to be known:

1. The TCP position as compared to the outer, critical corner, of the insertion shape. The distance is the  $R_{max}$ .
2. Clearance between the robot handled part and its mating part.

The  $R_{max}$  can be defined either as it is (mm), or in the x and y direction individually. The clearance needs to be specified separately in the x and y direction.

Figure 12 shows a robot that inserts a part with two separate sections; one with a rectangular shape and one with a circular shape. The robot gripper holds the part centered over the tool center point (TCP).

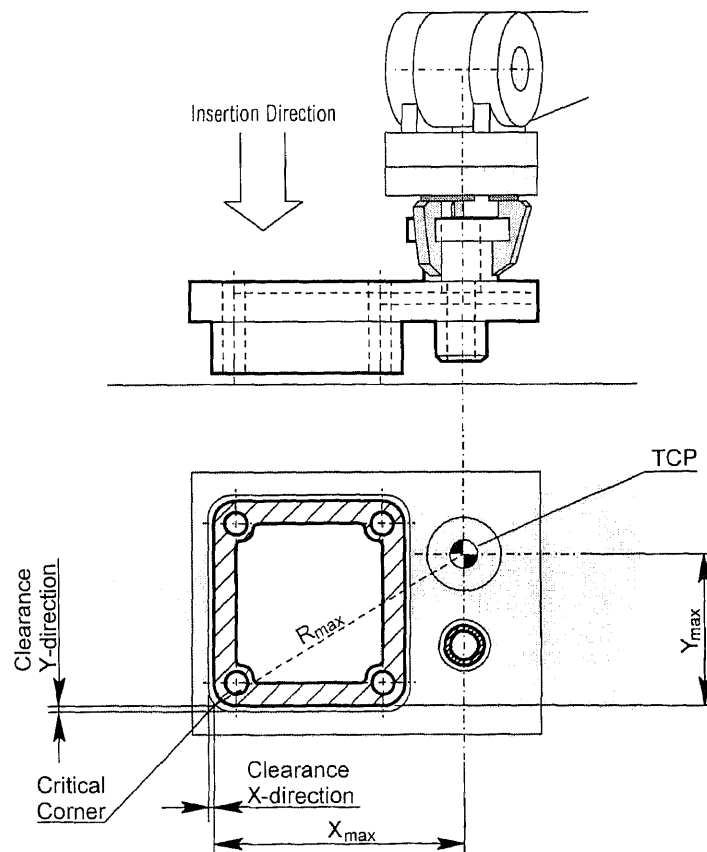


Figure 12 General Shaped Parts



### 3.3 Peg-In-a-Hole Input Parameters

The Peg-In-a-Hole option screen, shown in Figure 12, shows a schematic side view of the peg and the hole.

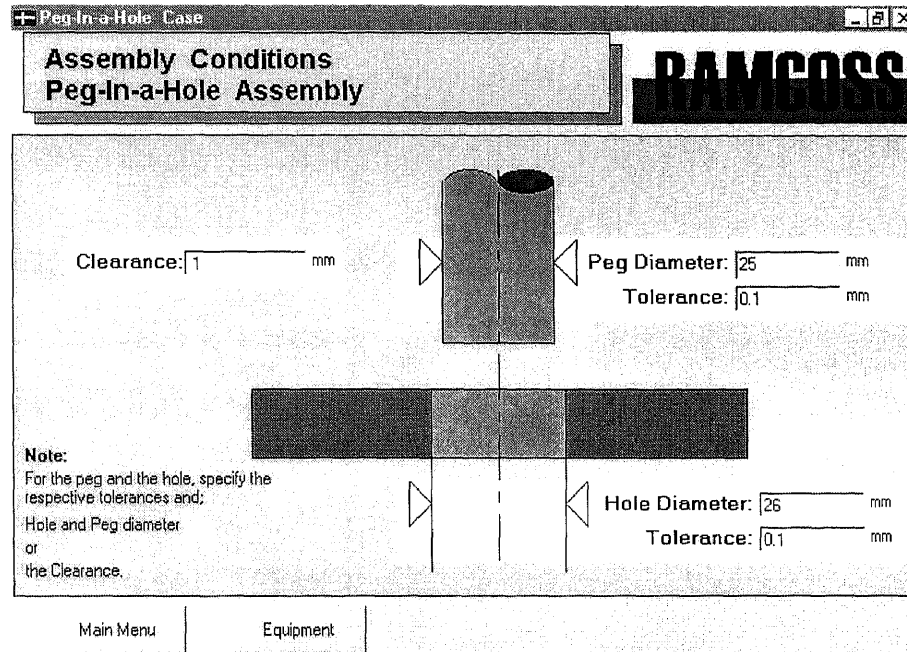


Figure 13 Peg-In-a-Hole Parameter Input Screen

#### How to Define Critical Dimensions

In order to enter one of the parameters, move the pointer to the desired type-in box, or move the cursor there with the **Tab** button.

Peg-In-a-Hole In the **Peg-In-a-Hole** specify the following;

- **Peg Diameter** (mm),
- **Peg Tolerance** (mm),
- **Hole Diameter** (mm),
- **Hole Tolerance** (mm).

Or

- **Clearance** (mm),
- **Peg Tolerance** (mm),
- **Hole Tolerance** (mm),

The clearance will appear automatically when the peg and the hole diameter and the tolerances are entered.

### 3.4 General Shape Input Parameters

The General Shape Alternative screen shows a figure of the assembly part in a view from above. The blue circle is the TCP, while the red circle symbolizes the critical corner. See Figure 14.

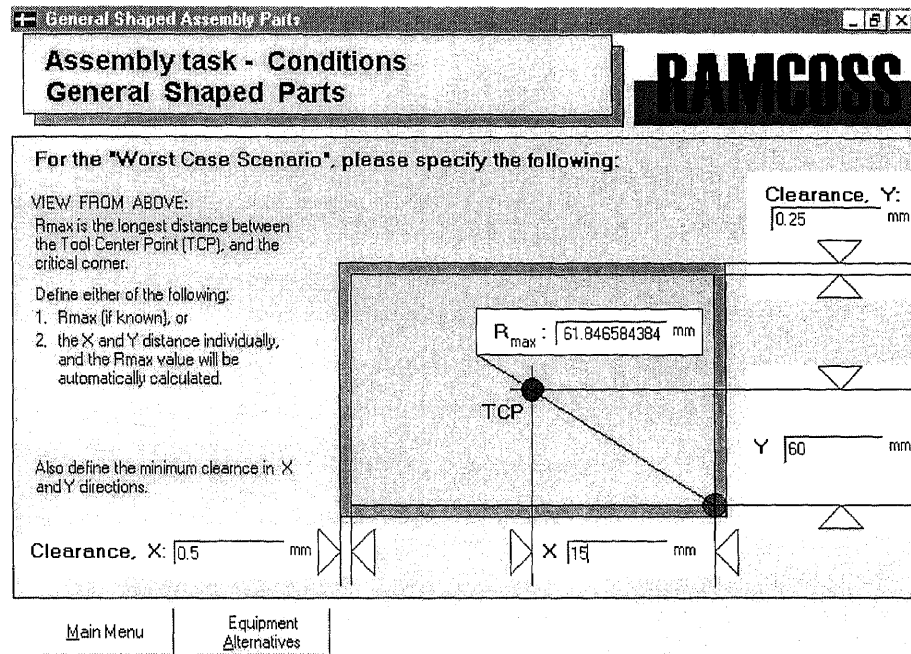


Figure 14 The General Shape Parameter Input Screen

General Shape In the **General Shape** option screen, define the following;

- **Clearance X-direction (mm),**
  - **Clearance Y-direction (mm),**
- And
- **Distance  $R_{max}$  between the Tool Center Point (TCP) and the Critical Corner (mm).**
- Or
- **Distance in X-direction between the Tool Center Point (TCP) and the Critical Corner (mm),**
  - **Distance in Y-direction between the Tool Center Point (TCP) and the Critical Corner (mm).**

The user has the option to either specify  $R_{max}$  directly, or, if not known, by x and y directions individually.

### *Cylinder (Peg shaped) Insertion Assembly Using Alternative 1*

If we wish to select both a robot and a machining center component for a Peg-In-a-Hole scenario, the General Shape alternative is used as follows;

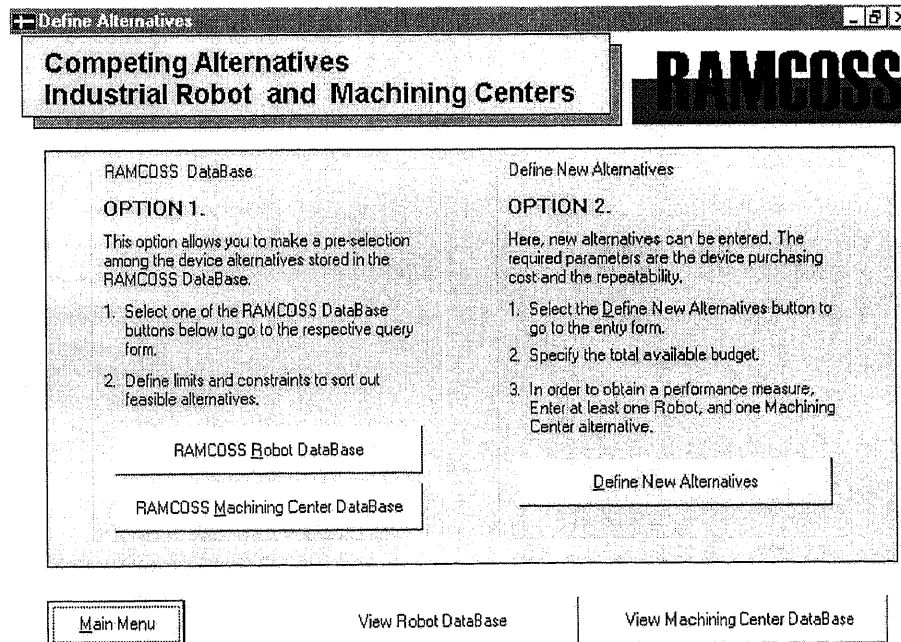
- A single, circular shaped cross section, with  $R_{\max} = 0$ , (that is, the TCP is aligned with the center line of the cylinder part), does not need to be modified. Simply specify the x and y dimensions as the cylinder radius, together with the clearance.

## 3.5 Equipment Alternatives

The RAMCOSS optimization module will calculate the performance measure of either a robot alternative, or a combination of a robot and a machining center. The set of competing component alternatives can be obtained either from the RAMCOSS data base or by defining new alternatives for a specific case.

### *Equipment Alternatives Menu*

The Device Alternatives sub menu, shown in Figure 15, shows the two options



*Figure 15 Device Alternatives Sub Menu*

Data Base  
Alternatives

### USING EXISTING ROBOT AND MACHINING CENTER ALTERNATIVES STORED IN THE DATA BASE

If the user wishes to use the robot and machining center alternatives stored in the RAMCOSS data base, we use option 1.

- Choose either **RAMCOSS Robot Data** Base or
- **RAMCOSS Machining Center Data Base.**

Either of the Option 1-buttons will lead to the corresponding pre-selection window.

#### *How to Define Search Criteria in the RAMCOSS Optimization Module*

Figure 16 shows the pre-selection screen for the machining center data base.

**Pre-Selection Machining Centers**

Manufacturer:

Model Name:

Model Description:

Spindel Speed:  RPM

Spindel Effect:  kW

Power Supply:  kVA

Tool Capacity:

Unit Weight:  kg

Length:  mm

Width:  mm

Height:  mm

Machine Cost:  \$

Z:  mm

Accuracy:  mm

Repeatability:  mm

Feed Rate:  ipm

Cutting Rate:  ipm

CNC System:  EIA/ISO:

*Figure 16 The Machining Center Pre-Selection Window*

- Pre-Selection In order to specify a numerical search criterium, follow these instructions:
- Minimum • The minimum value is typed in the *left box* for the respective attribute.
- Maximum • A maximum value is typed to the *right box* for the respective attribute.
- Range • A specific range is subsequently defined by entering both the minimum and maximum value. For example:

500    Travel Z: 800    mm

Once all criteria are specified, the **Select Machining Centers** (or **Select Robots**) button will activate the search.

#### *To use all Component Alternatives*

To see how the defined assembly conditions will affect the performance measure of all the devices stored in the data base, one can simply choose all alternatives by first selecting **Clear All** and then **Select Robots** to obtain a set of all available alternatives in the data base.

*Warning* Using a large number of alternatives, especially when optimizing a combination of a robot and a machining center, will require a longer processing time. Therefore, the program prompts the user to verify that the entire data base will be selected.

Once the pre-selection is made, the window shown in Figure 17 appears.

#### **ADD AND DELETE COMPONENT ALTERNATIVES**

The other option in the equipment alternative sub menu is to specify new components without using the data base. This feature, however, can also be used to modify a pre-search of the data base.

In order to use this feature, click on **Define New Alternatives** button in the device alternative sub-menu. This will display the window shown in Figure 17.

- Add New Device
- Click on the **Add Robot** or **Add Machine** button.
  - In the dialog box that appears, type in **Model Name**, **Repeatability**, and **Clearance** in respective type-in box.
  - To add the new device, click **OK**.

**Device Competitors**

**Competing Device Alternatives**  
Industrial Robot and Machining Center

**Total Available Budget**  
Specify the total, feasible budget for Robot and Machining Center Combination: 150000 U.S. Dollars

Robot Alternatives			Machining Center Alternatives		
Robot Name	Repeatability	Cost	Machining Center	Repeatability	Cost
XM3064	.015	30000	CT-6	.0025	59750
XM3105	.015	36000	5 HP 7,200 RPM	.0127	37995
TT8450-BN	.02	32000	VF-0	.0025	51900
TT8550-BN	.02	33000	VF-4	.0025	79900
TT8700-BN	.025	35000	VF-6	.0025	124900
TT8800-BN	.025	36000	VF-8	.0025	149900
RT3300	.015	38000	VK45II	.001	0
			VK55II	.001	0
			SV-50	.001	0

Buttons: Add New Robot, Delete Robot, Clear All, Add New Machine, Delete Machine, Clear All, Main Menu, Optimize, Save Alternatives, Alternatives

*Figure 17 The Competing Device Alternatives Window*

- Delete Device
- As a reminder, this feature is also useful in the option where the alternatives are obtained from the RAMCOSS data base.
- Place the cursor on the device that should be deleted.
  - Click on the **Delete Robot** or **Delete Machine** button.

Clear All This will clear all the devices in the respective column. The program therefore will prompt for confirmation on this command.

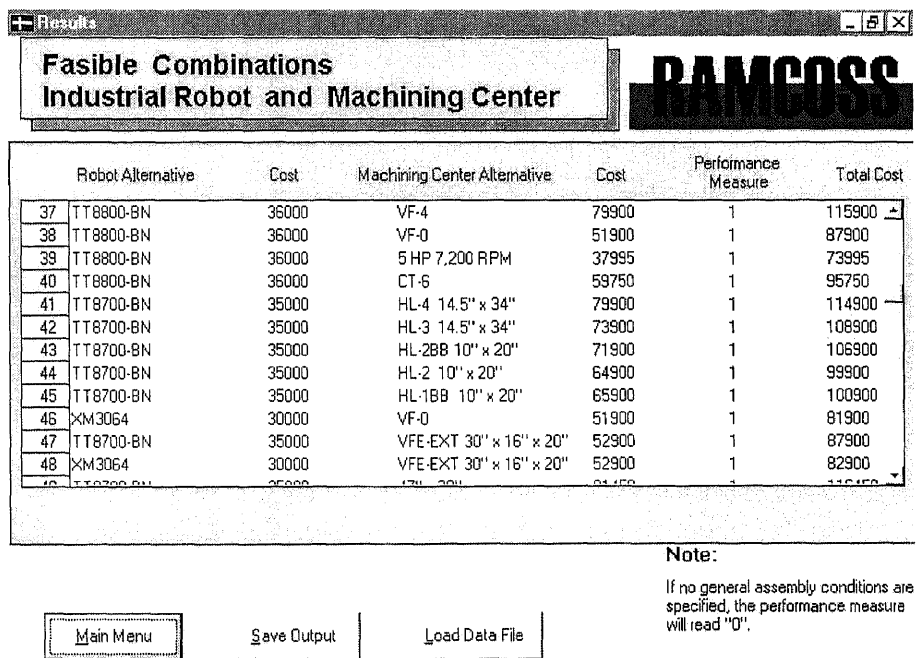
- Click on the **Clear All**.

**Specifying Maximum Available Budget**

Available Budget This only applies to the general shape case. It sorts out all combinations that has too high total cost.

### 3.6 Optimization

Once the set of feasible device alternatives is specified, the optimization is activated by pushing the **Optimize** button. The result window of robot and machining center combinations is shown in Figure 18.



*Figure 18 The Result Window*

In the peg-in-a-hole case, the result window shows only the robot model name, repeatability, cost, and performance measure.

## 4 DEFINITIONS

### 4.1 Industrial Robot

There are not many, if any, documented standards for industrial robot definitions. Since the robot producers often customize special solutions for the users, there are an enormous amount of existing industrial robots in the industry today. Here, however, the most common definitions for the most usual types of robots will be described.

#### DEGREES OF FREEDOM

This is probably the most frequently used classification that defines the number of axes around which the robot can move. There is also the possibility that the robot can move reciprocally, along one axes, which is then considered as one degree of freedom.

#### ROBOT CONFIGURATION

The robot configurations attempts to, more thoroughly than the degrees of freedom concept, capture the type and classify it into one of the following five categories. See also Figure 19.

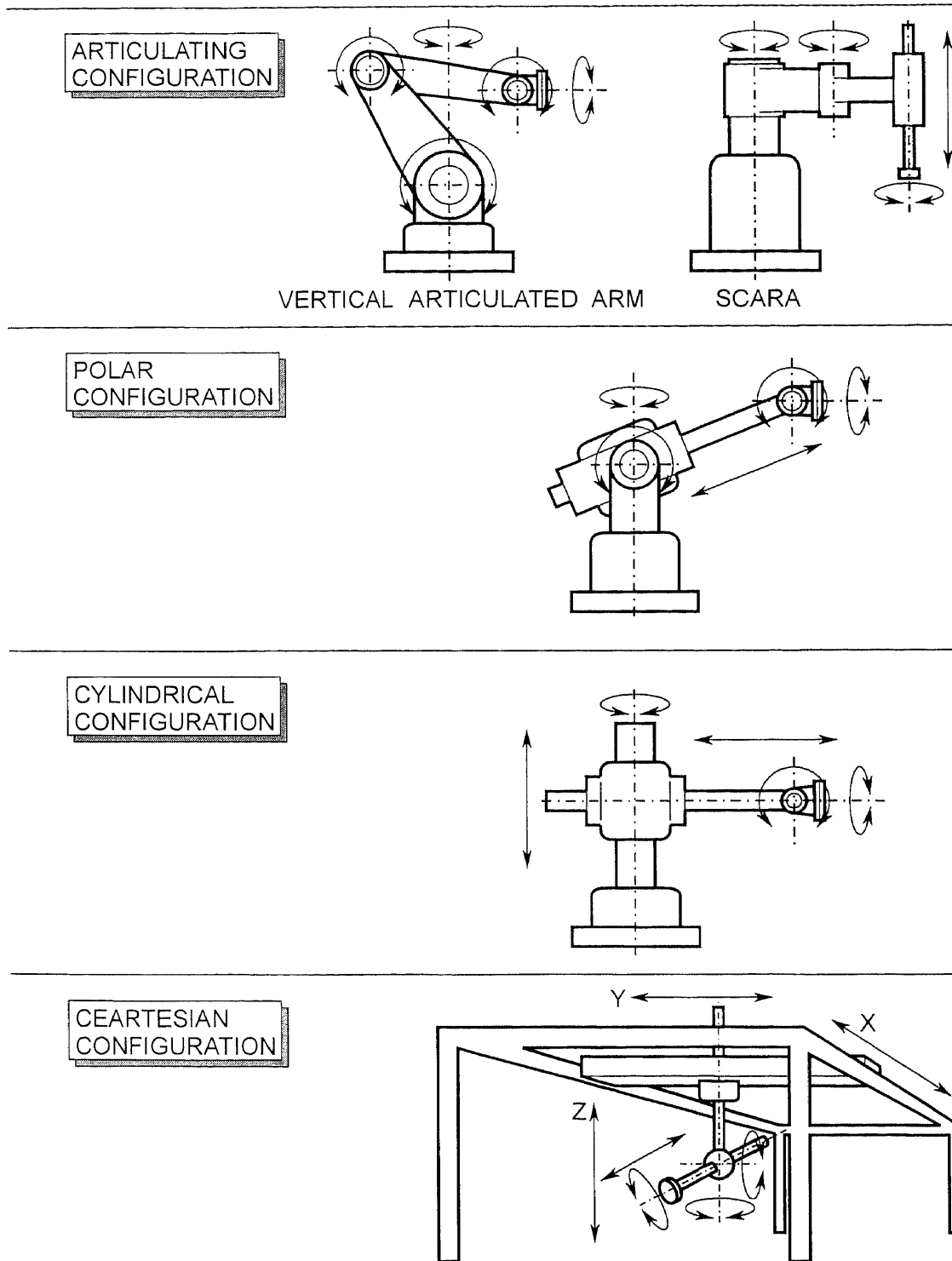
##### *Articulating Configurations*

These types of robots, also called *Vertical Articulated Arm* (or simply *Jointed Arm*), have a vertical axes around which the robot arm is rotating. The links in the arm can be either horizontal or vertical. The latter of the two is a very popular configuration that more or less has its own classification; the Selective Compliance Assembly Robot Arm - *SCARA*. This robot type is ideal for vertical insertion and pick-and-place tasks. Due to its usually competitive price and good repeatability, it has become very popular.

##### *Polar Configuration*

Aside from the articulating configuration's third elbow type degree of freedom, the polar or *Spherical Configuration* robots has an extension axes. Usually this third axis is powered by a pneumatic or hydraulic cylinder. This type is often is used to elevate work pieces with fixed orientation along a vertical path. The polar configuration is popular, especially in the automotive industry.





*Figure 19 Common Industrial Robot Configurations*

### ***Cylindrical Configuration***

Looking at the basic cylindrical configuration, one can count four basic degrees of freedom. The first vertical rotation axis, a vertical reciprocating, the third extension axis that also can roll/rotate - the fourth. Sometimes, this is also called a *Cylindrical Coordinate Configuration*.

### ***Cartesian Configuration***

A Cartesian coordinate robot configuration, or *Gantry Configuration*, uses the x, y, and z axes as the first three degrees of freedom. The robot arm is in most cases mounted on a gantry, that can be customized for the particular workspace.

### ***Mobile Robot Configurations***

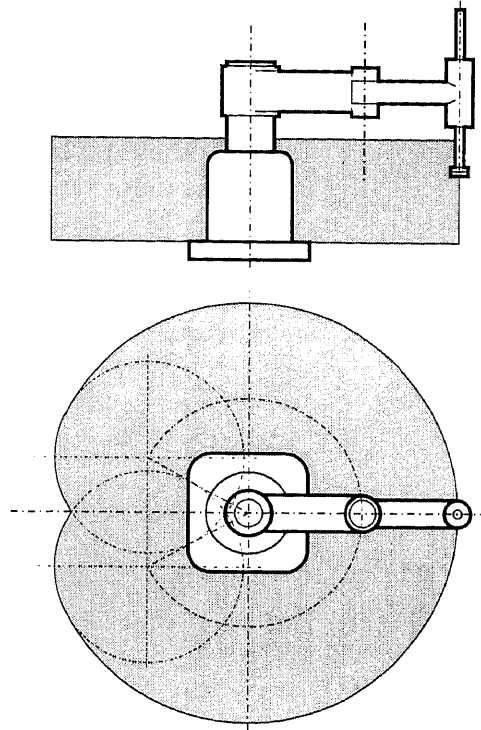
All of the previous robot configurations are restricted to a certain workspace in the immediate surroundings of the robot position. For some applications, however, the robots need to operate at more than one location, and can then be mounted on a moving device. This is particularly useful for material handling on an AGV, or for part loading and unloading where one robot can serve several machines. Also, all types of special devices for work in limited or environmentally dangerous situations, fall into the mobile robot configuration group.

## **WORK ENVELOPE**

A robots' work envelope is the volume of work space in which the robot reaches and can operate. The work envelope depends on the type, and the size of the robot. Figure 20, shows the work envelope of a SCARA robot.

## **SPEED**

The maximum rated speed is the highest velocity that a robot can attain. The speed will naturally impact on the cycle time for an operation. The acceleration and deceleration will also affect the cycle time. A robot that has the same degrees of freedom and the same work envelope, can have different speed or cycle time capacities, depending on the maximum payload, the effect of the servo motors, and the motion and path routines.



*Figure 20 Work Envelope for a SCARA Robot*

## ROBOT DRIVE

The type of robot drive simply indicates the robot's power source, and also gives an indication of the performance and the application field.

### *Hydraulic*

This is the most powerful class that allows the robot to apply large forces both at the robot joints, and at the gripper tool. As hydraulic robots also require equipment for generating the fluid pressure, it is a relatively expensive class. One of its unique characteristics is that this type, unlike the pneumatic or electric types, can work in explosion risk environments, and also under water. The hydraulic robots are often used in the auto industry for spot welding and spray painting applications.

***Pneumatic***

The pneumatic robots are often used for simple, light weight pick and place tasks. It has become an inexpensive and popular solution and this type has a widely used set of standard and modular components.

***Electric***

This is maybe the most accurate type of robot, which has the most possibilities to control the robot movements. The stepper motor type can be used for both closed- and open-loop type movement. The servo driven motor type that uses feedback loops can accomplish the finest and smoothest types of movement. The use of electric drives is increasing and is used in several general purpose robots.

## MOTION CONTROL

***Axes Limit***

The axes limit, or the *two-position control* is the least sophisticated type of robot motion control, and has therefore also the lowest relative cost. As this type of motion for pneumatic and hydraulic powered robots is between two extreme points (the axes limits), there is no (or very limited), possibility to control the speed. This type is often used for loading and unloading.

***Point-To-Point (PTP)***

As the name implies, the PTP control moves between specified points within the work envelope. Often the speed and in most cases the path are not completely controllable. Common applications are one direction component insertion, hole drilling and spot welding.

***Contouring***

This is the most sophisticated type, that allows full control over both path, speed and positions. With today's advanced micro computers, the contouring is becoming increasingly used. This type of motion control is necessary for applications such as high end spray painting, finishing, gluing and arc welding.

***Line Tracking***

This is a form of advanced contouring where the robot performs an operation while continuously following a moving conveyor or track, for example spray painting.

## PAYLOAD

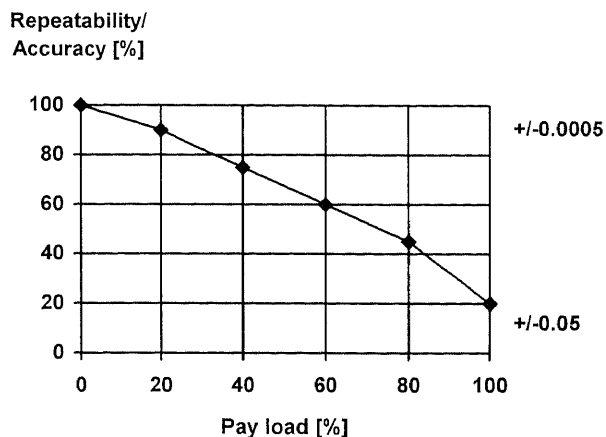
The payload indicates the carrying capacity of the robot. Depending on the type and the class of robot, the payload can vary from a few grams up to several 100 kg.

## REPEATABILITY & ACCURACY

The robot repeatability and accuracy are two different indications of robot performance. The repeatability indicates how precisely the robot repeatedly can return to a certain, taught point. Typical repeatability specifications can vary from  $\pm 0.005$  mm for microposition robots to  $\pm 2$  mm for a larger spot-welding robot.

The accuracy is a measure of how accurate the robot can reach a certain, specified point. Since the accuracy is complex to measure, the manufacturers rarely specify this. However, the repeatability, which is a better indicator of how well the robot will be suited for the particular task, is usually indicated.

Although it is easier to measure the Repeatability, there is a lot of confusion regarding this matter. The repeatability of a robot is destined to change as the load increases, as shown in Figure 21. Similarly, when the speed increases the accuracy and the repeatability deteriorates. A robot that is operating with maximum load at maximum speed will have quite a different repeatability than what might be specified by the manufacturer. This is one of the big causes of confusion. There is no standardized measuring method that is used by every robot manufacturer. Almost always, the engineering and cost attributes tends to put the presumptive buyer of a robot in a trade-off situation where the robot capacity, repeatability, or any other feature increases at the same time with the cost. Another fact to keep in mind is that there are also situations where different robot engineering attributes are conflicting with each other, such as repeatability and speed, repeatability and payload.



*Figure 21 The Payload Affects the Repeatability Negatively.*

#### VENDOR-RELATED ATTRIBUTES

The Vendor-related attributes focus on the manufacturers abilities and qualities such as service and warranty issues. These type of attributes are often complex to compare and measure. One example of a vendor, or more accurate manufacturer attribute, is the **Reliability**, which with no doubt is the most important feature in a robot, since a failure completely disables the robot to perform any task at all. Usually, a subjective reliability like reputation, can indicate the reliability of a robot manufacturer (how long the company has been in business, the volume of produced robots, and the number of robots that is used today). In the case where a robot model has been produced for some time, the manufacturers often indicates the robot reliability as the mean time between failure (MTBF).

#### COST ATTRIBUTES

The most important cost factors when selecting a robot is the actual cost of purchasing the robot. Other attributes includes cost of installation, tooling cost, and maintenance cost.

## 4.2 Machining Center

Although the number of definitions and specific attributes concerning machining centers might seem smaller, and maybe more familiar than the corresponding industrial robots', in the following we give a few introductory definitions.

### CONFIGURATIONS

The machining center data base is designed primarily with the following configurations in mind;

- **CNC Milling Machines**
- **Vertical Machining Centers**
- **Horizontal Machining Centers**
- **Universal Machining Centers**

and also:

- **CNC Lathes / Turning Centers**

The latter, the CNC lathe, might seem to belong in a separate data base. However, many of the modern machining centers have up to 4, and sometimes even 5 axes (or degrees of freedom), providing them with the compatibility of a turning center. Also, as the turning centers often have the capability of a combined turning and milling operation, except for the work space, the data base also can be used for the CNC lathe / turning center category. The 4, and 5 axes machining centers are often also referred to as 'mill-turn' centers.

### AUTOMATIC TOOL CHANGING

Most of the more advanced machining centers have this feature as a built-in function. When the machine has completed one machining operation and is moving to the following, the cutting tool must first be changed. With automatic tool changing, specific procedures in the CNC program indicate when the machine should exchange the tools. The various tools are stored in a storage drum or magazine, that usually can store between 16 and 80 tools.

### **PALLET SHUTTLES**

Often, when a machine is processing big volumes of small parts, fixture pallets are used to pre-load the parts before they are going into the machine. This way, the process time can be reduced as compared to the case where all the parts have to be loaded into the machine individually. One pallet can have several setup positions for the parts. While one pallet is being processed, other pallets can be (manually or automatically by a robot) loaded, unloaded, or changed to the following setup position outside the machine.

The actual pallet shuttle is the device that switches between the previously processed one and the prepared one outside the machine.

### **AUTOMATIC WORK PART POSITIONING**

Every machining center having more than 3 degrees of freedom, such as the combined mill-turning centers, requires this feature to properly position the work part before carrying out the operations that are non-symmetrical to the part geometry.



## The Creation of RAMCOSS

RAMCOSS has been developed as part of a thesis project; *A Decision Support System for the Equipment Selection of Robotic Manufacturing Cells*. The thesis is submitted to the faculty of the Industrial and Manufacturing Engineering Department at the New Jersey Institute of Technology, in partial fulfillment for the degree of Master of Science in Industrial Engineering.

### Acknowledgment

A special thanks is extended to Mohamed H. Badr for assistance in the coding of the RAMCOSS optimization module. The author would like to acknowledge partial support by the National Science Foundation through grants DMI 9525745 and DDM 9313322. The author especially wishes to acknowledge the "Marcus Wallenberg, Ph.D., Foundation for Education in International and Industrial Enterprising" for funds received, without which this work would not have been possible.

New Jersey Institute of Technology  
August 1997

Lars Johan Resare

# RAMCOSS

## Version 1.0

RAMCOSS (Robot And Machining Center Optimization Selection System) is a software package designed to assist in the selection and decision making process of choosing appropriate robot and the machining center equipment for flexible manufacturing cells.

RAMCOSS consists of two modules: A data base containing two separate sub-data bases, storing information on industrial robot and machining center equipment. The data base can be utilized separately to search and obtain feasible component alternatives, subject to specified search criteria. The second part is the optimization module. It asks for a set of parameters that describes the product parts' geometrical specifications. The user has the option of making a pre-cut selection among component alternatives stored in the data base, or to define new ones. The optimization module generates a performance measure of the feasible device alternatives.

### SYSTEM REQUIREMENTS:

The RAMCOSS data base is created in Microsoft Access 7.0, and the optimization is developed in Microsoft Visual Basic 4.0.

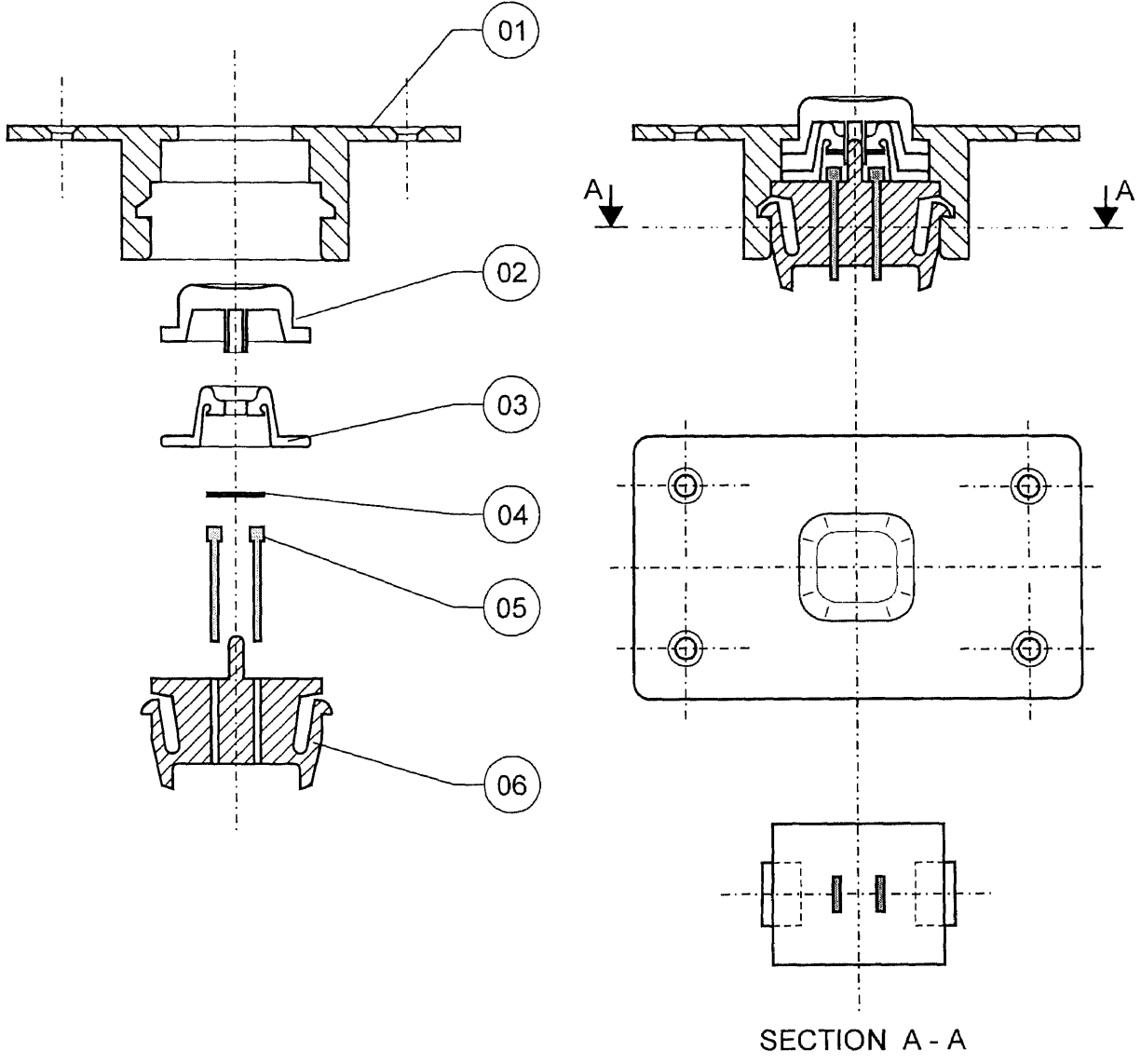
Operating System:	Windows 3.x, Windows 95 (or later)
CPU:	486 (or higher)
Disk Space:	2 Mb (with initial data base configuration, containing 50 data records)
Software:	Microsoft Access, version 7.0 (or later)

The optimization module may be utilized separately if Access is not available. All robot and machining center alternatives then have to be interactively entered into the module.

## APPENDIX D

### CASE STUDIES: DRAWINGS

<b>Drawing No.</b>	<b>Description</b>	<b>Page</b>
<i>Case Study No. 1</i>		
A - 10 101:	Electric Switch, Assembly, Proposal No. 1 .....	D.132
A - 10 102:	Electric Switch, Bill Of Material, Proposal No. 1 .....	D.133
A - 10 201:	Electric Switch, Assembly, Final Design.....	D.134
A - 10 202:	Electric Switch, Bill Of Material, Final Design.....	D.135
<i>Case Study No. 2</i>		
B - 20 001:	Shaft .....	D.136
<i>Case Study No. 3</i>		
A - 30 101:	Flange, Assembly, Proposal No. 1 .....	D.137
A - 30 102:	Flange, Proposal No. 1 .....	D.138
A - 30 201:	Flange, Assembly, Proposal No. 2.....	D.139
A - 30 202:	Flange, Proposal No. 2.....	D.140
A - 30 301:	Flange, Assembly, Final Design .....	D.141
A - 30 302:	Flange, Final Design .....	D.142



SECTION A - A

06	1	BASE	A - 10 1xx	
05	2	CONNECTOR PINS	A - 10 1xx	
04	1	CONNECTOR WASHER	A - 10 1xx	
03	1	MILYR DOME	A - 10 1xx	
02	1	CONTROL BUTTON	A - 10 1xx	
01	1	HOUSING	A - 10 1xx	
Detail No:	No:	Description:	Dimension / Detail Drawing No:	Weight:

METRIC UNITS

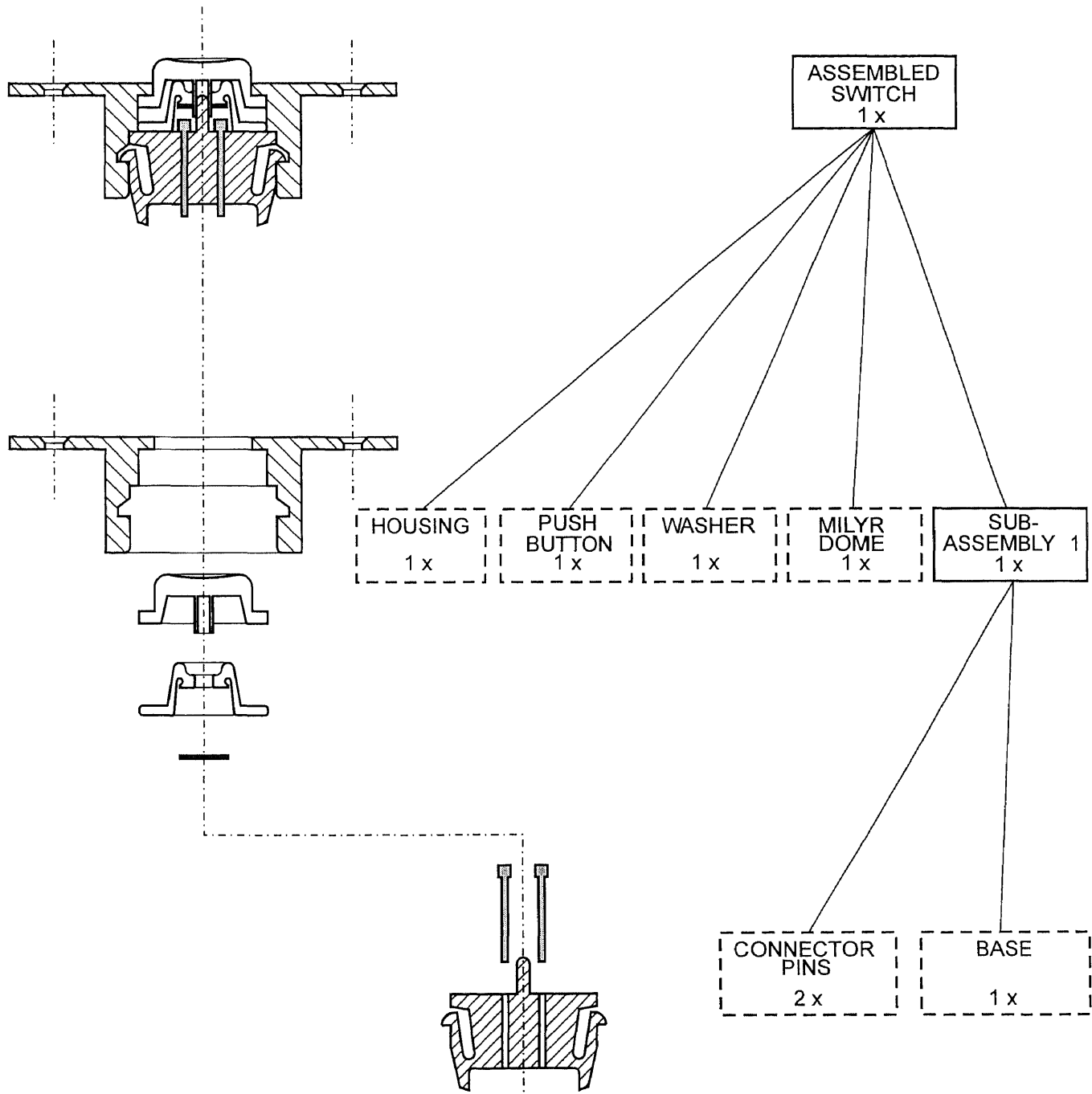
EUROPEAN VIEW PROJECTION

Design: Lars Johan Resare  
 Drawing: Lars Johan Resare  
 Scale: 1:1  
 Date: April 10, 1997

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 Project Name: CASE STUDY No. 1

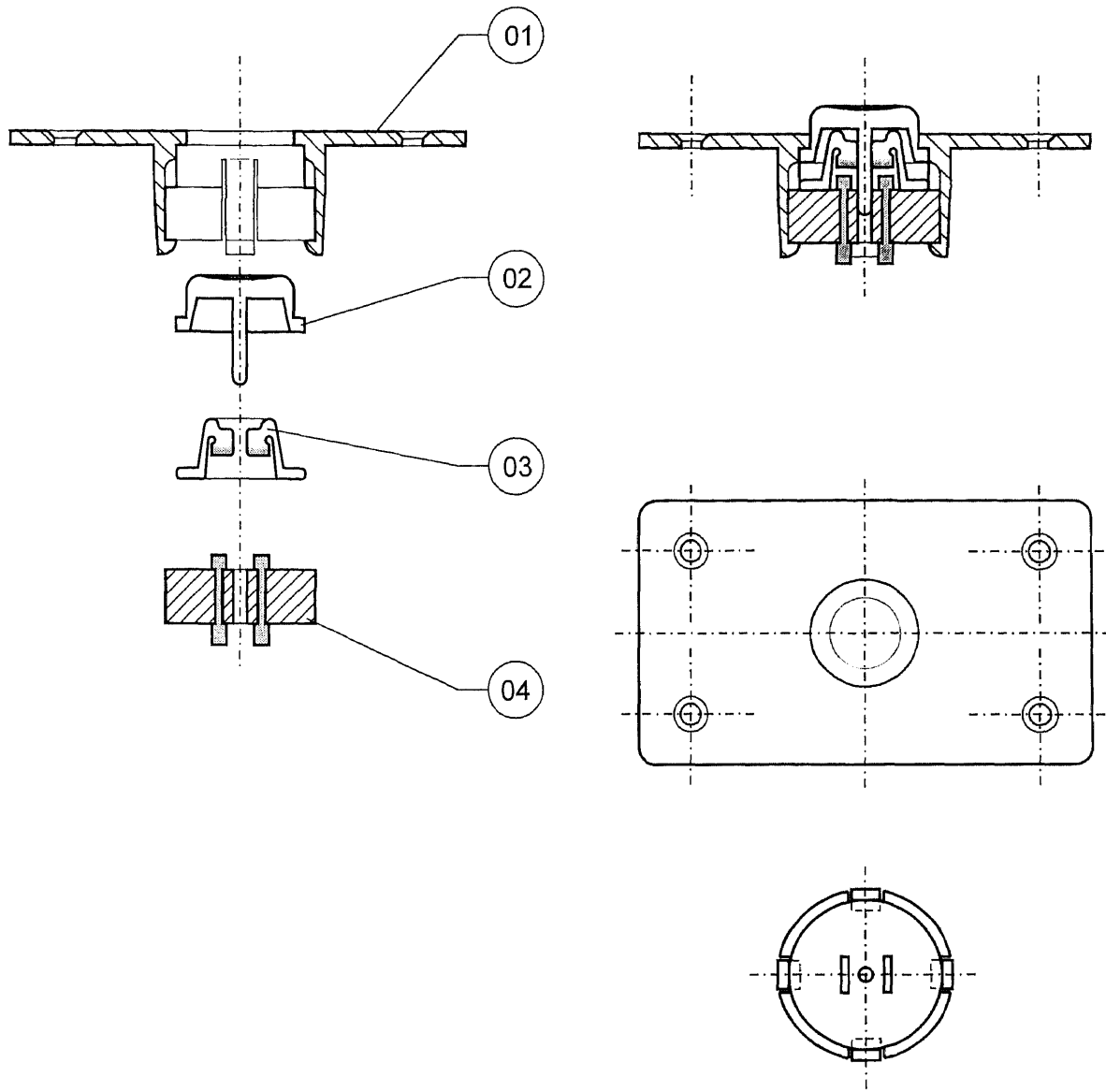
**RAMCOSS**

Drawing No: A - 10 101



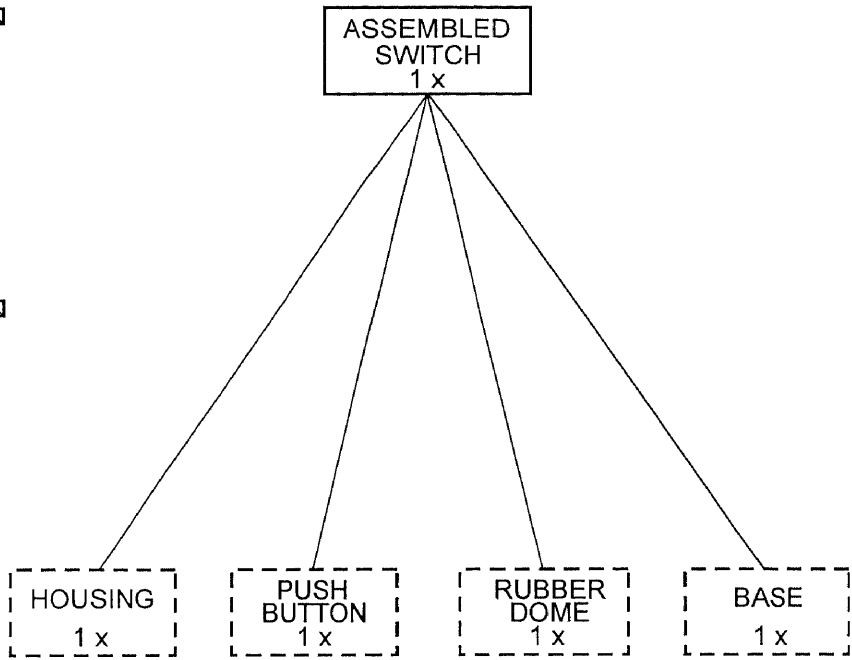
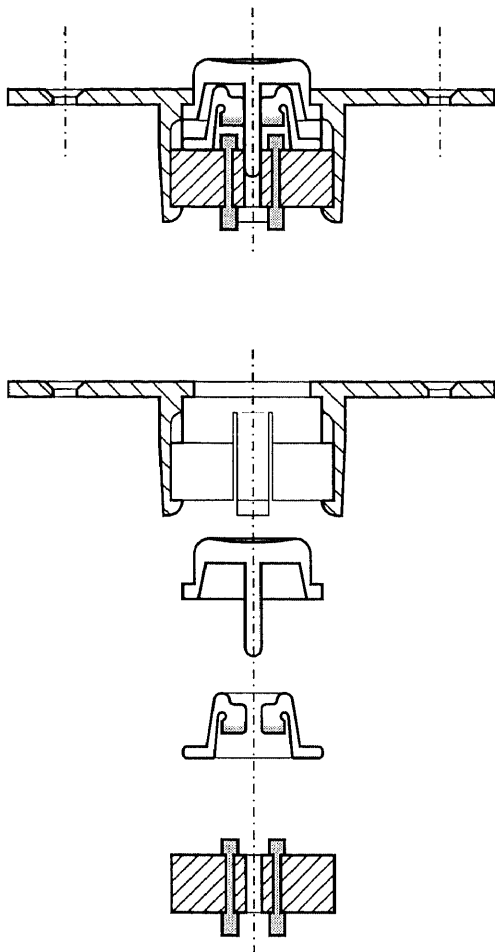
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	Date:	April 10, 1997			

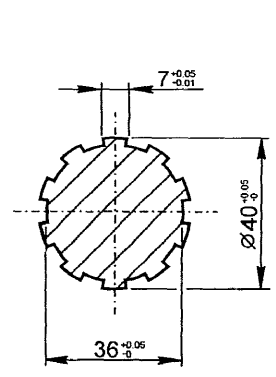
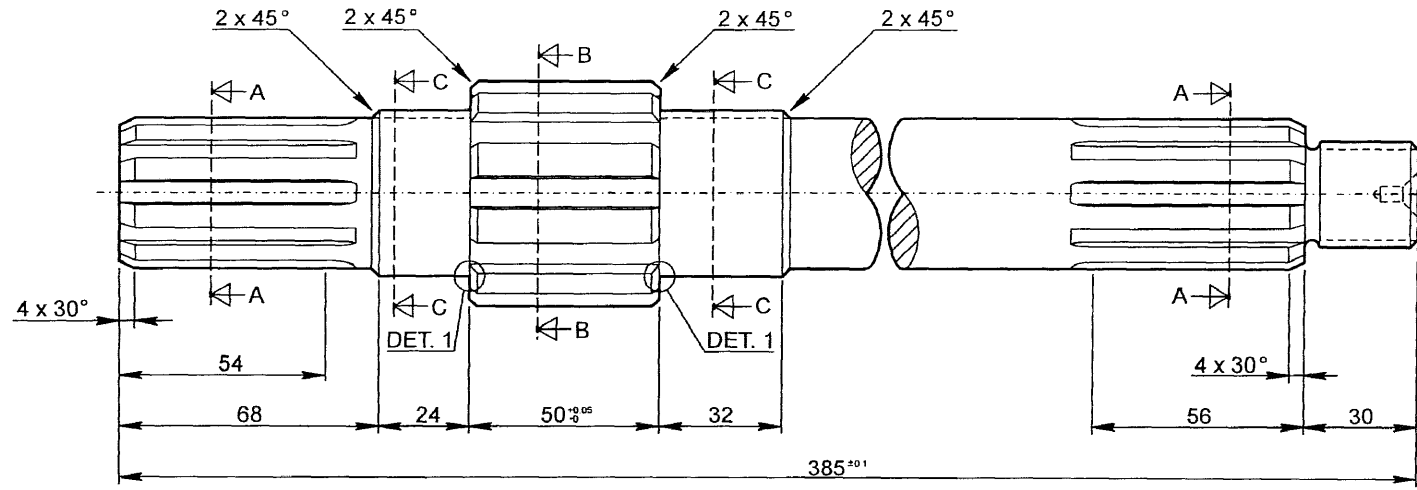


Detail No:	No:	Description:	Dimension / Detail Drawing No:	Weight:
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03	1	MILYR DOME	A - 10 2xx	
02	1	CONTROL BUTTON	A - 10 2xx	
01	1	HOUSING	A - 10 2xx	

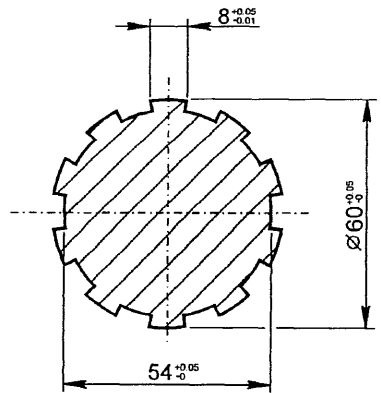
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	<p>Drawing: Lars Johan Resare</p>	<p>Project Name: CASE STUDY No. 1</p>
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	<p>Date: April 12, 1997</p>	



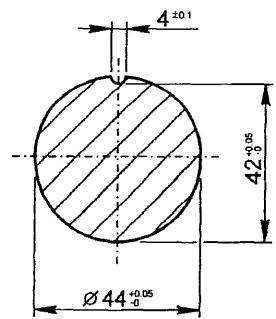
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<p><b>RAMCOSS</b></p>			<p>Drawing No: A - 10 202</p>	



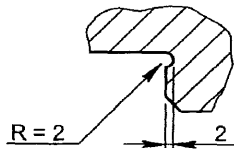
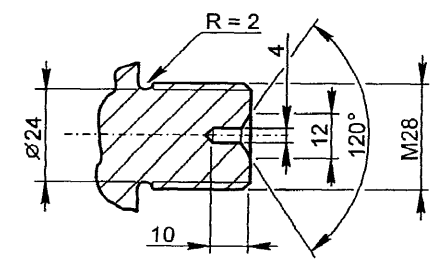
SECT A - A



SECT B - B

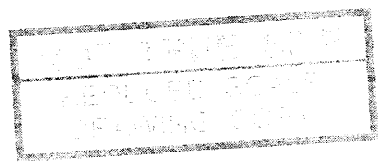


SECT C - C



DETAIL 1

SCALE 2:1



NOTE:  
ALL EDGES ROUNDED  
UNLESS OTHERWISE SPECIFIED

UNLESS OTHERWISE SPECIFIED:  
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0.0 ±0.01  
ALL SURFACES 1.6

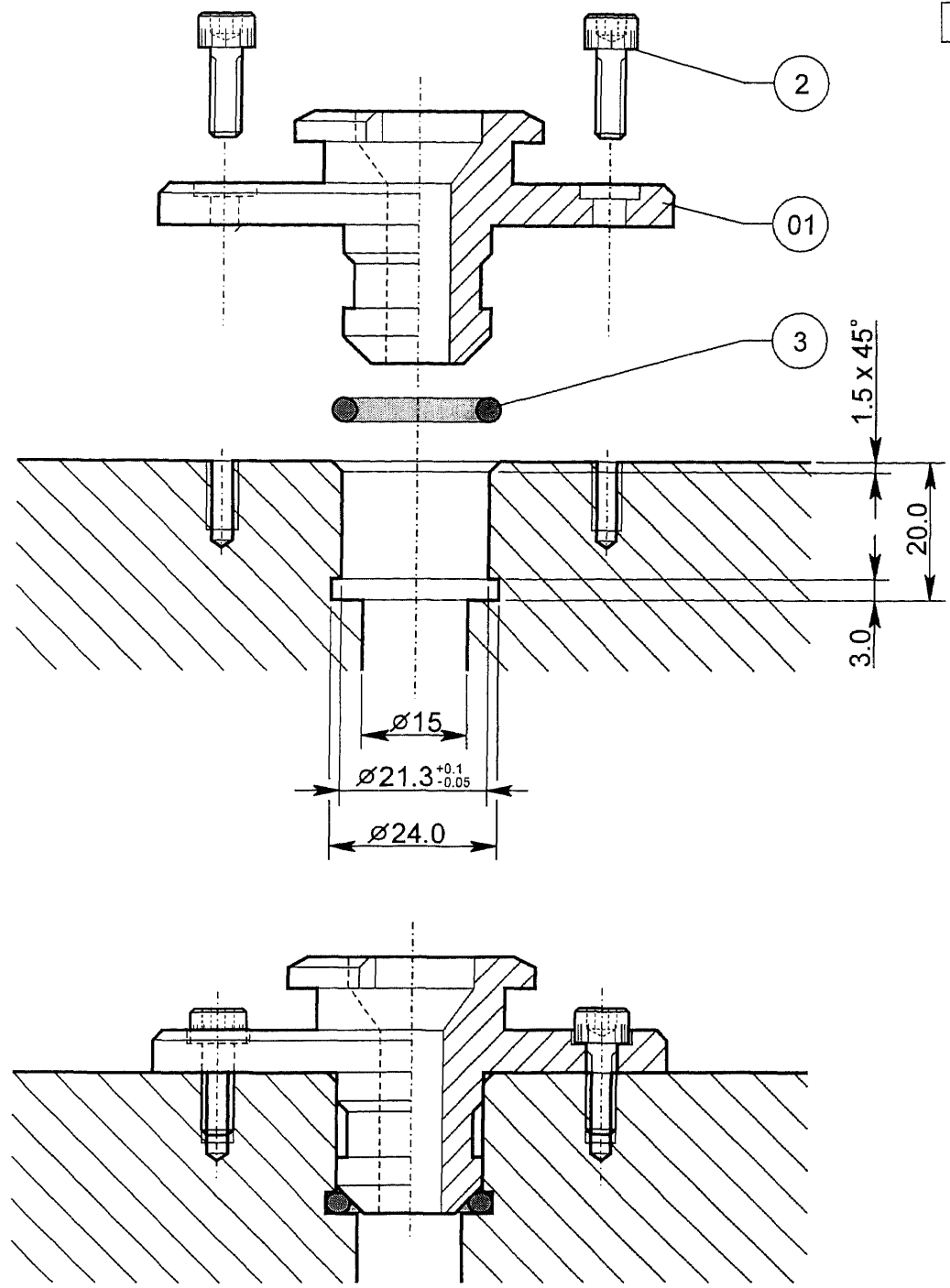
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METRIC UNITS  EUROPEAN VIEW PROJECTION		Drawing No: <b>RAMCOSS</b> B - 20 001	

D.136



U.S. Letter Size: 8 1/2 x 11 in

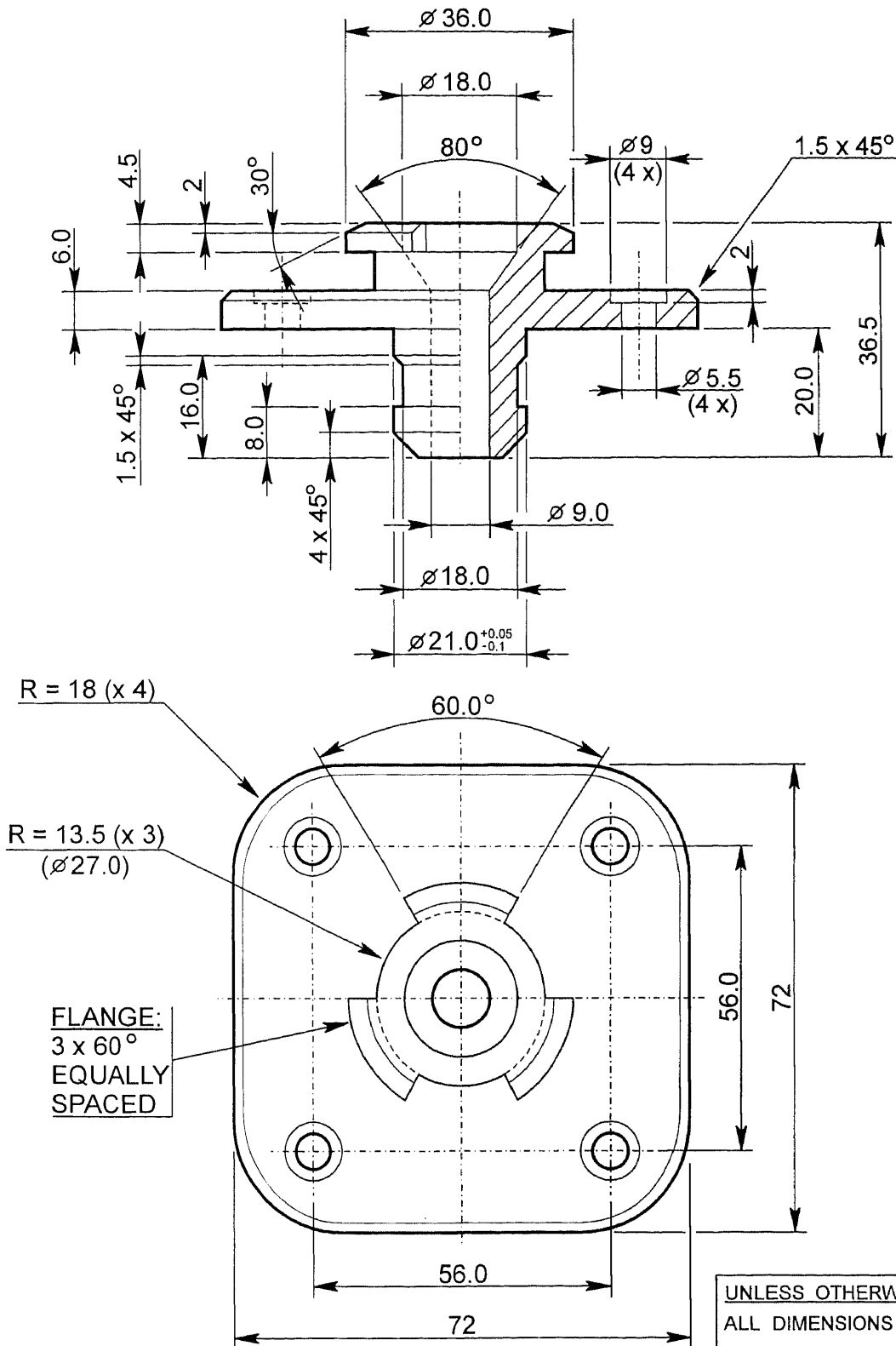
D.137



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	Date:	April 25, 1997			

Lars Johan Resare 1996

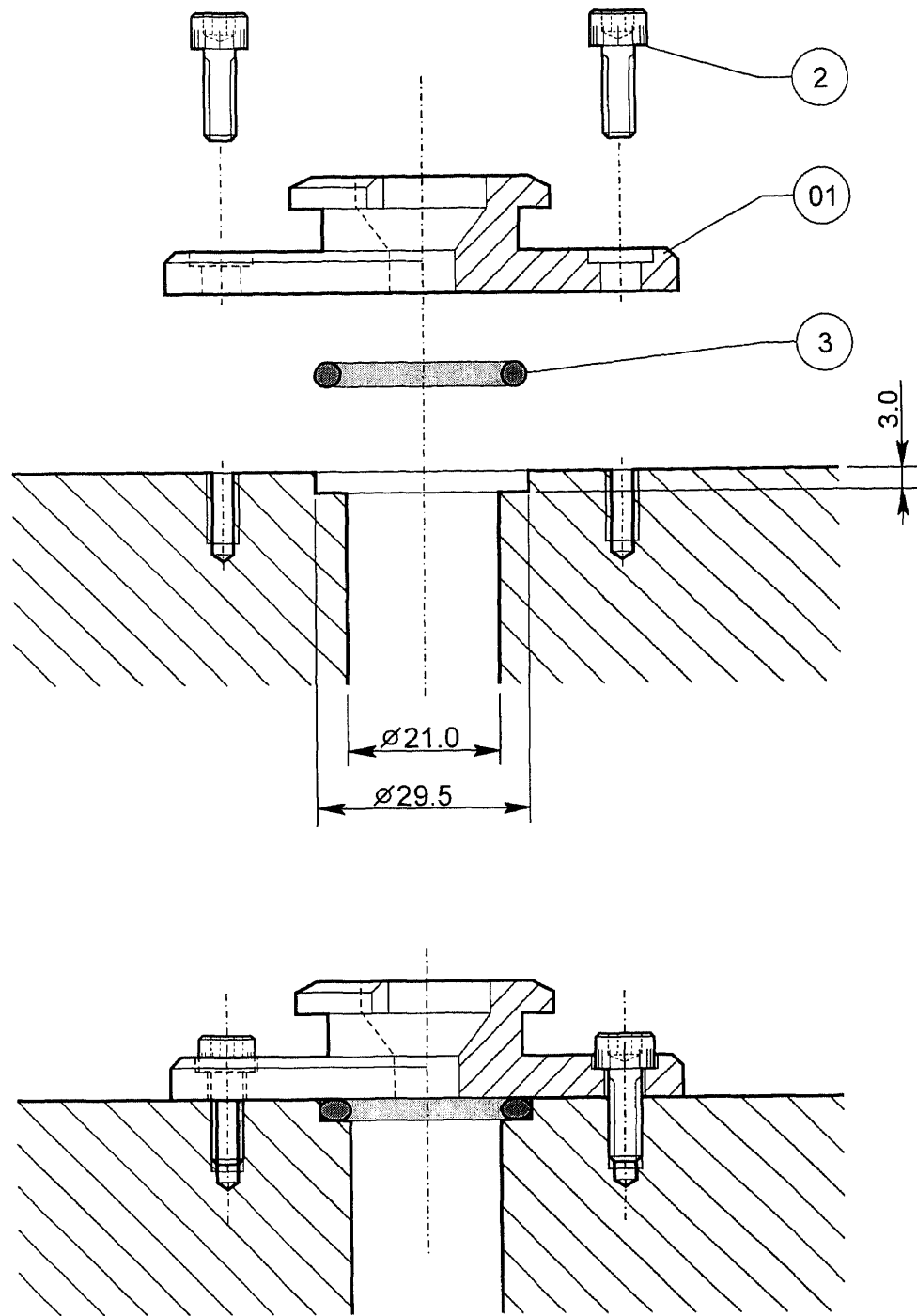


UNLESS OTHERWISE SPECIFIED:  
 ALL DIMENSIONS 0. ±0.1  
 0.0 ±0.01  
 ALL SURFACES 1.6/

ASSEMBLY DRAWING A - 30 101

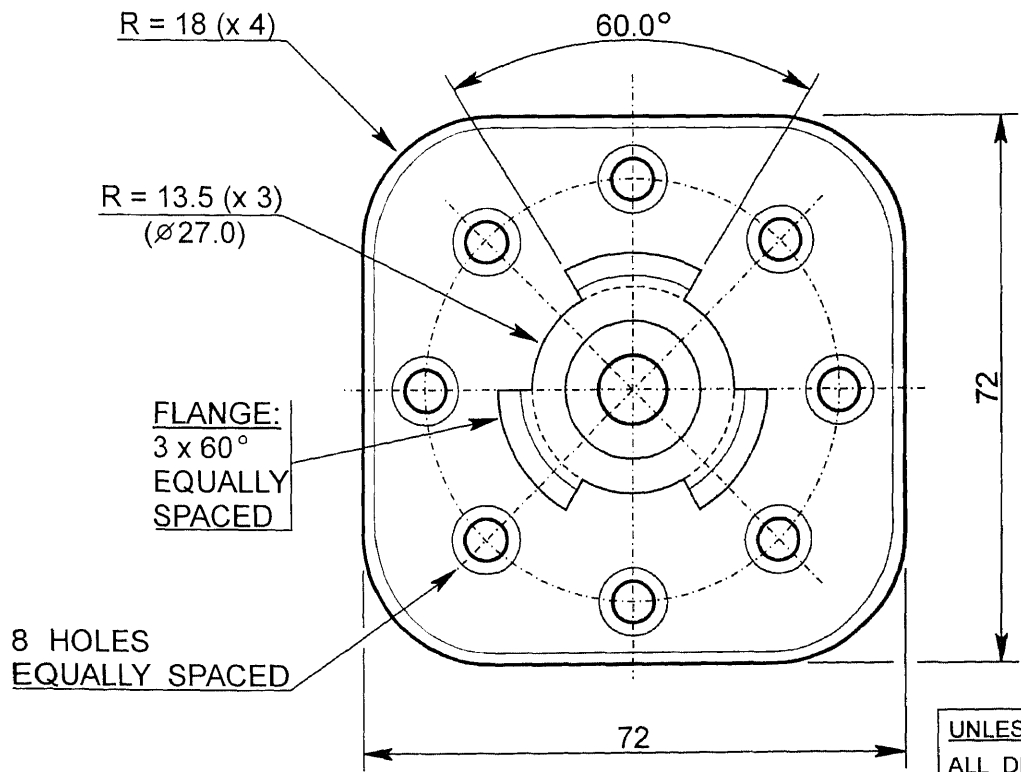
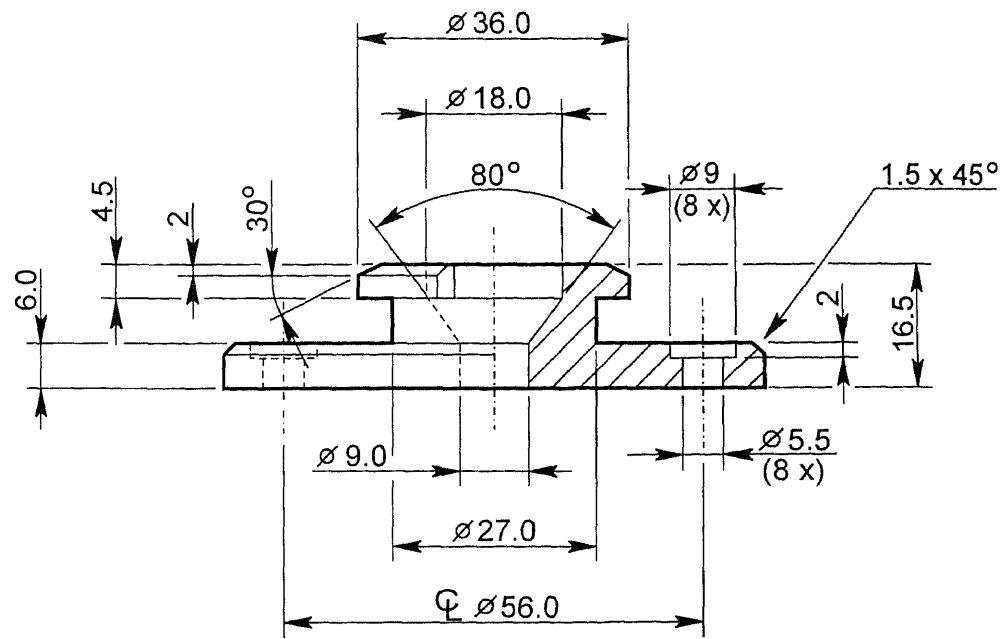
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	Drawing: Lars Johan Resare	Project Name: CASE STUDY No. 3
	Scale: 1:1	
	Date: April 25, 1997	



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2	8	M5 x 0.8 L=12, STAINLESS STEEL		
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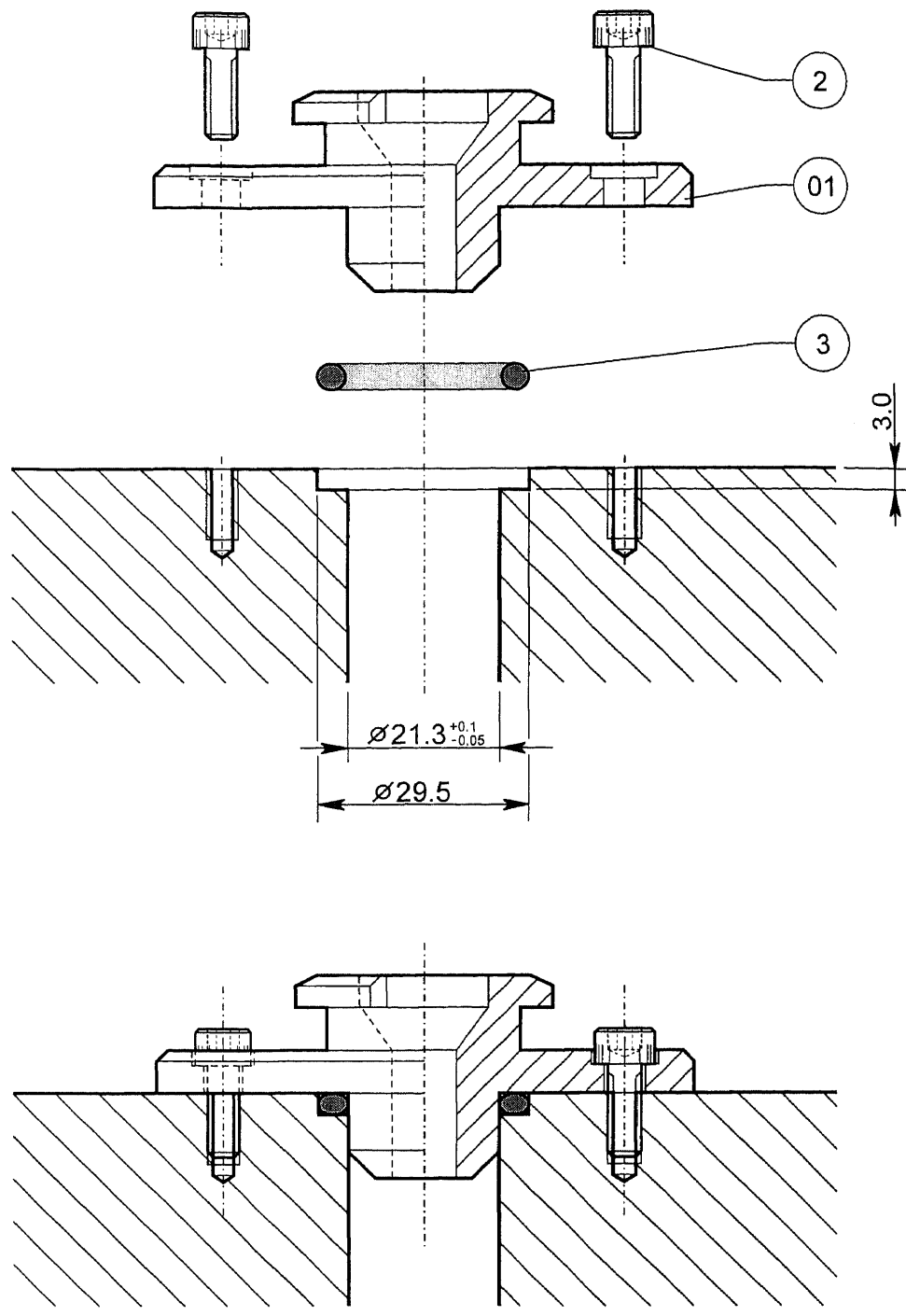


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 0.0 ±0.01  
 ALL SURFACES 1.6/√

ASSEMBLY DRAWING A - 30 201

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	Drawing:	Lars Johan Resare	Project Name:	CASE STUDY No. 3
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	Date:	May 1, 1997		
			Drawing No:	A - 30 202



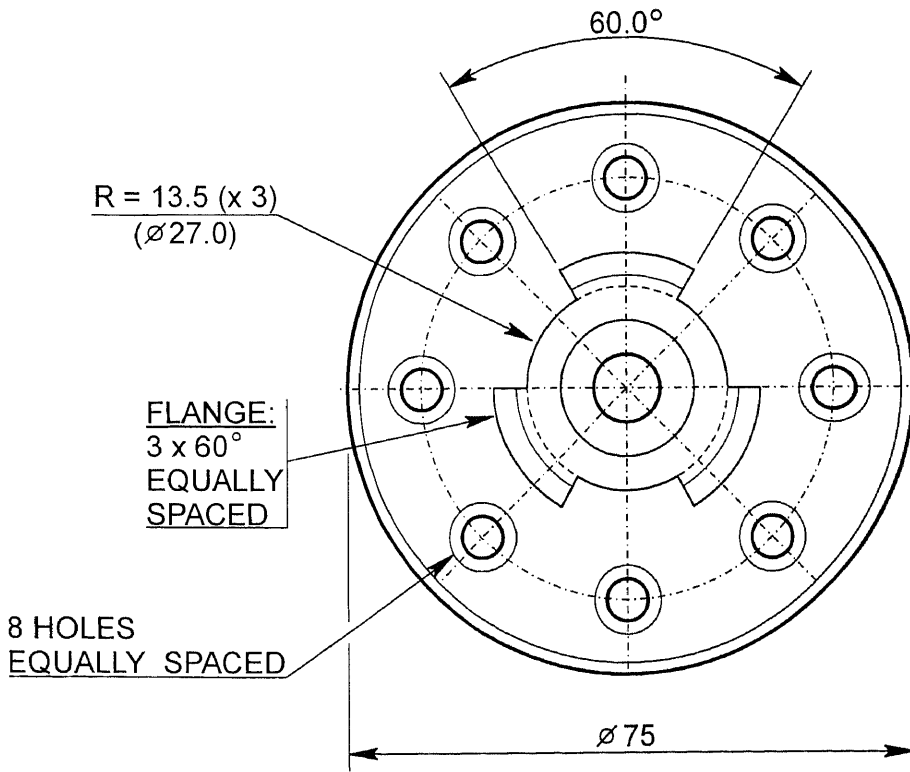
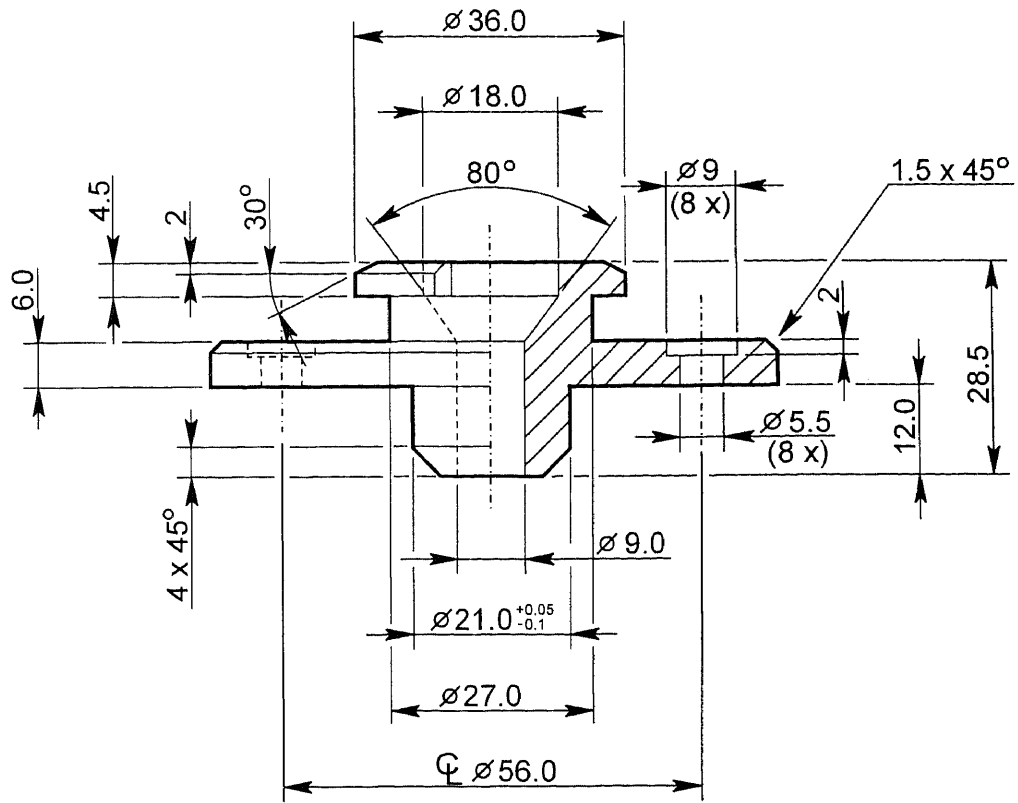
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METRIC UNITS

EUROPEAN VIEW PROJECTION

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Date:	May 3, 1997		





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 ALL SURFACES 1.6

ASSEMBLY DRAWING A - 30 301

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				<b>RAMCOSS</b>			

## REFERENCES

1. Abdel-Malek, L. L. and Boucher, T. O., "A Framework for the Economic Evaluation of Production System and Production Design Alternatives for Robotic Assembly" *International Journal of Production Research*, vol. 23, pp. 197-208, No. 1, 1985.
2. Abdel-Malek, L. L., "A Case Study on the Use of Robots in Assembly Processes" *Engineering Costs and Production Economics*, vol. 9, pp. 99-103, 1985.
3. Abdel-Malek, L. L., "A Framework for the Robotic Assembly of Parts with General Geometries" *International Journal of Production Research*, vol. 24, pp. 1025-1041, No. 5, 1986.
4. Abdel-Malek, L. L., "Robot's Economic Repeatability" *Engineering Costs and Production Economics*, vol. 12, pp. 93-97, 1987.
5. Abdel-Malek, L. L., "Assessment of the Economic Feasibility of Robotic Assembly while Conveyor Tracking (RACT)" *International Journal of Production Research*, vol. 27, pp. 1209-1224, No. 7, 1989.
6. Abdel-Malek, L. L. and Li, Z., "Robot Location for Minimum Cycle Time" *Engineering Costs and Production Economics*, vol. 17, pp. 29-34, February 1989.
7. Abdel-Malek, L. L., "Design for Automated Assembly of Circular Parts: An Algorithm" *International Journal of Production Economics*, vol. 41, pp.45-50, 1995.
8. Abdel-Malek, L. L., "Analytical Approach to Automated Assembly" *Engineering Design and Automation*, pp. 149-162, No 1(3), 1995.
9. Abdel-Malek, L. L. and Resare, L. J., "Analytically Based Algorithm for DFA of Polyhedron Shapes" Proceedings of the Twelfth International Conference on *CAD/CAM Robotics and Factories of the Future*, pp. 922-927, London, England, 1996.
10. Agrawal, V. P., Kohli, V., and Gupta, S., "Computer Aided Robot Selection: The 'Multiple Attribute Decision Making' Approach" *International Journal of Production Research*, vol. 29, pp. 1629-1644, No. 8, 1991.
11. Allen, A. O., *Probability, Statistics, and Queuing Theory With Computer Science Applications*, Academic Press Inc., NY, NY, 1978.
12. Asfahl, C. R., *Robots and Manufacturing Automation*, John Wiley & Sons, Inc., NY, 1992.

**REFERENCES**  
**(Continued)**

13. Beaulieu, A., Gharbi, A., and Ait-Kadi, "An Algorithm for Cell Formation and the Machine Selection Problems in the Design of a Cellular Manufacturing System" *International Journal of Production Research*, vol. 35, pp. 1857-1874, No. 7, 1997.
14. Boubekri, N., Sahoui, M., and Lakrib, C. "Development of an Expert System for Industrial Robot Selection" *Computers and Industrial Engineering*, vol. 20, pp. 119-127, No. 1, 1991.
15. Box, G. E. P., Hunter, W. G., and Stuart Hunter, J. *Statistics for Experimenters; An Introduction to Design, Data Analysis, and Model Building*, John Wiley & Sons, Inc. NY, 1978.
16. Doydum, C. and Perreira, N. D., "A Method for Selecting Dimensions, Tolerances and Precisions for Alignment" *International Journal of Production Research*, vol. 29, pp. 1035-1052, No. 5, 1991.
17. Elsayed, E. A. and Boucher T. O. *Analysis and Control of Production Systems*, Prentice Hall, Englewood Cliffs, NJ, second ed., 1994.
18. Groeneveld, R. A., *An Introduction to Probability and Statistics Using BASIC*. Marcel Dekker, Inc., NY, NY, 1979.
19. Groover, M. P. *Fundamentals of Modern Manufacturing; Materials, Processes, and Systems*, Prentice Hall, Englewood Cliffs, NJ, 1996.
20. Hoshizaki, J. and Bopp, E., *Robot Applications Design Manual*, John Wiley & Sons, Inc., NY, 1990.
21. Jones, M. S., Malmborg, C. J., and Agee, M. H., "Decision Support System Used for Robot Selection" *Industrial Engineering*, vol. 17, pp. 66-73, September 1985.
22. Khouja, M. and Offodile, O. F., "The Industrial Robot Selection Problem: Literature Review and Directions for Future Research" *Industrial Engineering Research & Development*, vol. 26, pp. 50-61, July 1994.
23. Kim, H. and Park, S., "A Strong Cutting Plane Algorithm for the Robotic Assembly Line Balancing Problem" *International Journal of Production Research*, vol. 33, pp. 2311-2323, No. 8, 1995.
24. McDermott, K. J. "An Industrial Data Base and Retrieval System" *Robot 8 Conference Proceedings*, Vol. 1, June 4-7, Detroit, Michigan, U.S.A., 1984.



**REFERENCES**  
**(Continued)**

25. Nnaji, B. O. "Evaluation Methodology for Performance and System Economics for Robotic Devices" *Computers and Industrial Engineering*, vol. 14, pp. 27-39, No. 1, 1988.
26. Nof, S. Y. *Handbook of Industrial Robotics*, John Wiley & Sons, NY, 1985.
27. Offodile, O. F., Lambert, B. K., and Dudek, R. A. "Development of a Computer Aided Robot Selection Procedure (CARSP)" *International Journal of Production Research*, vol. 25, pp. 1109-1121, No. 8, 1987.
28. Ostwald, P. F. and Blake, M. O., "Estimating cost Associated With Dimensional Tolerance" *Manufacturing Review*, pp. 277-282, No. 2(4), 1989.
29. Patel, S. A. and Kamrani, A. K., "Expert System Technology in Diagnosis and Maintenance" *Engineering Design and Automation*, pp. 163-186, No. 1(3), 1995.
30. Ranky, P. G., *Concurrent /Simultaneous Engineering*, CIMware Limited. Guildford, Surrey, England 1994.
31. Win, Z., Elmaraghy W. H., and Elmaraghy, H. A., "Evaluation of Cost-Tolerance Algorithms for Design Tolerance Analysis and Synthesis" *Manufacturing Review*, pp. 168-169, No. 1, 1988.
32. Zeid, I., *CAD/CAM Theory and Practice*, McGraw-Hill, Inc. New York, NY, 1991.