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Evaluation of coding and classification systems in the design of robotic grippers

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by

Jeoung Sung Cho

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I. INTRODUCTION

In the past, the introduction of industrial robots has commonly addressed only one task in the manufacturing environments. One gripper has been usually attached to the industrial robot to do one task in the manufacturing process. Unique tooling is usually fabricated to adapt the robot to the specific gripping task at hand. Often, a change in production design or model will require removal and/or replacement of the end effector in order to be compatible with the current operating configuration. Thus, a universal robot equipped with a special end effector becomes specialized and can work only with parts and objects of certain types and sizes. This limits the handling of the different part geometries that can be grasped.

Historically, the inability of commercial grippers to handle several part geometries has prompted users either to modify commercially available grippers physically to fit the task at hand, or to fabricate a gripper for a specific application. Both commercial and user-fabricated grippers still lack versatility. Another approach to improve the gripper's versatility is to use Quick-Tool-Changing (X-change) gripper. These devices are now commercial available and usually have four or more different grippers which are stored in a gripper magazine. Most efforts, in which the X-change grippers have been developed, have emphasized on the tool changing mechanism [36,76]. Little work has been done in the design of gripper to handle a wide variety of part geometries. Figure 1 shows the commercial available X-change gripper.

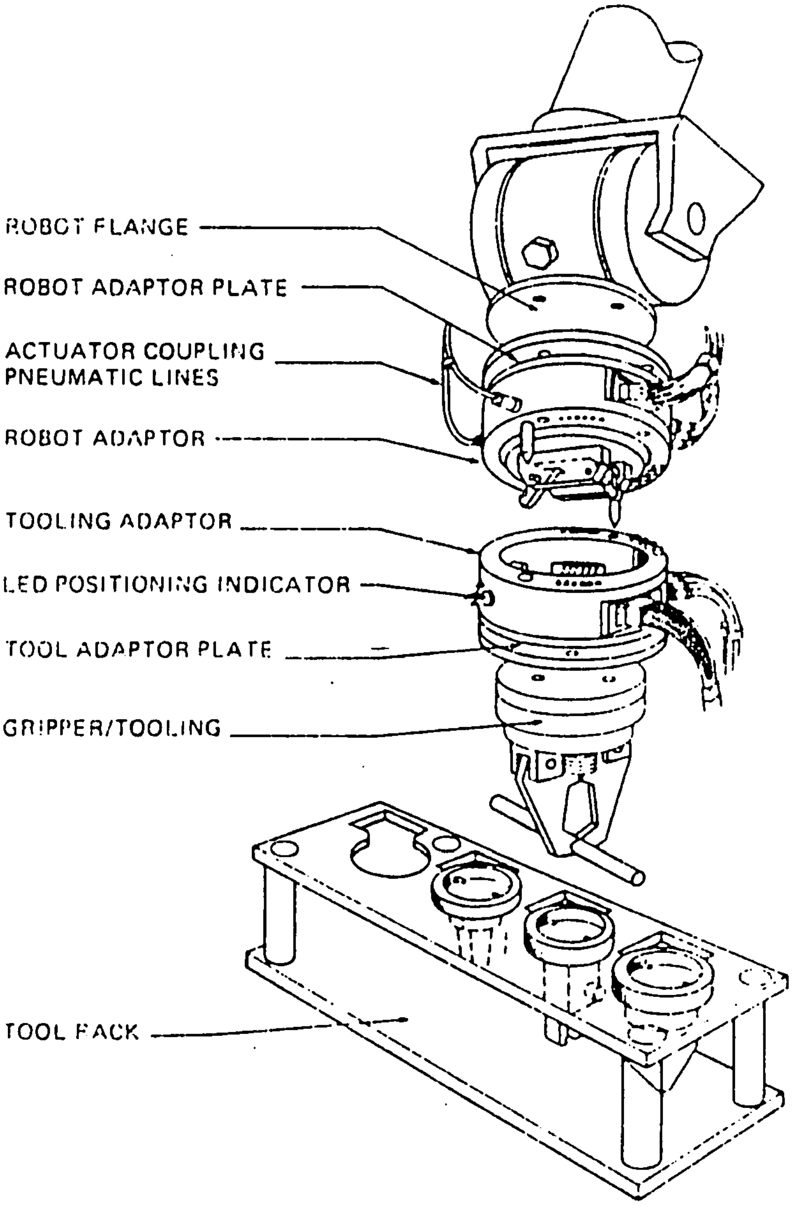


FIGURE 1. Quick-Tool-Changing gripper [24]

Mutter [41] has stated that even the most exotic robot with a substandard hand or end-effector can not be truly effective. The author suggests using families of parts in designing grippers. Group technology has been used as a technique for identifying and bringing together related or similar components in production process in order to take advantage of their geometric and process similarities.

In this study, four different coding and classification methods have been used to analyze and define sets of grippers. These methods include two different coding methods and two different classification methods. The coding methods include production flow analysis (PFA) and the Opitz system. The classification methods include rank order cluster analysis (ROCA) and cluster analysis with similarity coefficients (CASC). The following four methods have been used in this study to group parts into families.

- PFA/ROCA
- PFA/CASC
- OPITZ/ROCA
- OPITZ/CASC

The purpose of using each coding and classification system is to reduce the number of grippers required in each gripper set by taking advantage of geometrical similarities within a part family.

Chelpanov and Kolpashnikov have classified the grasping mechanism into the following elements [9]:

- Clamping or working element
- Elements for linking the clamping elements with the executive mechanism.

- Executive mechanism
- Transmission mechanism between the drive and the executive mechanism

The authors have also presented a detailed classification of clamping elements shown in Figure 2. In this study, the geometrical features and surface properties of the clamping element have been determined to handle a variety of part geometries.

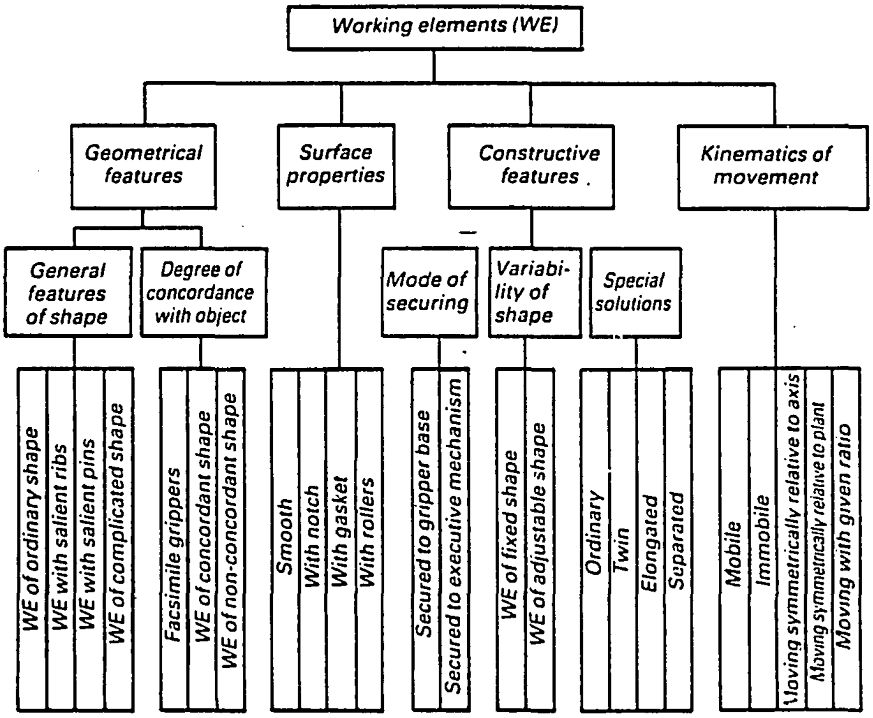


FIGURE 2. Classification of clamping elements [9]

This research has addressed three specific objectives which include the following:

- Determine what characteristics or features should be present in a gripper set contained in the X-change gripper magazine. The objective has been to define gripper characteristics to maximize the number of different part that can be grasped.
- Determine which coding and classification method is the best in terms of the maximum number of parts which can be successfully grasped.
- Determine what reasonable percentages of parts within a part family that a gripper set can grasp successfully.

II. LITERATURE REVIEW

A. Introduction

Industrial robots, commercially available for the past two decades, have been used in a variety of production applications. Industrial robots used for assembly are rapidly finding positions on manufacturers' shop floors throughout the world. As industrial robots are used more for assembly operations, grippers must be able to handle a greater variety of part shapes.

In the past, the introduction of robotics has commonly addressed a singular task in the assembly process. Most of robots in the U.S. are in the automotive industry, where they paint, spot weld, load machines, and perform other handling tasks. In most robotic applications, unique tooling is usually fabricated to adapt the robot to the specific gripping task at hand.

Grippers are often designed to suit the geometry and complexity of a particular component. Whenever possible, the gripper should include some flexibility so it can be used for handling and manipulating all the components being processed by the robot. Unfortunately, such a universal gripper does not presently exist, though it is possible that it will be available in the foreseeable future.

The designs that come closest to satisfying the ideal of universality are those for artificial hands designed specifically for robots. These usually have three fingers - thought to give virtually the same capability as the human's five fingers. At present these devices are more suited to experimental work than to the real world of industry and automated assembly processes.

Historically, the inability of commercial grippers to handle several part geometries has prompted users either to modify commercially available grippers physically to fit the task at hand, or to fabricate a gripper for a specific application. Thus, the design of versatile grippers in the automatic assembly is of paramount importance for a successful implementation of a industrial robot for an assembly process.

Much research has been done in recent years to develop versatile grippers. The following design aspects have been emphasized:

- Developing multi-degrees-of-freedom grippers based on the structure of a human hand.
- Developing a form-adaptable gripper.
- Developing a jaw profile to fit various part geometries.
- Developing quick-tool-changing grippers.

Until recently, little was known about the geometries of parts that could be successfully grasped with a general purpose gripper. Trivedi [69] investigated different techniques of classifying parts in a manufacturing setting. Many algorithms have been developed to group manufacturing components into part families.

Schafer and Malstrom [59,60,61] investigated the effectiveness of the two-finger, parallel-jaw gripper on a variety of geometric shapes using a miniature robot as manipulator. The authors found that a significant number of different part geometries could be grasped successfully with a single end effector.

In this chapter, the research efforts on developing the versatile grippers are reviewed first. Next, a form-adaptable gripper research efforts are summarized. Research on the design of gripper jaw profiles follows. Finally, Quick-Tool-Changing grippers are described.

B. Gripper Design

Grippers are either generally designed around a number of parameters (e.g., jaw opening and capacity) or specifically designed to handle one component and/or one task. In most applications of robotics in assembly processes today, a single gripper is used to perform a limited number of different tasks. This is because no universal grippers are available at present.

Much research has been done on developing universal grippers. In this section, these efforts are reviewed. The difficulties of implementing universal grippers in an assembly operation are discussed. As will be seen, only few of the investigations have utilized the component's geometry in the design of a universal gripper.

1. Special purpose grippers

Grippers form one of the most important parts of a robot. Without the gripper the robot would be incapable of carrying out its task. An ideal gripper is one that will completely emulate the human hand. The human hand has been a continuous subject of investigation to help design new versatile grippers. To date, it has not been possible to completely emulate the human hand. The design and selection of the gripper is very strongly application dependent. The shape, size and material of the component to be handled and the environment in which the grippers have to work vary for each application. Special purpose grippers have therefore been developed and built to match the requirements of each application. Typical special purpose grippers are shown in Figure 3.

A review of industrial robots performing assembly tasks reveals a large variety of gripper designs, most using two fingers. Each design is specific to the shape of the piece to be grasped by virtue of the form of the fingers.

2. Multi-degrees-of-freedom grippers

Advanced mechanical hands have been designed in recent years. These devices possess three or more articulated fingers capable of not only holding any irregularly shaped objects but also manipulating them. The idea of these devices was from the analysis of a human hand. The anthropometry of the human hand has been analyzed to form the design basis for versatile mechanical grippers.

Versatile mechanical hands exhibit the following characteristics [36]:

- Number of degrees of freedom: around 22
- Independent movements in the wrist: 6
- Types of sensors with interconnected subcontrol

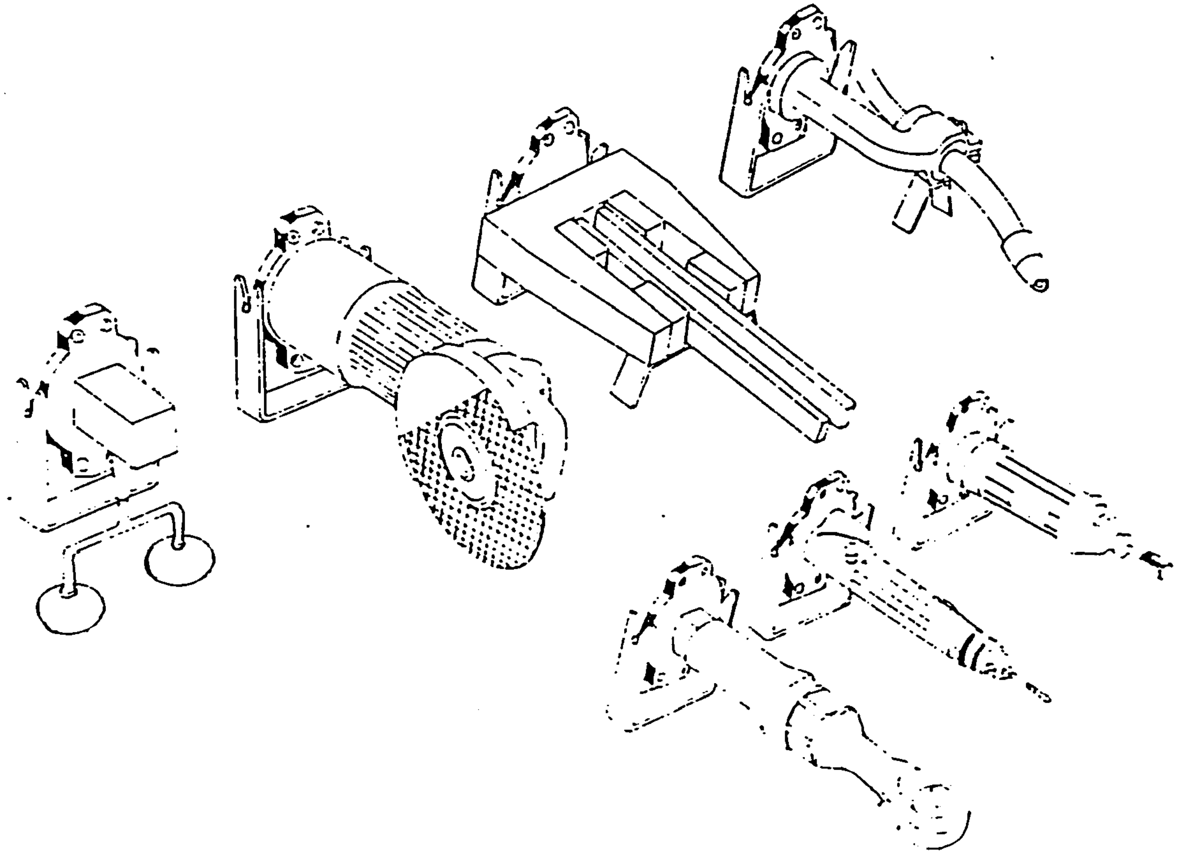


Figure 3. Some special purpose gripper [24]

systems: force, temperature, position, etc.

. Ways of gripping (external, internal, hooking, etc)

Because of the numerous degrees of freedom of a human hand, a human hand has many prehensile (gripping) modes. These have been described by Taylor and Schwarz [67]. The authors described six prehensile modes. These include the cylindrical, hook, lateral, palmar, spherical and tip modes. The authors also defined three mechanical equivalents corresponding to six prehensile modes of a human hand. The prehensile patterns and their mechanical equivalents are shown in Figure 4.

Bianchi and Rovetta [3] examined the mechanics of grasping irregularly shaped objects by a planal gripper consisting of two articulated fingers and a compliantly mounted palm. The prototype of the gripper is shown in Figure 5. In particular, the motion of the object relative to the fingers and the palm and the role of friction during the grasping process were studied by the authors.

Crossley and Umholtz proposed a three finger manipulator which was designed for remote control in space, with possible additional use as a prosthesis [14]. Based on the human hand, the device is capable of picking up an object and drawing it into a nested grip against a palm. It is capable of holding a pistol-like tool, such as an electric drill, and pulling the trigger at the same time.

Skinner [64] developed multiple prehension manipulator systems (MPMS). The objective of the research was to produce a highly versatile hand with a minimum number of moving parts, a dependable drive system, and an optimum number of degrees-of-freedom.

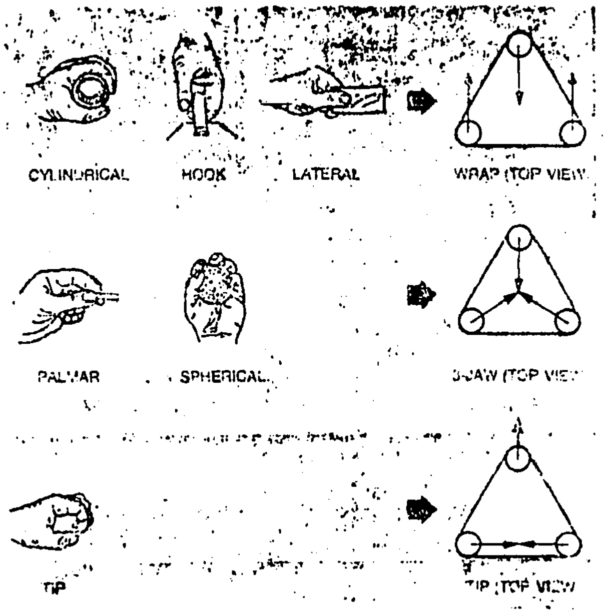


FIGURE 4. Six prehensile patterns and their mechanical equivalents [69]

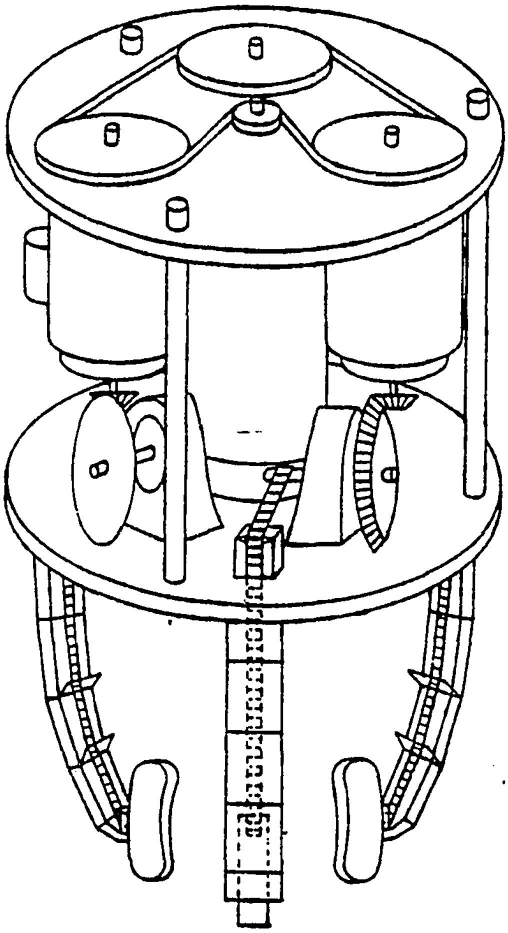


FIGURE 5. Schematic illustration of the planal gripper [3]

The author defined the optimum of the number of degrees-of-freedom as follows:

> The number of degrees-of-freedom is considered optimum when it is estimated that the manipulator can grasp all of the basic geometrical shapes from any aspect with the minimum number of external control inputs.

The author defined those basic shapes as rectangular and triangular prisms, spheres, and cylinders. The author considered the six basic prehensile patterns, shown in Figure 4, selected by Taylor and Schwarz [67] as an MPMS design objective. The author viewed that if a mechanical hand could achieve those patterns (lateral, hook, tip, palmar, spherical, and cylindrical) the hand would be nearly as adaptable to shapes as the human hand.

The author stated the following basic assumptions to design a hand for MPMS.

- The hand should be an assembly of motors and mechanisms, called fingers, intended for prehension.
- The fingers should have one or more bending sections.
- Externally, a finger with its bending sections, referred to as links, should be resemble an open linkage.
- Each finger link should be a component of a closed linkage which can "drive" or rotate the link.
- Fingers should not translate but should be mechanically identical and substantially attached to the hand's base.
- Three fingers were considered necessary and sufficient in the construction of the hand and these should be able to approach, contact, or pass one another during prehensile operation.

- The hand should contain all its motors, either in the base or finger units.

- The hand was considered to be an isolated unit, not subject to adjustment by external mechanisms.

- The hand would be mounted on a wrist having six degrees-of-freedom.

The author developed two prototype hands, the NASA Skylab MPMS Hand and the Industrial Robot MPMS Hand. The author made the following conclusions:

- A hand built with four motors and four control inputs can approximate the prehensile modes of the human hand.

- Rotating fingers with revolute joints are preferable to universal-special jointed fingers.

- Cross four-bar chains are the simplest and most reliable finger-driving mechanisms that meet the objectives of the project.

- Spread prehension is a desirable capability of a mechanical hand.

- A finger-turning mechanism that rotates two fingers can achieve the prehensile modes three-jaw, wrap, spread, and tip.

- A "double-dwell" mechanism will turn three fingers through the prehensile modes of three-jaw, wrap, spread, and tip.

- When fingers are turned by a "double-dwell" mechanism, they only need to bend in one direction from their straightened position.

- Testing of the MPMS hand proves it will operate within the conventional robot loading criteria with versatile prehension capabilities.

Jacobsen et al. [25,26,27] developed a high-performance hand with tactile sensing. The hand is also approximately anthropomorphic, having three fingers and a thumb, all with four degrees of freedom and operated by 'tendons'. Although having fewer degrees of freedom would still enable the hand to function adequately, kinematic redundancy was deliberately introduced to maximize dexterity and minimize reliance on friction for stable grasping.

Okada [44,45,46] developed a gripper with three cable driven fingers, each possessing four degrees of freedom. The versatility of this device has been demonstrated in such tasks as picking up a nut, assembling it to a bolt, and then tightening it.

Salisbury and Roth [57] extended the work on the mechanics of gripping by Chelpanov and Kolpashnikov [9] and Bianchi and Rovetta [3]. The authors concentrated on the kinematic aspects of prehension and manipulation by articulated hands. The system comprising the hand and the gripped object was modeled as a multi-linkage with true joints (the hand's articulation) as well as pseudo ones (the contacts between hand and object). Six hundred linkage configurations incorporated hands with up to three digits. Each had no more than three articulations and was capable of touching the object in one of five ways. Connectivity analysis was applied to reduce this list of candidates to 39 potentially acceptable hand designs which could grasp a workpiece securely and also impart small motions to it. Unlike the devices presented in previous researches [25,46], the selected design was not anthropomorphic. It is consisted of three articulated three-degrees-of-freedom fingers gripping the workpiece via contact points located at the fingertips.

3. Grippers for odd-shaped components

This section reviews the research efforts which treat a difficult area of gripper technology. The gripping of irregularly shaped objects by what might be termed form-adaptable grippers is overviewed in this section.

Perovskii [49] has described a gripper with jaws in the form of rubber bags containing small spherical particles. Normally the particles are free to move relative to one another. When the jaws are pressed against the object to be gripped, the particles flow in a such way that the bags mold themselves to the shape of the object. Air is then evacuated from the bags, which causes the spherical particles to become more densely packed, and the jaws to solidify against the gripped object, providing a firm stable grasp.

Tella et al. [68] presented a vacuum operated gripper made up of a matrix of vacuum cups, each flexibly connected at the end of a rod. Each rod can slide in a block so as to allow the cup to conform to the surface being gripped. The authors pointed out that by monitoring the position of the rods, it is possible also to gain information on the three-dimensional geometry of the workpiece.

Schmidt [62] developed flexible molding jaws for grippers. The devices reported in the paper were a mechanical variation of Perovskii's gripper. Schmidt's emphasis centered on the creation of modular designs. Schmidt suggested three possible solutions to the problem of flexible grippers which have been developed at the Institut fur Produktionstechnik und Automatisierung (IPA), Stuttgart. Schmidt concluded that the three solutions can be used for many different gripping tasks, but they are only a part of the possible gripping problem solutions.

Scott [63] invented the 'OMNIGRIPPER', a form of universal gripper. The gripper consisted of an array of 8 X 16 closely space pins which can ride vertically up and down independently of each other. Scott's device, as shown in Figure 6, is a mechanical variation of Tella's gripper.

Scott mounted the Omnigripper on a Unimation Puma model 560 robot. Experiments with the Omnigripper were made to decide whether the gripper could handle various part geometries. The experiments showed that the Omnigripper was capable of consistently picking up a very wide range of objects. These included cubic, cylindrical and triangular shapes of varying sizes. One major drawback of this gripper is that sophisticated control devices as shown in Figure 7, are required for its operation.

Vassura and Nerozzi [71] investigated the problems connected with gripping components of a generic shape and nature while handling them during the course of industrial processes. The authors presented a gripper with 20 fingers. Each finger was a rod capable of pivoting about one of four parallel axes. Figure 8 shows the handling of various generic shapes with the gripper. Having a large number of fingers ensured that the objects to be gripped are touched at several

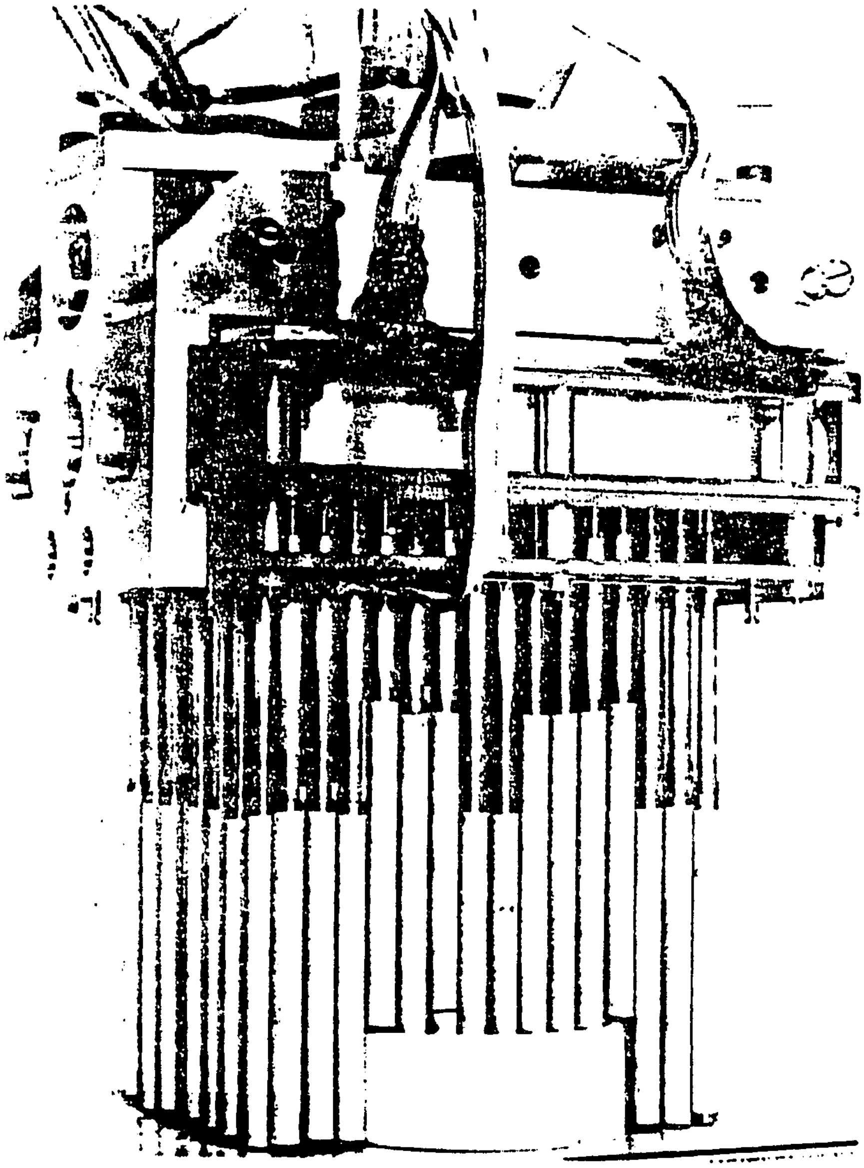


FIGURE 6. The Omnigripper [63]

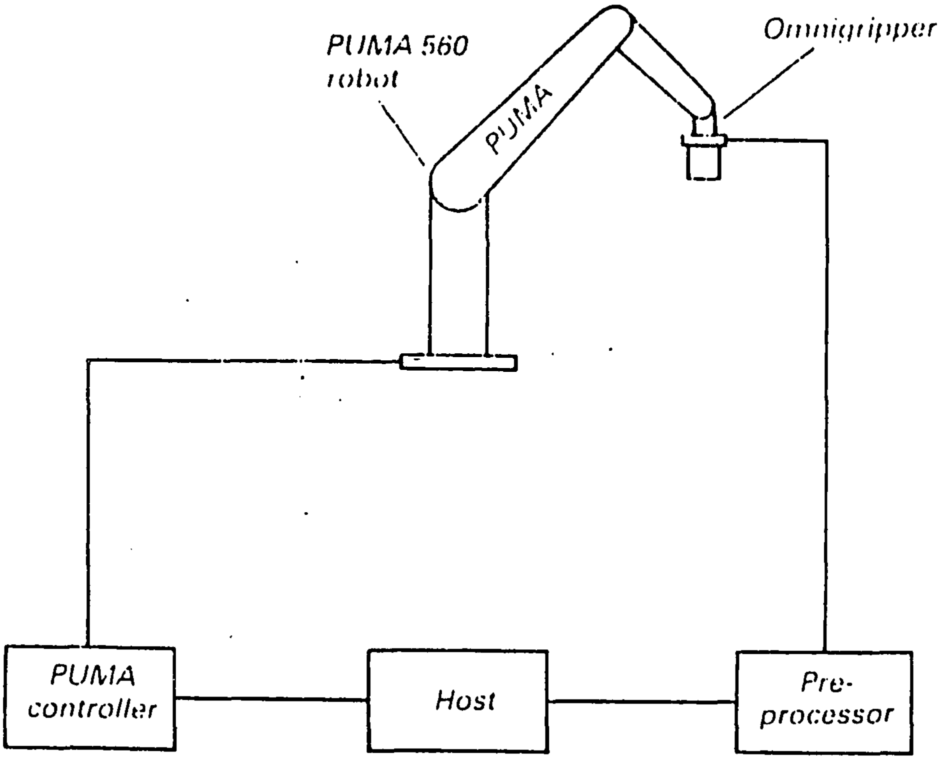


FIGURE 7. Main hardware elements of system [63]

locations. The limits the contact pressure required at each location to ensure a good grasp.

C. Jaw Design

Arai and Asada [2] compared three types of jaw pairs: two circular shaped jaws, two V-shaped jaws, and a combination of a V-shaped jaws and flat jaws. Their analysis was for grippers where the jaw opening-and-closing action is similar to that of a pair of tongs or scissors. Schematic views of three types of hands are shown in Figure 9.

The criteria used in the comparison were the gripping forces which could be applied, the displacement imparted to circular workpieces when their diameters changed, and the sensitivity of the relative position of the workpieces and the jaws to the friction between them. The authors found that, on the whole, twin V-shaped jaws tend to have the best performance.

Pham and Yeo [50] described the design of jaws to handle cylindrical workpieces of different diameters concentrically. The jaws were quasi-parallel grippers which had circular jaw movements but maintained the orientation of the jaws. Examples of quasi-parallel grippers are shown in Figure 10.

Bracken [4] examined the practical aspects of designing grippers, particularly for assembly robots. A variety factors regarded as relevant to the designer were discussed in this research. These included the size of the part to be gripped, the geometry of the part

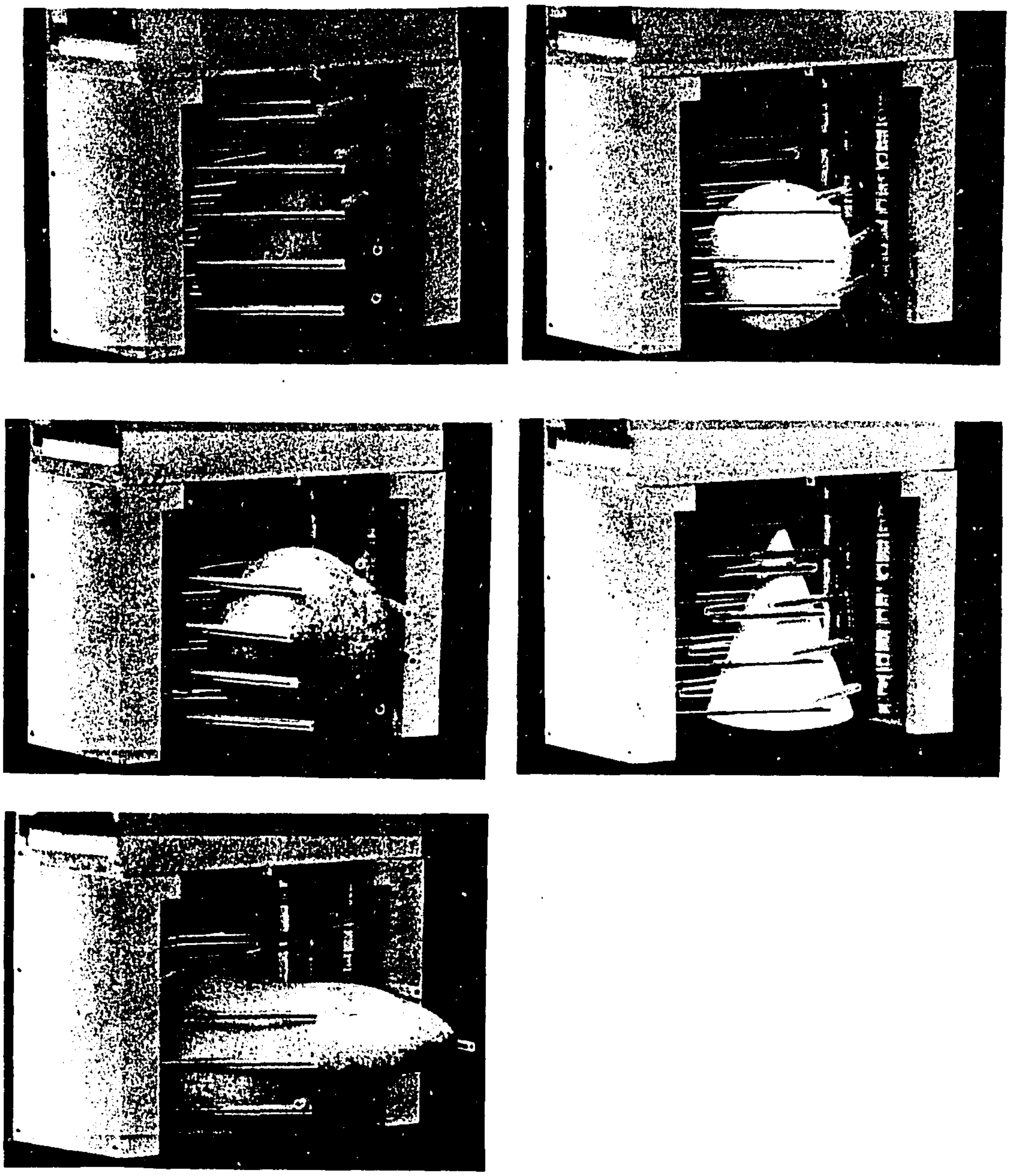
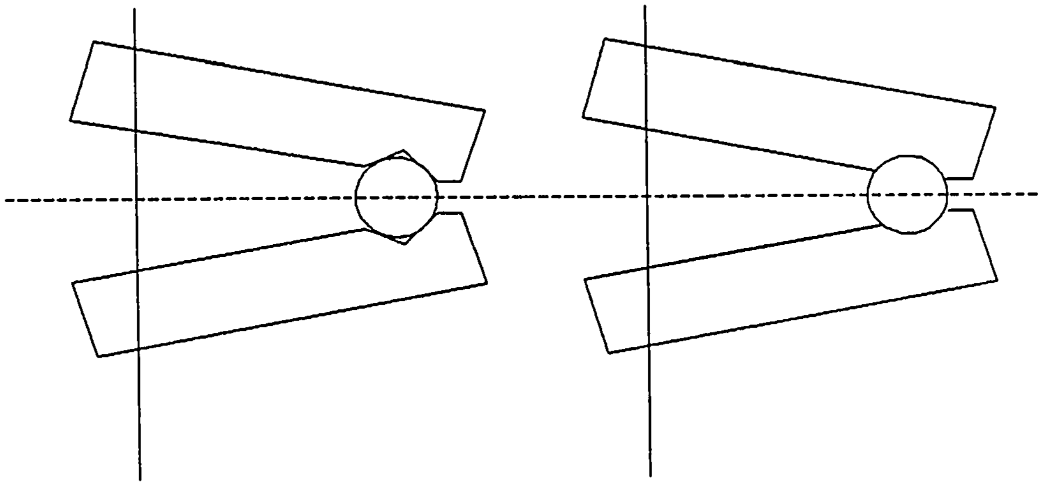
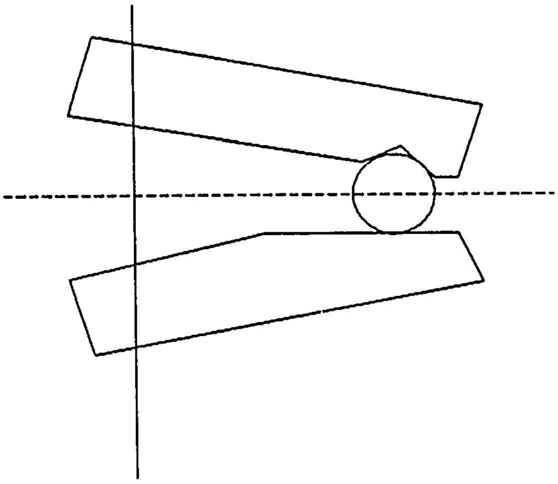


FIGURE 8. MIP2 gripper handling [71]



Twin V-shaped notch fingers   Twin semi-circular notch fingers



V-shaped notch finger and plane finger

FIGURE 9. Schematic view of three types of hands [2]

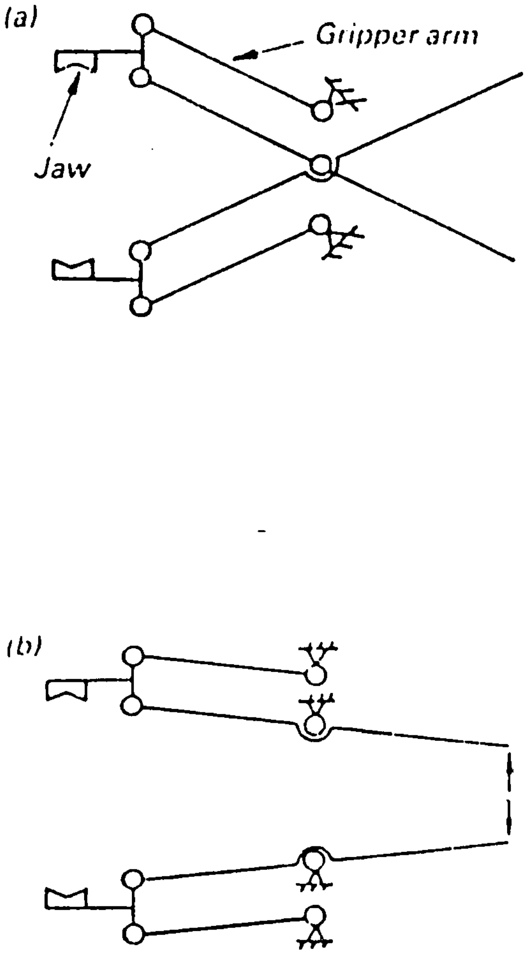


FIGURE 10. Example of quasi-parallel grippers [50]

surface presented to the gripper, the need for intermediate retaining devices or other assembly aids, and the possibility of interference with parts already assembled. An example was used to illustrate the design of a two-fingered gripper to handle a variety of parts. The approach proposed was to classify the parts into families and incorporate geometric features in the fingers appropriate for each family.

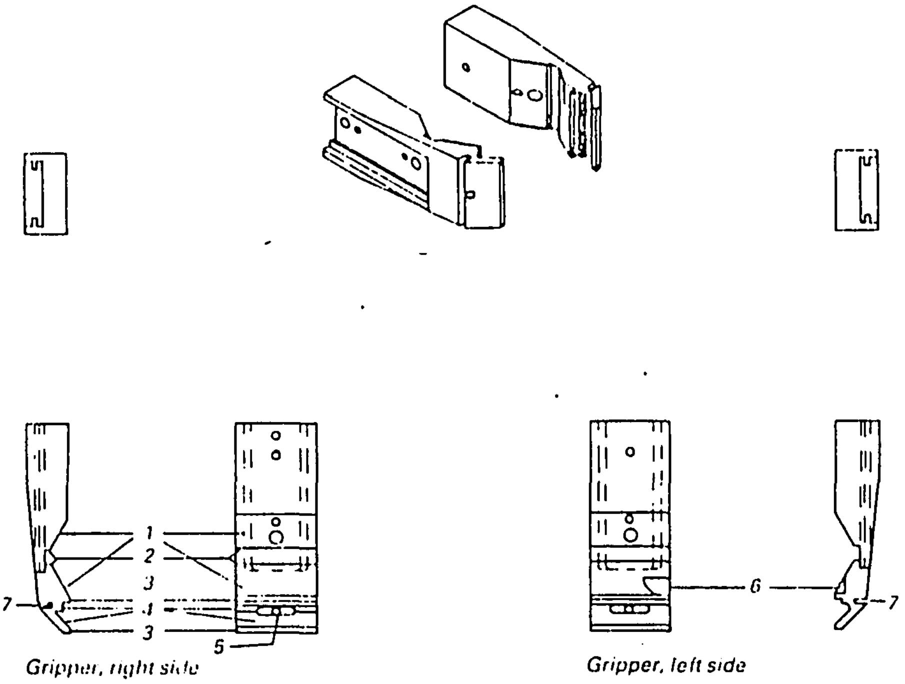
Bracken used a printing mechanism assembly as an example. The author classified printing mechanism components into the following five families:

- Cylindrical
- Rectangular
- Flexible
- Triangular
- Elliptical

Bracken defined the following five concerns the designer must take into account in the design of a gripper:

- The size of the part
- The surface contour presented to the gripper
- Determine if an assembly aid is required to hold a part in the assembly until it is secured by other parts or fasteners.
- The interference
- Choosing the right datum on the part for grasping and for insertion accuracy

Bracken designed seven features at the gripper as shown in Figure 11. The two fingered gripper with these seven features successfully assembled the printing mechanism.



Gripper, right side

Gripper, left side

FIGURE 11. The grippers designed by Bracken [4]

D. Interchangeable Grippers and Jaws

Consider a situation when a single gripper or one pair of jaws alone cannot handle a variety of parts and the robot is not sufficiently strong to carry multiple gripping devices. Under these conditions, a mechanism is required to enable the robot to change grippers or their jaws. A review of the design of gripper sets and jaw changers is the subject of this section.

Luo [37] described an automatic quick-change mechanism for jaws. The jaws were actively held on to the gripper base by airdriven locking pins. Provision was made in the jaw-gripper interface for sensors in the jaws to be electrically connected to the robot controller.

Vranish [72] developed automatically changing complete grippers. In addition to mechanical and electrical interfaces, there were also means for channelling fluid and fiber-optic signals from the robot to the gripper or vice-versa. To accommodate both pneumatically and hydraulically actuated grippers, air as well as oil could be supplied through the fluid channels provided. Since the system was designed for heavy-duty operation, special attention was devoted to the design of the cam and locking-pin assembly for securing the gripper to the robot wrist.

The gripper changers discussed by Rusterholtz [56] and Wright [75] were generally similar to the device developed by Vranish, except that they were designed only for light assembly tasks. Hence, the emphasis was on compactness, low weight and accuracy. There were no hydraulic lines as high grip strength was not required. Instead features were designed for connecting small vacuum pick-ups and electric servo-driven grippers. The mechanical coupling of these grippers to the robot wrist was achieved by pneumatic clamping in Rusterholtz's research and by combination of screwing and clutch engagement in Wright's work.

III. METHOD OF ANALYSIS

A. Introduction

Over the past decade or so, many batch production firms have been attempting to use group technology (GT) concepts in their organizations. The basic idea behind group technology is grouping together similar parts in families on the basis of such features as shape, size, material, tolerance, finish and required production operations. A part family formation provides the opportunity to take advantage of design and manufacturing process similarities.

Similar parts often use the same tooling, jigs, and gages in production. Without a classification system there is no easy way to identify what parts may be using the same equipment, so the equipment must be designed and produced for each part. When a classification system is implemented, parts using the same tooling, jigs, and gages can be quickly identified as they will be grouped together. Duplicates can then be eliminated. When new parts are designed, existing tooling, jigs, and gages can be identified and used rather than being designed and produced again.

In this research, four different methods of the part family formation were used to take advantage of part similarities in designing a gripper set. These four methods have been evaluated to find the best coding and classification system in terms of the number of parts that can be grasped successfully. The four methods are described in the following sections.

B. Methods of Part Family Formation

A part family can be described as a collection of related similar or identical parts. Generally, the parts in one part family will have similar geometrical shapes and/or require similar machining operations.

Generally, there are four different methods to use for forming part families. These include:

1. Peripatetic and ocular method
2. Production flow analysis method
3. Classification and coding
4. Mathematical programming method (cluster analysis, pattern recognition, fuzzy mathematics, etc.)

The ocular method is a manual operating method. The part families formed by this method depend on the knowledge and understanding of the parts and the manufacturing system. This method has limitations and has not been used in this analysis.

The production flow analysis (PFA) is one of the most popular methods for formation of part families and machine groups. It is concerned with the methods of production and does not consider the design features or geometries of the given parts.

The group technology classification and coding system can reflect the design and production information of a product in terms of code numbers. For instance, most coding systems are designed to reflect the component type, dimensions, shape features, auxiliary holes, material, processing methods, accuracy, etc. However, doing this in itself does not lead directly to the formation of part families.

The production flow analysis (PFA) and the Opitz system were adopted as a coding systems in this research. Two clustering algorithms were used. These include Rank Order Clustering Analysis (ROCA) and Cluster Analysis with Similarity Coefficient (CASC). Both clustering systems were combined with the two coding systems. The result was four different methods for grouping parts into families. Each method is described in the following sections.

C. Production Flow Analysis

1. Overview

The first of the coding methods to be used is production flow analysis (PFA). This method has been described by Burbidge [5,6]. The method has particular appeal in that it is relatively simple to implement and can be applied to the reorganization of existing as well as the design of new manufacturing systems. The method requires only the use of route sheets for identification of part families and corresponding groups of machines. The method usually consists of four stages. These four stages are briefly described in the following sections.

2. Outline of the PFA method

The PFA method involves the systematic analysis of route cards for all the parts made in manufacturing company. It is based on the assumption that there is family-group structure in all manufacturing organizations. The PFA method seeks to find the existing natural association between particular families, or lists of parts, and particular groups, or lists of machines.

The method uses a progressive form of analysis, with four main stages. Those four main stages can be summarized as follows:

Stage 1: Machines are classified by a number according to type, on the basis of operations that can be performed. Machines capable of performing similar operations are usually given the same type number. Specific characteristics of parts are considered when classifying these machines.

Stage 2: This stage involves extensive checking of the parts list and route card information to ensure the correctness of information on operations to be undertaken and the machines to be required.

Stage 3: The third stage is termed "factory flow analysis". It involves a macro-examination of parts flow through machines. This allows the problem to be organized into a number of major part-machine groups.

Stage 4: Finally, examination and sorting of the part-machine matrix are completed to form distinct groups of parts and machines.

Stage 1 involves classifying the machines by a number according to type, on the basis of the operations that can be performed. Machine capable of performing similar operations are usually classified with the same type number. The specific needs of parts for particular machines within the type are considered when allocating these machines to the groups which need them. Machines required for minor and ancillary operations are excluded from the analysis.

Stage 2 entails the extensive checking of the parts list and production route sheet information to identify and ensure correctness of the essential information for the analysis. The operations to be undertaken should to be checked for each part. The machine necessary to perform each of these operations should be also checked.

Stage 3, called factory flow analysis, involves a macro examination of the flow of parts through the machines. It allows the problem to be decomposed into a number of major-component groups.

Although the first three stages are essential to the process of the PFA method, the stages are merely necessary preliminaries for the provision of the data required. The ultimate purpose of the analysis is that of determining appropriate machine-part sub-groupings for a GT layout. This fourth and final stage is called group analysis. At this stage, a clustering algorithm is required to make part families. In the following section, the group analysis is described in detail.

3. Group analysis

The group analysis represents the identification method. This method uses the information contained on the process route sheets. For each part, the particular machines in the routing are identified. The sequence of operations and the frequency of a particular machine is not important. The data are arranged in matrix where,

$$b_{ij} = \begin{cases} 1 & \text{if part } i \text{ is processed on machine } j \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

where $i=1,2,\ldots.N$; N is the set of parts
$j=1,2,\ldots.M$; M is the set of machines

Part-machine group analysis problem may, in its simplest form, be expressed as that of making, by a process of row and column exchanges of the matrix B, a conversion from rough pattern of "1" entries into an arrangement whereby the "1" entries are contained in mutually exclusive groups arranged along the diagonal of the matrix. Figure 12 is an example of an initial part-machine matrix involving five machines (labeled 01 to 05) and six components (labeled 1 to 6). Figure 13 shows the same matrix after modification by selected row and column exchanges. It can be seen that although the original cell entries b_{ij} are unaffected by these exchanges, the result of this manipulation of the matrix has been to produce a division of the entries into two distinct part-machine groups.

In a simple case like this, it is not difficult to see intuitively what row and column exchanges are necessary to achieve the desired result. While an intuitive manual method may be adequate for small problems, this approach is progressively less manageable as larger problems are analyzed. The need for a more analytical method, particularly for large problems, is apparent.

Two methods, suitable for computer applications, will be considered to classify the parts in the data base into families. This will yield the first two of the four coding and classification schemes to be evaluated. Each classification method is described separately in the following sections.

$$\begin{array}{lll} & & \text{Parts} \\ & & \begin{array}{ccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{array} \\ \text{Machines} & \begin{array}{c} 01 \\ 02 \\ 03 \\ 04 \\ 05 \end{array} & \left[\begin{array}{ccccccc} 0 & 1 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 \end{array}\right] \end{array}$$

FIGURE 12. Example of initial part-machine matrix

$$\begin{array}{lll} & & \text{Parts} \\ & & \begin{array}{ccccccc} 1 & 3 & 7 & 2 & 4 & 6 & 5 \end{array} \\ \text{Machines} & \begin{array}{c} 03 \\ 02 \\ 05 \\ 01 \\ 04 \end{array} & \left[\begin{array}{ccccccc} 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 \end{array}\right] \end{array}$$

FIGURE 13. Example of final part-machine matrix

D. Opitz System Based Coding and Classification Method

1. Overview

Most systems for group technology have as their goal the establishment of part families whose manufacturing process sequences and requirements are similar. Such families may not have geometrical features that are similar enough to permit most of the parts within a family to be grasped by a single robotic gripper.

The third and fourth methods of coding and classification will rely on the analyses of part geometry as opposed to the production flow of the part. Parts in the data base will be coded on the basis of the presence or absence of certain geometric feature. For example, the coding might consist of separating cylindrical parts requiring rotational machining. Additional features of the cylindrical parts will include length to diameter ratios, holes, flat surfaces, and internal/external shape elements. Other features will address parts will flat surfaces, including parts with cubic/rectangular shape configurations. The Opitz system [47], shown in Figure 14, will be used to define the geometric features of parts that will be analyzed. The system was adopted because it is the best known system.

A binary system of coding will be developed on the basis of presence or absence of certain geometric features. Each part in the data base will be coded in this manner. The part will then be classified into families using both rank order classification analysis (ROCA) and cluster analysis using similarity coefficients (CASC).

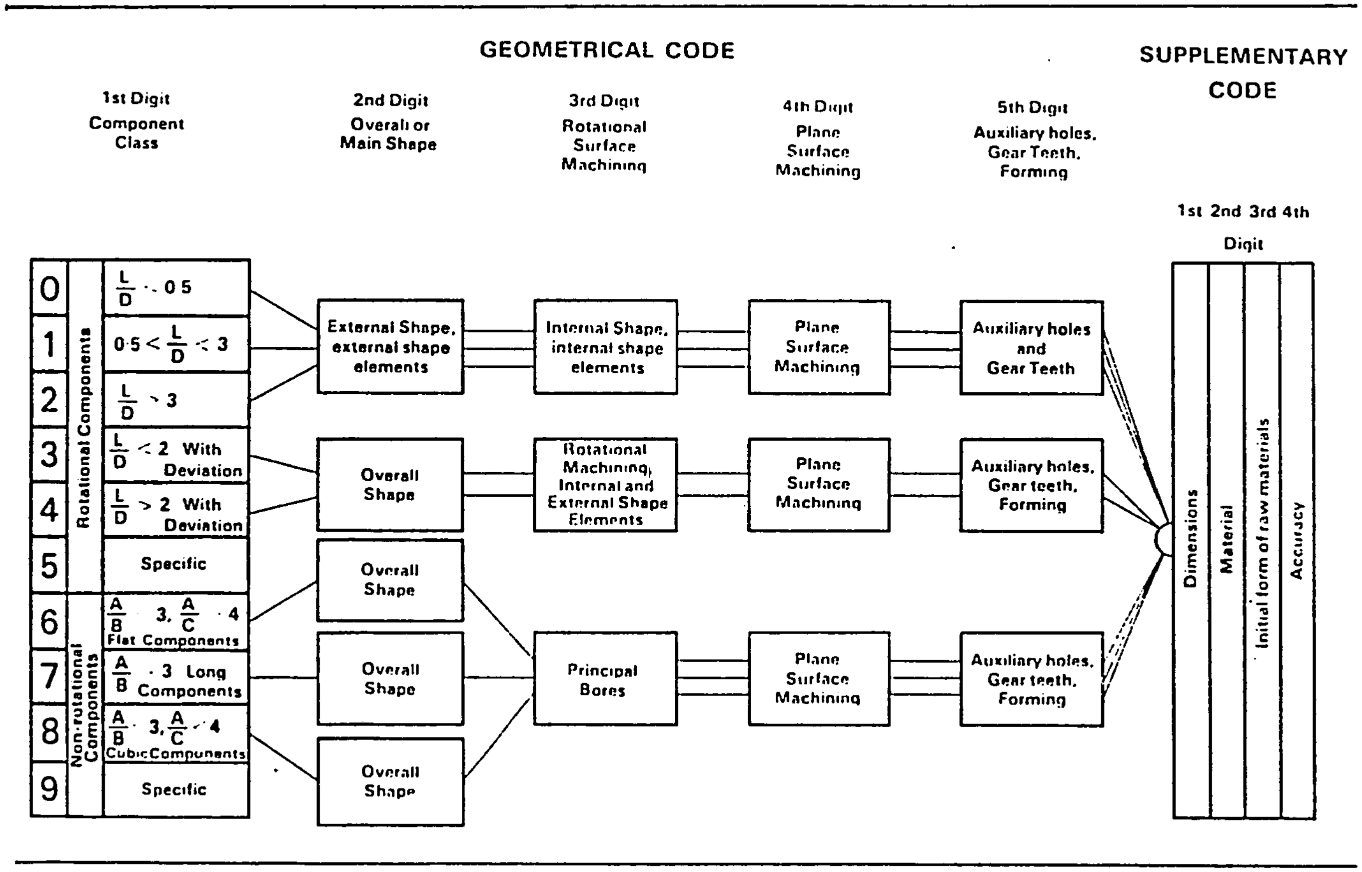


FIGURE 14. The Opitz coding and classification system

These combinations will be the third and fourth coding and classification systems to be studied. These classification methods will be explained later in this chapter.

2. Coding based on Opitz system

The Opitz system, as shown in Figure 14, uses nine digits to represent both geometrical and technological information of a part. The first five digits characterize the geometrical characteristics of a part. The remaining four digits show other supplementary information such as materials, dimension, initial forms and accuracy.

The coding and classification of the Opitz system is based on the geometrical features of a part. Thus, the component drawing must be referenced when a part is to be coded. The main shape, the shape as machined, the initial shape, the material, accuracy and the dimensions are representative of information that is coded.

Basically, the final shape of the part (the shape of the part after machining and before assembly) is represented by the geometrical code. The initial shape (the shape of the part before machining) is given separately in the supplementary code. The initial shape often shows the essential geometrical elements of the final shape and these are then used for the description of the main shape.

3. The use of the Opitz system

The initial arrangement of a component into one of the component classes depends on the dimensional ratios according to the overall shape of the part. The geometrical overall shape of a part is the least circumscribing cylinder or rectangular prism, oriented according to the axis of the main shape of the part.

The overall shape of rotational components, with and without deviations, is given by a cylinder with dimensional ratio of length L to diameter D. For rotational parts without deviations and rotational parts with deviations with only axis of rotation, it is the L/D ration of the cylinder whose geometrical axis coincides with the rotational axis of the part and that envelopes the finish-machined part being coded.

For rotational components with deviations and several axes of rotation, the L/D ratio is that of the longest rotational axis to the largest relevant diameter resulting from the rotation of the part.

Non-rotational parts are enclosed in the rectangular prism of least volume. This is described by the lengths of its edges A, B and C. In this description A > B > C. Figure 15 and Figure 16 show an examples of the coding using the Opitz system.

E. Rank Order Cluster Analysis

1. Overview

Two rank order cluster analyses (ROCA) have been suggested for use by King [29,30]. Both ROCA methods provide a simple, effective, and efficient analytical technique for defining groups of parts and machines. The methods are specially developed for computer

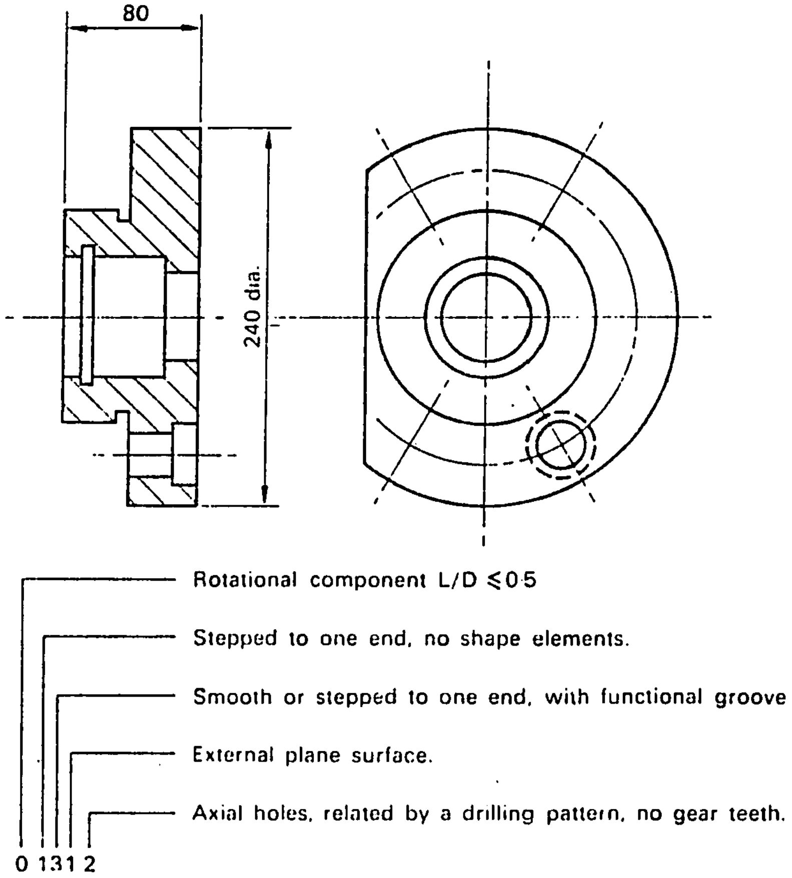
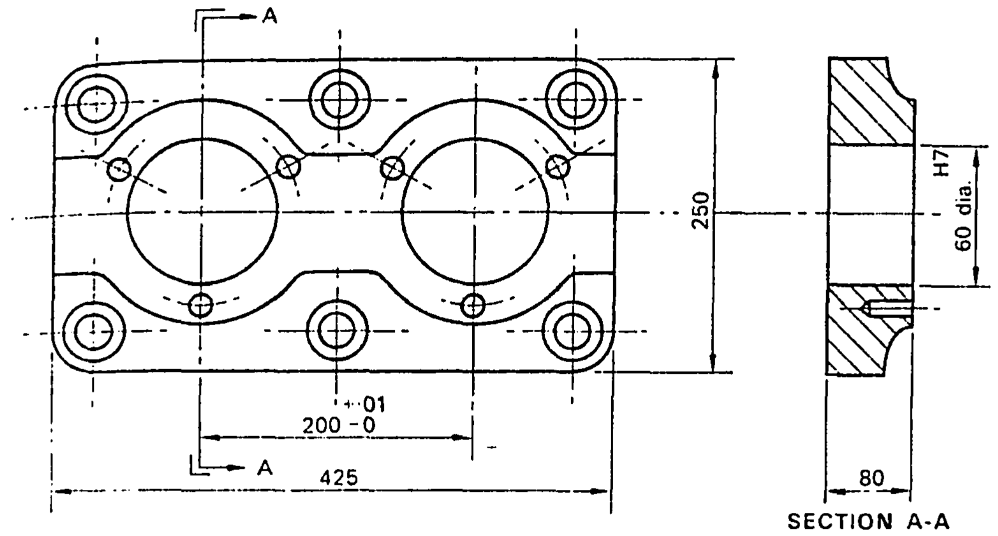


FIGURE 15. Illustration of coding of a rotational part with the Opitz system [47]



Non-rotational component, flat component
A/B ≤ 3, A/C > 4

Flat component, rectangular with small deviations due to casting, welding or forming.

Two principal bores, parallel.

Plane stepped surfaces, at right angles, inclined and/or opposite.

Holes related by a drilling pattern, drilled in one direction, no gear teeth, no forming.

6 5 4 4 3

FIGURE 16. Illustration of coding of a flat part with the Opitz system [47]

application. It is possible to use them with manual computation if required, particularly for smaller problems. The methods uses a part-machine matrix as input data.

In the first algorithm, every row or column pattern of unity or blank entries in the matrix is considered equivalent to a binary number with a corresponding unique decimal number equivalent form. The ROCA algorithm at its previous stage of development has a number of major limitations. First, the storage of a part-machine matrix as a two dimensional array places a severe limit on the size of the problem that can be addressed. A moderate problem with 50 machines and 2000 components, together with the program would require core storage in excess of 120 K bytes. Secondly, because the sorting procedure has a complexity of a cubic order, efficient implementation is not possible for very large problems. The first algorithm that reads the entries as binary words has some computational limitations. Since the largest integer representation in most computers is $2^{48}-1$ or less, the maximum number of rows or columns that can be dealt with this way would be 47. Thus, King [30] developed a new and more efficient version of the previously developed ROCA algorithm. In this research, the second algorithm developed by King was used because the data for the analysis are fairly large.

2. Algorithm

The ROCA algorithm generates a block diagonal structure if it exists. More commonly the elements in the matrix are such that they cannot be divided into mutually exclusive diagonal groups. The ROCA algorithm still generates a diagonal structure which contains one or more elements that do not conform to the block form. These elements are considered as exceptional elements comprising part-machine combinations that do not form part of the matrix represented by the remaining pure diagonal block.

The algorithm is based on a ranking process for rows and columns in a part-machine matrix. The matrix should have a "1" entry to indicate a process relationship for any given part and machine and a "0" entry for the absence of such a relationship.

The algorithm uses element by element comparisons for carrying out row or column ranking. The iteration continues until no further change in rank order is possible. By sorting with several rows or columns at the same time, instead of element by element, the efficiency of the sorting procedure can be improved. The whole sorting procedure is then reduced to that of shifting the order of rows and columns in the manner described by the following algorithm:

Step 1: For each row of the part-machine matrix, locate the the rows with entries and move the rows with entries to the head of the row list, maintaining the previous order of the entries.

Step 2: Are the current matrix row order and the rank order just decided the same?
If yes, stop. If not, goto step 3.

Step 3: Rearrange rows of the part-machine matrix according to the rank order just decided.

Step 4: For each column of the part-machine matrix, locate the columns with entries and move the columns with entries to the head of the column list, maintaining the previous order of the entries.

Step 5: Are the current matrix column order and the rank order just decided the same?
If yes, stop. If not, goto step 6.

Step 6: Re arrange of columns of the part-machine matrix according to the column rank just decided.
Goto step 1

Thus, ROCA rearranges rows and columns in a finite number of iterations, producing a matrix in which all rows and columns form diagonal groupings of the part-machine matrix entries. The algorithm would normally begin with the original part-machine matrix. However, the choice of initial matrix does not matter because the procedure is iterative. Finally, the ROCA is simply a ranking and not an optimizing procedure, as groups indicated by ROCA may not be optimal based on certain criteria of interest. Figure 17 shows the application of ROCA to a simple problem and the iterative steps involved.

F. Cluster Analysis with Similarity Coefficients

1. Overview

An alternative method of classification is more general and has been used by biologists to group plants into families on the basis of their geometric features [65,66]. This method examines the "degree of similarity" between all possible pairs of objects. The next step is to create groups of objects such that all pairs included in a group have a similarity greater than or equal to some specified level of similarity. It then successively lowers the level of admission by steps of predetermined equal magnitude. This indicates the need for an

MACHINES

PARTS	01	02	03	04	05	06	DECIMAL EQUIV.	RANK ORDER
1	0	0	1	0	1	0	10	5
2	0	1	1	0	0	0	24	4
3	1	0	0	1	0	0	36	2
4	0	1	1	0	1	0	26	3
5	1	0	0	1	0	1	37	1

MACHINES

PARTS	01	02	03	04	05	06
5	1	0	0	1	0	1
3	1	0	0	1	0	0
4	0	1	1	0	1	0
2	0	1	1	0	0	0
1	0	0	1	0	1	0
DECIMAL EQUIV.	24	6	7	24	15	16
RANK ORDER	1	5	4	2	6	3

MACHINES

PARTS	01	04	06	03	02	05
5	1	1	1	0	0	0
3	1	1	0	0	0	0
4	0	0	0	1	1	1
2	0	0	0	1	1	0
1	0	0	0	1	0	1
DECIMAL EQUIV.	24	24	16	7	6	5
RANK ORDER	1	2	3	4	5	6

FIGURE 17. Illustration of Rank Order Clustering algorithm

appropriate criterion of similarity. A measure called "similarity function" or "similarity coefficient" is widely used for this purpose.

2. The measure of similarity coefficients

Sneath and Sokal [65] Sokal and Sneath [66] define the similarity coefficient as "the quantification of resemblance between two objects". In a general sense, it is an "estimation of resemblance". This estimation begins with the collection of information about objects that are in the group to be studied. This information may already exist and merely require extraction from the literature, or it may have to be discovered, partly or entirely.

The actual computation of a similarity coefficient can be done in a number of ways, depending on availability of relevant information and acceptance of the criterion being used as sufficient and necessary to indicate similarity/dissimilarity. For PFA, relevant information in the form of part and machine attributes is available from the input data. Machines required to perform necessary operations on a part are said to be its attributes. Parts processed by a machine are identified as attributes for that machine.

Consider the illustration below. The "1" and "0" states for part I and part J represent 'presence' and 'absence' respectively. This is called the 2 X 2 frequency matrix. The entries shown in any two states for parts I and J are interpreted as follows:

a = number of machines visited by both parts I and J.
b = number of machines visited by part I but not by part J.
c = number of machines visited by part J but not by part I.
d = number of machines not visited by either part I or part J.

Using above notation, one measure of similarity between parts I and J is:

Similarity coefficient $(S) = a/n$ (2)

where $n = a + b + c$

This result is a fraction representing the degree of association between parts I and J (when number of machines visited is used as a criterion).

After calculating similarity coefficients, the next step is to store them in a matrix for future reference or use (for more than one pair of objects). Such a matrix is called the "similarity" or "resemblance" matrix. The matrix is square of the order t x t. It consists of $t(t - 1)/2$ entries, where t is the number of objects used in the study. The order of objects is the same in the rows as in the columns. The entries in the matrix are estimated of similarities (resemblances) for every object compared with every other object (except the entries in the principal diagonal, which represents an object compared with itself).

3. Clustering algorithm

For small problems it would be possible to search the similarity matrix and find clusters, by hand, directly for the values in the matrix. However, for large problems it is obvious that a method suitable for a computer application is required.

The method adopted in this research was based on the algorithm described by Gower and Ross [19]. This method makes use of the concept of Minimum Spanning Trees (MST). The author showed that all the information required for Single Linkage Cluster Analysis (SLCA) of a set of points is contained in the MST.

The SLCA method first clusters together those parts with the highest possible similarity coefficients. It then successively lowers the level of admission by steps of predetermined equal magnitude. The admission of a part, or group of parts, into another group is by the criterion of single linkage. This means that if a specified similarity level would admit a part into a cluster then a single linkage at that level with any member of that cluster would suffice to warrant admission. Similarly, any pair of parts in two different clusters will make their clusters join if all of pairs are related at the critical similarity level.

G. Summary

After the coding and classification procedures described in the preceding sections have been completed, four sets of part families will exist. Each set will correspond to one of the four coding and classification methods. The data base for this investigation has been collected from four different industrial organizations. By identifying similar machines and production processes, the four sets of production data will effectively be merged into one data base. It is on this data set the classifications and coding analyses previously described will be performed.

The first method of coding will be by production flow analysis (PFA). The coded parts will then be classified and grouped into families by Rank Order Analysis (ROCA) and Cluster Analysis using Similarity Coefficients (CASC). These analyses will yield the first and second sets of part families.

A second method of coding will be by the Opitz system. After coding, ROCA and CASC will again be used to classify parts into families. These analyses will yield the third and fourth sets of part families.

Altogether, 272 parts were involved in the analysis. It is necessary that all drawings of the parts to be coded be made available, because the codes are formed from the parts' characteristics. Thus, the data for the analysis and design of a robotic gripper consists of part drawings and manufacturing process sheets from four different manufacturing organizations. The descriptions of the data are presented in Chapter V.

Four methods of coding and classification were explained in the previous sections. These four methods can be used in manual analyses. In this study, computer software was developed to complete coding and classification procedures efficiently. The software is explained in detail in Chapter VI. Gripper design methods are the subject of the chapter that follows.

IV. DATA COLLECTION

A. Introduction

Production data for the proposed analysis was collected from three different manufacturing organizations: Fisher Controls Company of Marshalltown, Iowa, Rockwell Collins of Cedar Rapids, Iowa, Caterpillar Company of Peoria, Illinois and Colt Industries of Pine Bluff, Arkansas.

The parts were selected as a representative cross section of the production output from each of the three facilities. It is likely that most parts are not from the same consumer bill of material. In other words, no assembly relationship exists between most of the parts selected for analysis. Collected data consisted of production drawings, process routings, types of machines used at each routing operation, material, and any other information required to classify the parts into families by each of four different methods.

B. Part Drawings

1. Overview

The coding with the Opitz system is based on the taxonomy of parts. In order to code parts with this system, part shape information is required. This information is obtained from the part drawing. Each company provided the part drawing with a process routing for all parts analyzed. In the next section, geometrical and technical information contained in a part drawing is overviewed.

2. Use of the part drawing

In order to use the Opitz system in this research, geometrical and supplementary information of a part is needed. Geometrical information includes an overall shape, external shape and shape elements, internal shape and shape elements, plane surface machining, holes, and gear teeth. Such information can be extracted from the drawing itself. Supplementary information on the drawing includes dimensions, material type, and tolerance specifications. Such information usually appears on the drawing's title block and the process routing.

To derive the geometrical characteristics from a part drawing, design standards should be understood. Part drawings use standard symbols and abbreviations to help users read and understand them. The necessary geometrical information can be obtained from those standard abbreviations and symbols.

The views of drawings are also important in determining geometrical characteristics. The designer selects only the views necessary to adequately and correctly illustrate the assembly or detail. Usually, one or two views are sufficient, but three views are drawn whenever they make the drawing easier to read and understand. Most drawings collected for this research are classified as third-angle projection. When convenient, the details of parts are shown in the same position. This helps users to read the geometrical characteristics by which parts are coded.

The overall part shape was determined from a front view of the third angle projection. Other information necessary in the Opitz system was obtained by either inspection of the drawing and the symbols and abbreviations used.

Holes and gear teeth features are usually shown in a note pointing to the feature showing its shape. Hole dimensions include the following information:

1. Diameter of hole as a fraction, decimal-inch, or metric dimension with tolerance.
2. Operation(s) necessary to make the holes, such as drilling, boring, countersinking, counterboring, etc.
3. Depth of hole if it does not run through the material.
4. Number of holes with similar features.
5. The detail from which the hole is located if the hole is not located in the detail drawn.
6. For tapped holes, the number of threads and thread from designed immediately after the diameter of the hole.

The above information was used to code parts using fifth digit of the Opitz system.

Where the diameters of a number of concentric cylindrical features are specified, such diameters are dimensioned in a longitudinal view. The largest diameter was selected for use in coding the first digit of the Opitz system.

Manufacturing companies supplied drawings and process routings for this research used various arrangements and layouts for their title blocks. All title blocks typically included the following information:

1. Size and form tolerance in fractional, decimal, angular and metric values.

2. Drawing, approval, and issuing dates.
3. Material note.
4. Part number and description.
5. Order or machine number.
6. Company and department title.
7. Drawing number.
8. Revision block.

The information contained in the title block was used to code supplementary digits of the Opitz system.

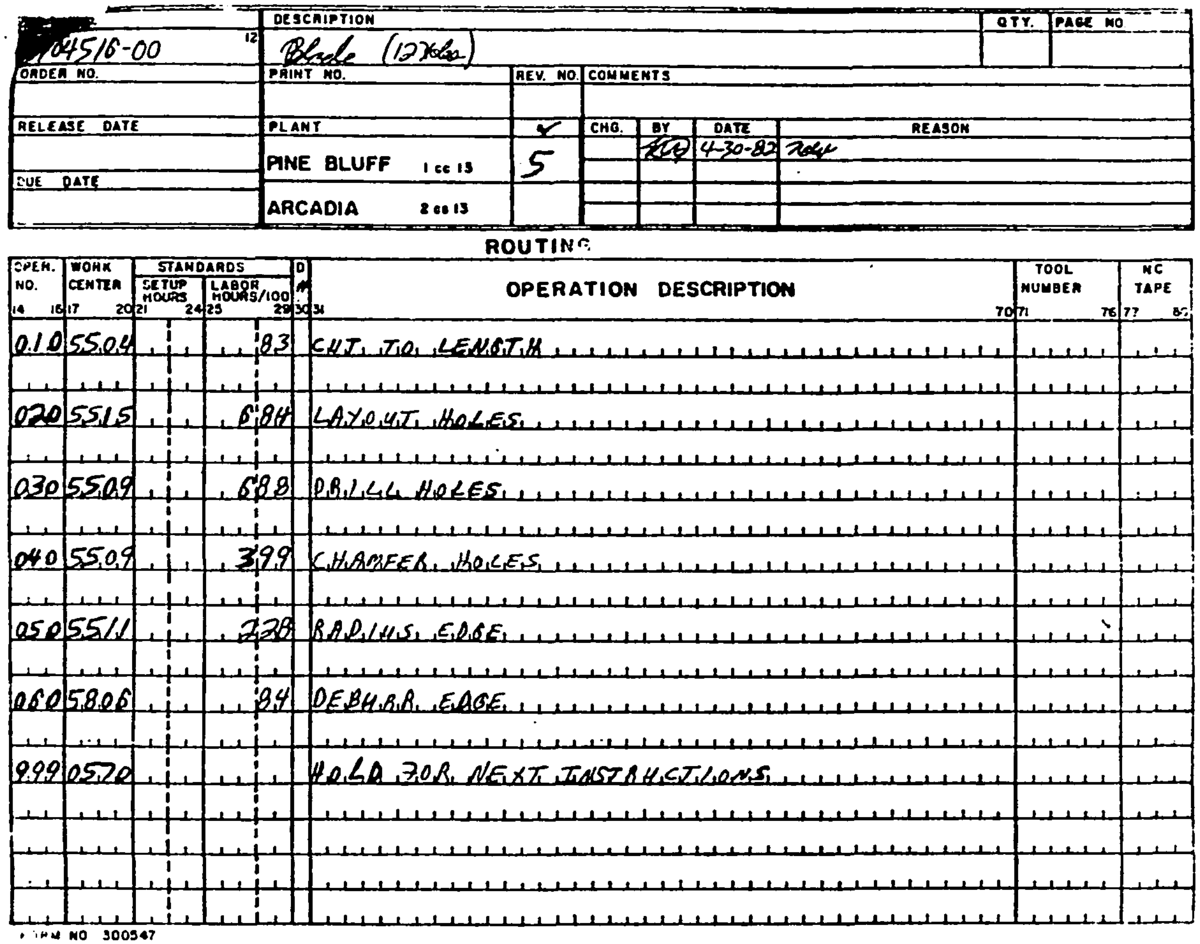
C. Process Route Sheets

1. Overview

The process routing supplies an input data for the PFA method. The process routing specifies the sequence of operations with which a part is produced. Each manufacturing company provided process routing sheets for all parts. In this section, how the process routing is used as an input data for the PFA method is explained.

2. Use of process routings

The process routings specify the sequence operations by which parts are manufactured. The process routing involves the division of processes into operations and the specification of machines on which the operations are completed. In the PFA analysis, the route sheet is only required to determine families of parts and groups of machines. A simple example of a route routing is illustrated in Figure 19.



[redacted]04516-00	12	DESCRIPTION Blade (12 Holes)	QTY.	PAGE NO
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DUE DATE		ARCADIA 2 cc 13		

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		4-30-82	Rdy

ROUTING

OPER. NO. 14 16	WORK CENTER 17 20	STANDARDS SETUP HOURS 21 24	STANDARDS LABOR HOURS/100 25 29	D # 30	OPERATION DESCRIPTION 31 70	TOOL NUMBER 71 76	NC TAPE 77 80
010	5504		83		CUT TO LENGTH		
020	5515		684		LAYOUT HOLES		
030	5509		688		DRILL HOLES		
040	5509		399		CHAMFER HOLES		
050	5511		228		RADIUS EDGE		
060	5806		84		DEBURR EDGE		
999	0570				HOLD FOR NEXT INSTRUCTIONS		

FORM NO 300547

FIGURE 19. Example of process routing

The process routing describes all the operations necessary to complete the steps of machining a particular part, in the order in which the steps must be completed. Also shown are the the work centers where the work is to be carried out.

The information needed for the PFA analysis is the sequence of machine centers. The processing requirements of the parts on the machines are specified by the incidence matrix representation. If there are two different operations on the same machine center, only the machine center is selected as entry to the incidence matrix. The method of generating the incidence matrix was discussed in detail in the PFA analysis of Chapter III.

D. Combining Data Sets

There are three different data sets which were from different manufacturing organizations. Each company use its own machine code. Thus, in order to apply the production flow analysis on these data sets, combining three sets was necessary.

In order to combine those data sets, the machines used in production of the parts were identified for each company data set. The machines used to manufacture the parts for each organization are shown in Tables 1, 2 and 3. It was determined whether there were machines which have same function among the three companies. Such machines were combined as one machine center. For example, all lathes were combined even if those machines were manufactured by different companies.

The new machine code was established which was applied to all data sets. A total of 38 machines was selected to represent the machines used in three manufacturing organizations. Table 4 shows the new machines and corresponding codes selected for this research. The process sequences were accordingly adjusted for all data according to new machine codes.

TABLE 1. Machine lists of Fisher Controls Corporation

No.	Machine Code	Description
1	0	
2	1	Furnace
3	2	
4	3	
5	12	
6	131	Gisholt 1L Turret Lathe - AC
7	133	Gisholt 2L Turret Lathe Masterline Saddle type
8	139	Gisholt 2L Turret Lathe
9	144	Gisholt #5 Turret Lathe-Chucker
10	176	J & L #5 Turret Lathe Ram Type
11	177	J & L #5 Turret Lathe Universal Ram Type
12	178	J & L #5 Turret Lathe Universal Ram Type
13	180	W & S 2A Turret Lathe
14	181	W & S 2A Turret Lathe
15	189	W & S 2A Turret Lathe
16	191	W & S #2 Bar
17	192	W & S #5 Turret Lathe-Chucker
18	193	W & S Turret Lathe-1 1/2" Bar Capacity
19	196	W & S Turret Lathe-AC
20	197	W & S Turret Lathe-2" Bar Capacity
21	231	Gisholt 12V Vertical Automatic Lathe
22	291	W & S 2AB Turret Lathe - Single Spindle Bar
23	293	W & S 2AC Turret Lathe - Single Spindle Chuck
24	294	W & S 1AC Turret Lathe- Automatic Chucker
25	295	W & S 4AC Turret Lathe - Chucker
26	297	W & S 2AC Turret Lathe - Single Spindle Chuck
27	298	W & S 3AB Turret Lathe - Single Spindle Bar
28	311	B & S #00 Ultramatic Screw Machine
29	314	B & S #2 Ultramatic Screw Machine
30	319	B & S #2 Automatic Screw Machine
31	320	B & S #00 Automatic Screw Machine
32	321	B & S #2 Automatic Screw Machine
33	322	B & S #2 Automatic Screw Machine
34	330	Citizen Cincom F12 Lathe
35	344	New Britten Multi-Spindle Lathe (From Mckinney)
36	348	
37	392	W & S 1 1/4" 6 Spindle Automatic-Bar
38	393	W & S 2 1/4" 5 Spindle Automatic-Bar
39	412	Avey #2 - 2 Spindle Drill
40	413	Avey MA-8 - 2 Spindle Drill
41	414	Avey #2MA-6 - 4 Spindle Drill
42	415	Avey #1BMA-4 - 6 Spindle Drill
43	416	Avey #2 - 8 Spindle Drill

TABLE 1 (continued)

No.	Machine Code	Description
44	421	Burgmaster 2BH Six Spindle Drill
45	422	Burgmaster 2BH Turret Drill
46	423	Burgmaster Econocenter T-330
47	426	Burgmaster 3BH Auto TD
48	429	Burgmaster Economaster VTC
49	431	Carlton Radial Drill 4'
50	432	Carlton Radial Drill 3'
51	434	Carlton Radial Drill 3A
52	438	Baker 18HU Horizontal Drill
53	442	Cincinnati 24" Bickford Drill
54	454	Snow DR-2 Drill
55	456	Powermatic 1200-217 Floor Drill
56	462	Natco G316 Multispindle Drill
57	463	
58	465	Natco G3b Multispindle Drill
59	466	Natco H6 Multispindle Drill
60	467	Natco F2B Multispindle Drill
61	468	Natco F58 Multispindle Drill
62	469	Natco F4B Multispindle Drill
63	521	Monarch Toolmakers Lathe-EE
64	528	Monarch 1610X30 Engine Lathe
65	536	Monarch 1610X30 Engine Lathe
66	550	Hardinge Superslant CNC Lathe
67	560	Churchill CTC4 Chucking & Bar Machine
68	561	Churchill CTC4 Chucking & Bar Machine
69	562	
70	635	K & T 307 S-12 Mill
71	636	K & T #3 D Milwaukee Mill
72	642	Nichols Twin Mill
73	722	Natco Model A-62 Hone
74	730	Hegenscheidt Roller Finisher
75	754	Greenard Arbor Press
76	755	Hannifin 25T Utility Press
77	762	Hartford Double End Tap
78	764	Davis & Thompson Shuttle Index
79	781	
80	784	Hardinge HSL-59 Speed Lathe
81	840	W & S 2SC Single Spindle
82	841	W & S SC-17 N/C Hexagon Turret Lathe
83	842	W & S SC-15 N/C 2 Slide Turret Lathe
84	846	
85	851	Toyoda Horizontal Machine-Center
86	860	L & S 1540 Chucking Lathe
87	862	L & S PT 40
88	864	L & S CNC 12/25 BC

TABLE 1 (continued)

No.	Machine Code	Description
89	866	L & S CNC 12/25 BC
90	903	Denison DM4-C64 Multi-press
91	912	Landis 1" Threading Machine
92	914	Pines End Finishing Machine
93	945	ALMCO DB-200 Deburr & Finish Machine
94	954	Gravitron Punch
95	959	ALMCO Spindle Deburr
96	966	
97	971	Electroless Nickel Line
98	972	Zinc Painting Line
99	973	
100	975	
101	4000	

TABLE 2. Machine lists of Rockwell International Company

No.	Machine Code	Description
1	300	
2	350	
3	370	
4	400	
5	500	
6	503	
7	600	
8	650	
9	700	
10	710	
11	720	
12	730	
13	800	
14	5100	Moore N/C - Jig Bore
15	5200	Moore Jig Borer
16	7400	DI-ARCO Power Brake
17	14102	
18	17104	Hammond Buffer
19	33200	Monarch Engine Lathe
20	33300	Monarch Engine Lathe
21	34200	Monarch T-Lathe
22	34206	Monarch T-Lathe
23	34300	W & S Turret Lathe
24	34400	J & L T-Lathe
25	35200	Lodge & Shipley N/C Lathe
26	37200	
27	37203	
28	38000	
29	39000	
30	39100	Bridgeport Universal Mill
31	39118	Gorton Universal Mill
32	39200	Van Norman Universal Mill
33	40300	
34	40401	
35	41800	Gorton Pantomill
36	42201	Bridgeport Machining Center
37	42401	Bridgeport N/C Vertical Mill
38	43300	Lindberg Heat Treat Oven
39	43600	
40	44100	Famco Arbor Press
41	47200	
42	48100	
43	48300	

TABLE 2 (continued)

No.	Machine Code	Description
44	49100	
45	50300	Leland Gifford Drill Press
46	53602	Ahmer Hole Locator
47	55121	Pratt & Whitney N/C Drill
48	56100	Whitney Jenseon Kick Press
49	57410	
50	58300	
51	58400	
52	58500	Version Punch-PS
53	59200	Behrens N/C Punch Press
54	60200	DI-ACRD Power Notcher
55	62100	
56	64400	Silk Screen
57	66200	
58	67100	6" Belt Sander
59	67301	6" Belt Sander
60	67501	9" Belt Sander
61	67503	16" Belt Sander
62	68100	Liquid Honer
63	68710	
64	69904	Deburring
65	71100	Tumbler
66	73100	Die Filer
67	75200	14" Band Saw
68	75300	
69	76300	Sheet Metal Saw
70	76308	
71	82200	Shear
72	82300	Power Shear
73	90420	
74	91199	
75	91400	
76	91410	
77	91420	
78	91421	
79	92100	Degreaser
80	93100	OXY-Ace. Welder
81	94000	
82	95900	Spot Welder

TABLE 3. Machine lists of Caterpillar Company

No.	Machine Code	Description
1	4832	
2	622782	De VLIEG 3H-48 Jigmill
3	623175	
4	626922	CIM-X 720 Pallet Shuttle
5	627583	Madison Rotary Grinder
6	660678	Hoefer Single Spindle Reamer
7	661191	
8	661192	
9	662726	Micromatic Hone #723
10	662794	
11	663137	Ex-Cell-O Boring Machine
12	663572	
13	663787	Carlton 4'11" Radial Drill
14	663794	Magnus Aja Lif
15	663952	Cin Duplex Mill 430-184
16	664113	Warner and Swasey Lathe 2AC
17	664223	Clausing Drill Press
18	664382	ICM Super Blast Honer
19	664832	
20	664834	ICM Superhone
21	665180	Dehoff Gun Reaming Machine
22	665291	Oloffson 2-Spindle Boring Machine
23	665952	W & S 2-SC Turret Lathe
24	665959	CIM-X 720
25	666017	CIM-X 720
26	666018	CIM-X 720
27	666086	CIM-X 720
28	666605	ICM Superhone
29	667031	Sidley Vertical Sizing Machine
30	667246	CIM-X 720
31	667301	
32	667592	CIM-X 720
33	667663	CIM-X 720
34	667793	Sherwood 6' Rotary Washer
35	667952	
36	667959	CIM-X 720
37	668065	Cinn Plain Mill
38	820024	
39	823838	
40	827042	
41	827438	
42	828450	

TABLE 4. New machine list and code

No.	Machine Code	Description
1	01	Bar machine
2	02	Bore
3	03	Buffer
4	04	Deburr
5	05	Die filler
6	06	Turret-Drill
7	07	Radial-Drill
8	08	Horizontal-Drill
9	09	Multispindle-Drill
10	10	Drill (include N/C drill)
11	11	Finisher
12	12	Furnace
13	13	Grinder
14	14	Honer
15	15	Index machine
16	16	Turret-Lathe
17	17	Engine-Lathe
18	18	Lathe
19	19	Multispindle-Lathe
20	20	Machine center
21	21	Mill
22	22	Notcher
23	23	Power Brake
24	24	Press
25	25	Reamer
26	26	Riveter
27	27	Sander
28	28	Saw
29	29	Screw machine
30	30	Shear
31	31	Silk screen
32	32	Sizing machine
33	33	Tap
34	34	Treading machine
35	35	Tumbler
36	36	Welder
37	37	Washing machine
38	38	Turning machine

V. GRIPPER DESIGN METHOD

A. Introduction

Many universal hands have been developed recently and include a gripper with multi-fingers, soft fingers and elastic fingers. However, these grippers are not suitable for assembly because of their slow movement, low reliability and marginal positioning accuracy [2]. Grippers with two fingers are the most popular in manufacturing industries because of their high reliability and good positioning accuracy. It has been estimated that from 60 to 70 % of all parts can be handled by two fingers. An additional 20 to 30 % can be handled by three fingers. Remaining parts require four or more fingers or other special types of grippers [4].

This research has dealt with the basic analysis of grippers from the viewpoints of geometry, statics and features necessary to handle the parts within classified families. Group technology has been used to form part families and derive the geometrical and dimensional information of each part family.

One goal of this investigation was to determine to what extent the defined part families can be grasped by Quick-Tool-Changing (X-change) robotic gripper sets. All four sets of part families are, by varying degrees, functions of part geometries. For example, one family or families might consist of parts with cylindrical geometries as shown in Figure 20. Other families might consist of sheet metal parts, parts that are milled, and those with other types of part geometries.

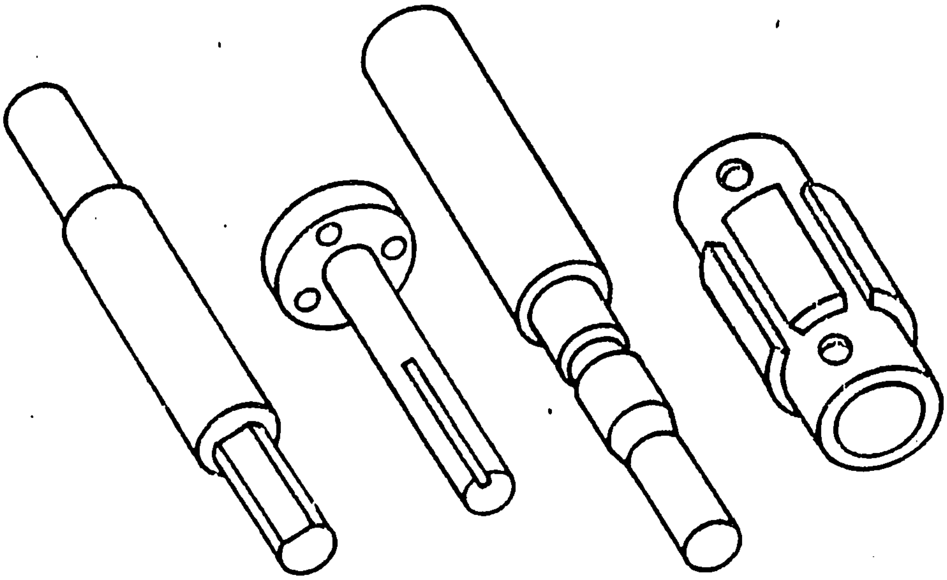


FIGURE 20. A cylindrical family of parts

To define a gripper for each part family, the shape of jaw was determined based on geometrical characteristics of each part family. This was followed by an analysis of the geometrical parameters which govern overall dimensions and a discussion of the rules for selecting these parameters to achieve compact jaw designs.

In this chapter, the specifications of selected gripper type for this research are described first. This will be followed presentation the criteria defining successful grips. The selection rules which define the best gripper for each family are also presented.

B. Gripper Specifications

1. Overview

The various control aspects of the gripper mechanism have evolved along with the development of robot controllers in general. To date, only three methods of gripping an object are available. These include the following:

- Mechanical grippers
- Suction grippers
- Magnetic grippers

Mechanical grippers with two fingers are most widely used in industry. Schafer and Malstrom [59,60,61] showed that two finger grippers with parallel finger motion and twin plane fingers can handle many different part geometries. There are two ways of constraining the part in these types of grippers. The first is by physical constriction of the part within the fingers. In this approach, the gripper fingers enclose the part to some extent, thereby constraining the motion of the part. This is usually accomplished by designing the contacting surfaces of the jaws to conform to the approximate shape of the part's geometry.

The second way of holding the part is by friction between the fingers and the part. With this approach, the fingers must supply a force that is sufficient to permit friction to retain the part against gravity, acceleration, and any other force that might arise during the holding portion of the work cycle. The fingers, or pads attached to the fingers which make contact with the part, are generally fabricated out of a material that is relatively soft. This tends to increase the coefficient of friction between the part and the contacting finger surface. It also serves to protect the part's surface from scratching or other damage.

In this research, a two finger mechanical gripper, a suction gripper, and a magnetic gripper were considered as possible grippers for each part family because of their popularity and commercial availability. The various jaw shapes of the two fingered gripper are also considered as a way of constraining a part in this research. The specifications and characteristics of these grippers are described in detail in the following sections.

2. Mechanical grippers

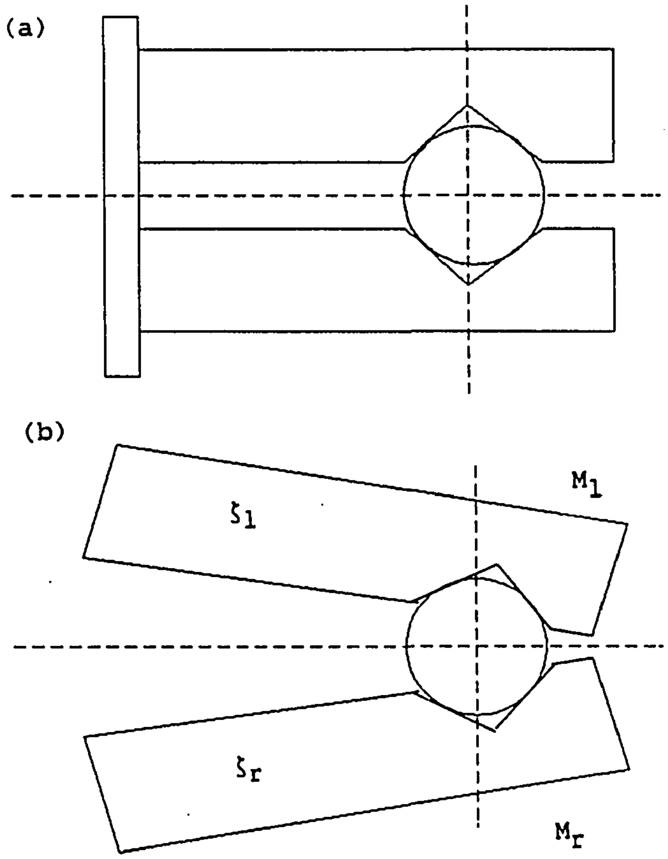
Grippers with one degree of freedom are very popular because of their simple structure and light weight. Thus, the grippers with two fingers have been considered in this research.

There are two types of finger motion with these mechanical grippers. The types of finger motion include a parallel motion and a rotational motion. These two motion types are shown in Figure 21. In this research, the parallel motion finger was selected for the gripping method because it is simple and more widely used gripping mechanism. Various jaw shapes for the two finger gripper have also been considered. The jaw shapes included in this study include a plane jaw, one with a semi-circular shape, and one with a V-notch shape. The dimensions of these fingers are shown in Figure 22.

In all combinations with two out of the three selected shapes, the following six grippers can be formed:

- Gripper with twin plane fingers (P-P type)
- Gripper with twin semi-circular notch fingers (C-C type)
- Gripper with twin V-shape notch fingers (V-V type)
- Gripper with one plane finger and one semi-circular shape finger (P-C type)
- Gripper with one plane finger and one V-shape finger (P-V type)
- Gripper with one semi-circular shape finger and one V-shape finger (C-V type)

The corresponding gripper shapes are shown in Figure 23. Among these six jaw shapes, grippers with the "C-C", "V-V", and "V-P"



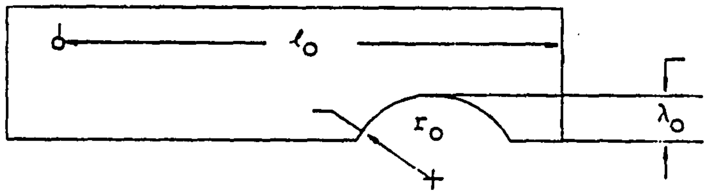
(a) equivalent torque ($M_r = M_l$)

(b) equivalent displacement ($\zeta_r = \zeta_l$)

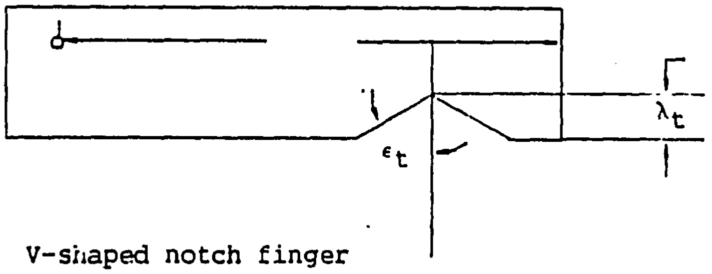
M_r, M_l: input torque

ζ_r, ζ_l: angle of rotation

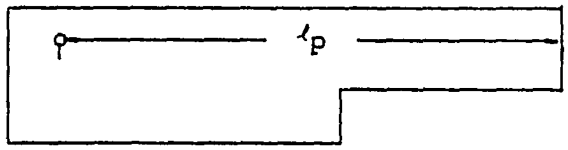
FIGURE 21. Two types of finger motion



Semi-circular notch finger



V-shaped notch finger



Plane finger

FIGURE 22. Dimensions for three kinds of fingers

configurations lend themselves toward grasping cylindrical parts. For rectangular parts, grippers with the "P-P" jaw shape are best. Thus, the following four gripper configurations were selected for analysis in this study:

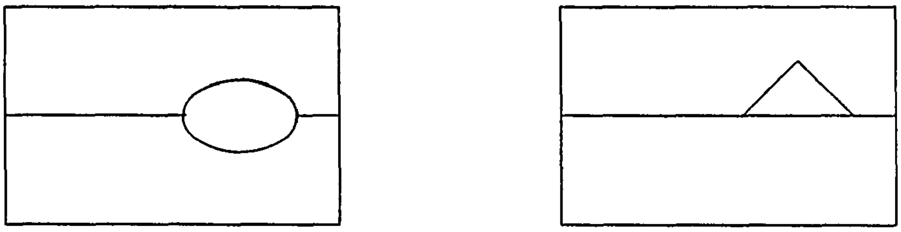
- Gripper with C-C type jaws
- Gripper with V-V type jaws
- Gripper with V-P type jaws
- Gripper with P-P type jaws

Schematic representations of these four jaw configurations are shown in Figure 24.

3. Vacuum Gripper

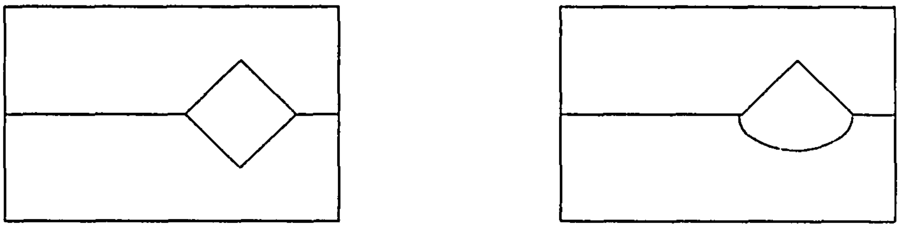
For handling parts made of sheet metal plates, vacuum has been used as the gripping force in many tooling applications. The part can be lifted by vacuum cups incorporated into the end-of-arm tooling. The lifting force is a function of the degree of vacuum achieved and the size of the area on the part where the vacuum is applied.

The most frequently used vacuum gripper uses suction or vacuum cups to hold the desired part. The gripper can have a single vacuum cup or a multiple pattern of pickup cups. In this study, a vacuum gripper with a single cup was selected. The usual requirements on the objects to be handled are that they be flat, smooth, and clean. This results in conditions necessary to form a satisfactory vacuum between the object and suction cup. The specifications of a vacuum pad are shown in Figure 25.



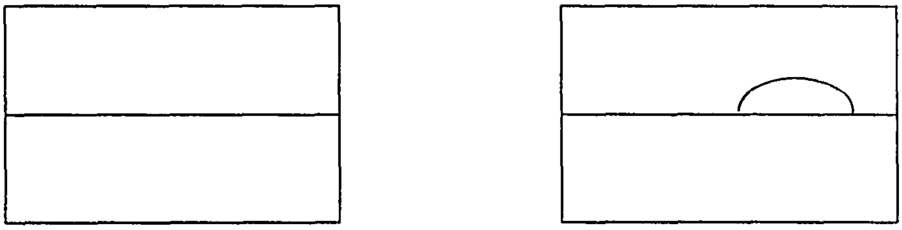
C-C jaw shape

P-V jaw shape



V-V jaw shape

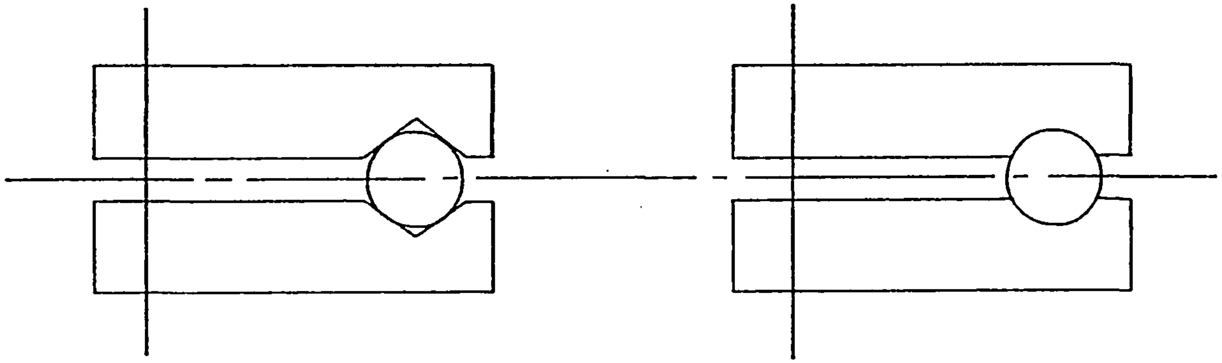
V-C jaw shape



P-P jaw shape

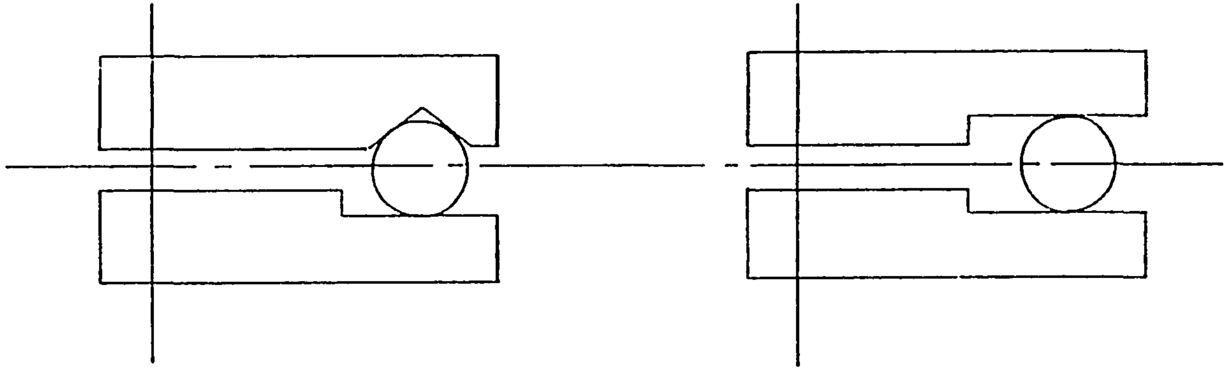
P-C jaw shape

FIGURE 23. Six grippers with different jaw shapes



Twin V-shaped notch jaws

Twin semi-circular notch jaws



V-shaped and plane jaws

Twin plane jaws

FIGURE 24. Schematic views of four types of a gripper

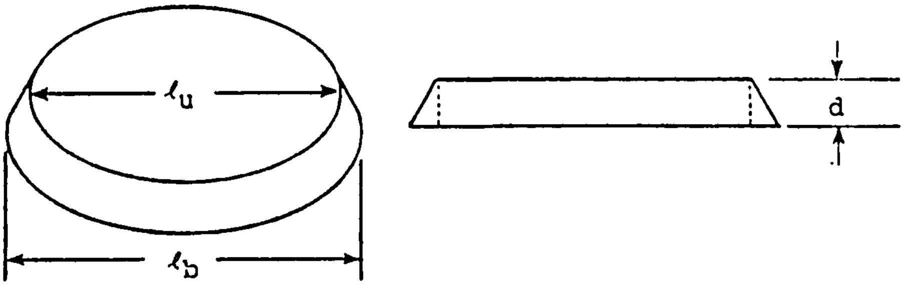


FIGURE 25. Dimensions of a vacuum pad

If the area of a vacuum pad is held constant, the suction or pull exerted by the pad is directly proportional to the air pressure outside the pad less the air pressure inside the pad. The effective pressure difference, ΔP, can never exceed the local air pressure. Because of leakage into the pad, the gripping force will often be far less than ambient air pressure.

Another limitation is that the pads may not exceed the size of the flat surface with which they must interface. Flatness is also a criterion, in that vacuum pads can accommodate very slightly curved surfaces, but the curve must be very slight indeed. Any generic irregularity part that interferes with the lip of the vacuum pad will defeat the vacuum action and prevent any lifting capability.

4. Magnetic gripper

Magnetic grippers have been regarded as a very feasible means of handling ferrous materials. Parts made of steel, excluding certain types of stainless steel, are suitable candidates for this means of handling, especially when the materials are handled in sheet or plate form.

In general, magnetic grippers offer the following advantages in robotic handling applications:

1. Pickup times are very fast
2. Variations in part size can be tolerated
3. They have the capability to handle metal parts with holes
4. They require only one surface for gripping

There are some disadvantages with these grippers. Disadvantages with these grippers include the residual magnetism remaining in the part which may cause a problem in subsequent handling, and the possible side slippage and other errors which limit the precision of this means of handling. Another potential disadvantage of a magnetic gripper is the problem of picking up only one sheet from a stack.

Magnetic grippers can be divided into two categories, those using electromagnets, and those using permanent magnets. Electromagenetic grippers are easier to control, but require a source of dc power and an appropriate controller unit. Permanent magnets have the advantage of not requiring an external power source to operate the magnet. However, there is a loss of control that accompanies this apparent advantage. For example, when the part is to be released at the end of the handling cycle. Some means of separating the part from the magnet must be provided. The device which accomplishes this is called a stripper or stripping device. Its function is to mechanically detach the part from the magnet.

In this research, the magnetic gripper with permanent magnets was considered as a mean of handling of flat sheet metal parts. It is assumed that there is some means of separating the part from the magnet.

5. Summary

Many features or characteristics of grippers can be considered as design factors to improve gripper versatility. This research has investigated these features in the design of gripper sets to handle different families of part geometries.

Mechanical grippers with two fingers, a gripper with a suction cup and a magnetic gripper were considered in this study. For mechanical grippers with two fingers, different jaw shapes were also considered. Thus, a total of six different types of grippers were evaluated. These included the following:

- Two finger grippers with parallel finger motion
    - . C-C jaw shape
    - . V-V jaw shape
    - . V-P jaw shape
    - . P-P jaw shape
- Suction gripper
- Magnetic Gripper

The criteria for successful grips for the six grippers are explained in the next section along with the criteria used to determine the design parameters for each gripper.

C. Gripper Configuration Methods

1. Overview

The part families obtained in this research had different part geometries. A gripper was configured for each part family. The gripper configuration began with selection of jaw shape based on the geometry of the part family. The dimensions of the gripper with the selected jaw shape were determined by using criteria for successful grips.

In the following sections, the selection methods of the jaw shape are presented. The criteria for successful grips are then explained. Finally, the geometrical analyses for the selected grippers are presented.

2. Determination of jaw shape

In order to define a best gripper for each part family, a jaw shape was selected first based upon geometrical characteristics of each part family. The first five digits of the Opitz system show geometrical characteristics of a part. The five digits show the following geometrical characteristics:

- The part's class.
- The overall or main shapes.
- The rotational surface machining.
- The plane surface machining.
- The auxiliary holes, gear teeth, and forming.

Each part family obtained from the cluster analysis is provided with the geometrical codes of the Opitz system representing the geometrical characteristics of the family. The jaw shape is then determined based on the geometrical characteristics.

For example, the first digit of the Opitz coding and classification system represents the part's class. The shapes included in the first digit are rotational parts without deviations, rotational parts with deviations, rectangular parts, long parts, and flat parts [47]. Thus, the overall shape for the part family can be the geometrical shape determined by the code number of the first digit with which a large number of parts are classified.

If a gripper is designed with different jaw shape other than a plane finger, the contacting of surfaces of jaws should be in the approximate shape of a part to constrain it physically. Thus, each jaw shape can handle limited part geometries. Table 5 shows the gripper type and the corresponding part geometries to be handled.

TABLE 5. Gripper types and part geometries to be handled

Gripper type		Part geometries to be handled
Gripping method	Jaw shape	
Mechanical	C-C type	Cylindrical external shape
	V-V type	Cylindrical external shape
	V-P type	Cylindrical external shape
	P-P type	Rectangular external shape
Suction		Flat (light metal sheet, gripping area is flat, no holes on the gripping area)
Magnetic		Flat (metal sheet)

The jaw shape of a gripper was defined according to the selected overall shape of each part family by applying the rules shown in Table 5. The dimensions of the selected gripper were then decided from the maximum and minimum dimensions and maximum weight of the family.

3. Criteria for successful grips

In defining gripper features, it is useful to complete a geometric and static force calculation of the gripper and the object being grasped together. Chen [11] has described the conditions for the successful design of a gripper. This research has adopted these conditions. The following conditions should be satisfied for successful grips:

- The geometry of a part should be enclosed within the jaw shape.
- The gripper must have suitable opening range to fit the part to be gripped.
- The gripper should produce enough force to lift the maximum weight of the part.
- The gripper should not produce excessive force that cause physical deformation.
- The weight of the gripper and the space it occupies should be as small as possible.

These conditions were selected as the criteria for determining the specifications of the grippers' dimensions. The first two conditions relate to the geometrical characteristics of part families. The third and fourth conditions relate to the gripping force required by the selected gripper type to handle maximum weight of a part within part family. The last condition was used to select the best gripper configuration if two or more grippers could be configured for a certain part family.

These criteria are presented for two finger mechanical grippers in the next section. For the suction and magnetic grippers, it is assumed that no slippage occurs due to the part geometry and the shape of gripper. Therefore, the criteria for these types of grippers is a gripping force sufficient to lift required part weights. Both geometric and static conditions for successful grips are described in the following sections.

4. Geometrical conditions of successful grips

The best characteristic which defines the geometrical condition of successful grips is that the fingers should grip a full range of dimensions. Each part family contains data on the maximum and minimum dimensions; length and diameter for rotational parts, and lengths of the part's edges for non-rotational parts.

In order to consistently design grippers for different part geometries, specific gripping conditions must be defined. The conditions used in this research are listed below:

- The gripping surface applies a force along an axis that passes through the center of gravity of the part.
- The gripping force is applied on the outside of the part.
- The contact points or area are the same for all types of grippers.

The P-P jaw shape is simple and most widely used in many industrial robots. This jaw shape can be used to handle rectangular parts. The dimensions of the jaw shape are shown in the Figure 26 along with the part to be handled. Because no shapes are involved with this type of jaw, the dimensions to be configured are the length of finger, ℓ_p, and maximum opening range, B_{open}. In order to grip full range of dimensions obtained from a part family with this type of jaw, the following condition must be satisfied:

$$B_{open} \geq D_{max} \tag{3}$$

where D_{max} = Maximum dimension obtained from a part family

The semi-circular notch (C-C) finger is used to handle mostly cylindrical parts. From the jaw shape, shown in Figure 26, it is obvious that the radius of the semi-circular notch, r_o, must be larger than $D_{max}/2$.

The diameter of a cylindrical part was selected from the dimensional characteristics of part families. Dimensions to be determined for this jaw shape are the length of the finger, ℓ_o, the radius of the semi-circular notch, r_o, the depth of the notch, λ_o, and the maximum opening range, B_{open}. In order to grip full range of dimensions obtained from a part family with this type of jaw shape, the following conditions must be satisfied:

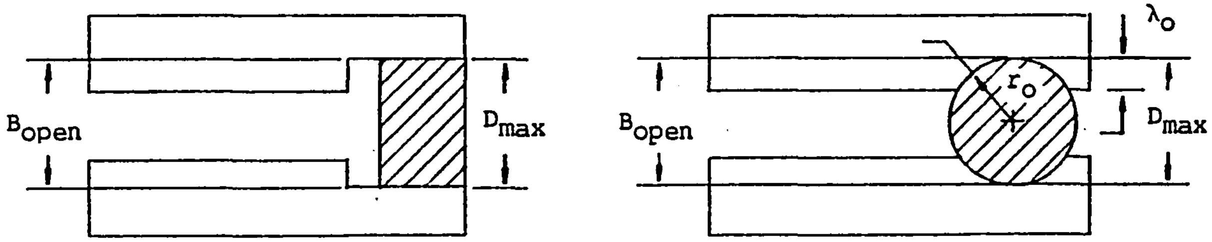
$$r_o \geq D_{max}/2 \tag{4}$$

$$\lambda_o \leq D_{min}/2 \tag{5}$$

$$B_{open} \geq D_{max} + 2\lambda_o \tag{6}$$

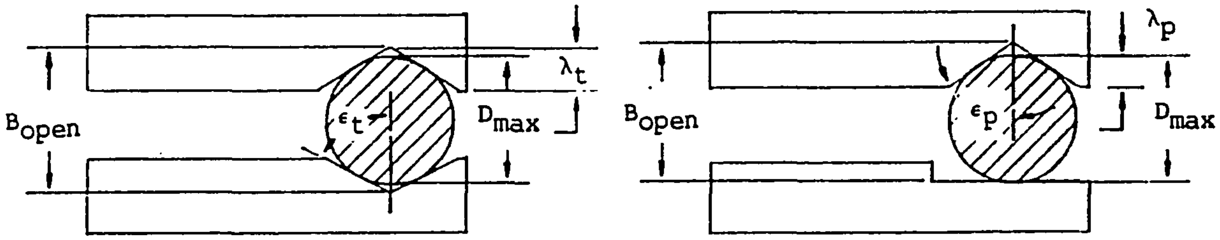
where: D_{max} = Maximum dimension obtained from a part family

D_{min} = Minimum dimension obtained from a part family



P-P Jaw

C-C Jaw



V-V Jaw

V-P Jaw

FIGURE 26. The dimensions of jaw shapes and parts to be handled

The dimensions for the V-V jaw shape are shown in Figure 26 along with the part to be handled. The dimensions to be configured for this jaw shape are then the length of the finger, ℓ_t, the angle of the V-shaped notch, ϵ_t, the depth of the notch, λ_t, and the maximum opening range, B_{open}. In order to grip full range of dimensions obtained from a part family with this type of jaw, the following conditions must be satisfied:

$$\lambda_{tmax} = D_{min}/2\sin\epsilon_t \tag{7}$$

$$\lambda_{tmin} = D_{max}*\cos\epsilon_t/2*\tan\epsilon_t \tag{8}$$

$$\cos\epsilon_t = \sqrt{D_{min}/D_{max}} \tag{9}$$

$$B_{open} \geq D_{max} + 2\lambda_t \tag{10}$$

where: D_{max} = Maximum dimension obtained from a part family
D_{min} = Minimum dimension obtained from a part family
λ_{tmax} = Maximum depth of the notch
λ_{tmin} = Minimum depth of the notch

The dimensions for the V-P jaw shape are shown in Figure 26 along with the part to be handled. The dimensions to be configured for this jaw shape are the length of the finger, ℓ_p, the angle of the V-shaped notch, ϵ_p, the depth of the notch, λ_p, and the maximum opening range, B_{open}. In order to grip full range of dimensions obtained from a part family with this type of jaw, the following conditions must be satisfied:

$$\lambda_{pmax} = (1+\sin\epsilon_p)D_{min}/2*\sin\epsilon_p \tag{11}$$

$$\lambda_{pmin} = D_{max}*\cos\epsilon_p/2*\tan\epsilon_p \tag{12}$$

$$\sin\epsilon_p = (D_{max} - D_{min})/D_{max} \tag{13}$$

$$B_{open} \geq D_{max} + \lambda_p \tag{14}$$

where D_{max} = Maximum dimension obtained from a part family
D_{min} = Minimum dimension obtained from a part family
λ_{pmax} = Maximum depth of the notch
λ_{pmin} = Minimum depth of the notch

D. Gripping Evaluation

1. Overview

This phase of this study addresses the determination of the percentage of parts within each part family that may be successfully grasped by the X-change robotic gripper set previously described. Four sets of part families will exist: one for each of the coding and classification schemes previously described. Four sets of robotic grippers will also exist for each defined part family. The "best" gripper set must be selected for the part family among the gripper types chosen for this research. The percentage of parts within each part family that can be successfully grasped must also be determined for each gripper/family combinations. These selection methods are the subject of the following sections.

2. Determination of successful grips for a part

In order to define a "best" gripper for each part family, a gripper from gripper types selected for this research was chosen based upon geometrical characteristics and the dimensions of each part within each family. The successful gripping criteria discussed in the previous sections were applied in making each selection.

The conditions of successful grips for each part were defined based on the criteria discussed previously. The following conditions must be satisfied for successful grips:

- If a gripper is configured with s jaw shape other than P-P, the contour of the part must be enclosed within the shape of the jaw.
- The maximum dimension of the part must be in the range of the maximum opening distance, B_{open}.
- The weight of a part must be less than the maximum weight determined by the part family.

The last condition was derived from the gripping force requirements of the criteria of the successful grips. The criteria stated that the gripping force must be enough to lift the maximum weight of a part. The force must not produce excessive force to cause physical deformation. These requirements usually have been satisfied by developed gripping mechanisms. In this research, it is assumed that the gripping mechanism is available to lift the maximum weight of a part within a part family.

For each part within a part family, the following characteristics were determined:

- The overall shape

- The shape of the contact point or area
- Rotational machined surfaces machining
- Plane machined surfaces machining
- Auxiliary holes, gear teeth and forming
- Dimensions
- Weight

By using the these geometrical characteristics and dimensional characteristics of a part, a determination can be made whether the part can be successfully grasped by the gripper configured for the family.

3. Gripper evaluation within a part family

The percentage of parts within each family that can be successfully grasped was determined for each part family with each gripper set. This analysis was completed for each of the four sets of part families corresponding to the different coding and classification methods. The coding and classification method(s) with the highest percentages of parts successfully grasped identify the approach that is best in terms of number of parts successfully grasped by the robotic gripper set.

For each part within a family, a determination was made as to whether the part could be successfully grasped by the robotic gripper assigned to the family of parts. In each case, the contact points between the part and the gripper were specified such that no interferences would occur at later assembly operations. The pick-up orientation of the part in relation to the gripper was specified as well.

4. Summary

The specifications and corresponding successful gripping conditions of the grippers selected for this research have been explained in this chapter. Among those selected grippers, the best gripper for each part family is selected based on the information of the part family. In selecting the gripper, the following criteria are applied:

- The gripper which can lift the maximum weight of a part within a family with minimum gripping force is selected.
- The gripper which can grasp the maximum and minimum of dimensions of a part within a family is selected.
- The gripper whose dimensional parameters are the smallest is selected to make the gripper compact.

Once the best gripper is selected for each family, there will be limits of parameters of the gripper which can grip and lift a part. The parameters are the geometry of a part, a dimensions of part and a friction force. If those parameters of a part are within ranges of limits, the part is grasped successfully.

VI. DEVELOPMENT OF COMPUTER SOFTWARE

A. Introduction

In spite of a large number of applications where the classification and coding techniques could be used very efficiently, such use is, unfortunately, not widespread. The classification and coding of manufactured parts has reached the point where there is a need for some mechanical aid to sort the data. Even though a computer can be used in all standard clustering techniques which are employed for hierarchical part family formation, only a very small number of parts can be handled without using efficient sorting algorithms. More efficient sorting algorithms have been implemented in the two types of clustering analysis used in this research.

To analyze the geometrical characteristics of part families in designing a standard robotic gripper set, data for 272 manufactured parts were collected from four different manufacturing organizations. As described in Chapter III, four coding and classification methods were selected to define part families. Computer software was developed to analyze the collected data by using BASIC language. Program listings for the developed software are presented in Appendix A.

The software programs include the production flow analysis (PFA) analysis, the Opitz coding and classification system and two clustering analyses; the rank order cluster analysis (ROCA), and the cluster analysis with similarity coefficients (CASC). The computer software for these four coding and classification methods is the subject of this chapter.

B. Computer Software for PFA

1. Overview

Production flow analysis (PFA) is one method of group technology which has particular appeal in that it requires no special part coding system. It is relatively simple to implement and can be applied to the reorganization of existing, as well as the design of new manufacturing systems. With PFA, the majority of components and machines must already belong to clearly defined families and groups. The problem is to find these existing families and groups.

The PFA method requires only the use of route sheets for identification of part families. Two clustering algorithms, the ROCA and CASC, are applied to the PFA method to form part families.

2. General procedures

As discussed in Chapter III, the PFA method consists of four major analysis stages. Two clustering algorithms, suitable for computer applications, were applied at the group analysis stage. The computer software for the two clustering algorithms is explained later in this chapter. The four analysis stages were implemented together with the two clustering analyses in the software. This defines the first two coding and classification methods; PFA/ROCA and PFA/CASC.

The first three stages of the PFA method are known as factory flow analysis. The objective of this analysis is to find the simplest and most efficient inter-departmental flow. Burbidge has suggested the following seven steps for the factory flow analysis [5]:

1. Divide into departments.
2. Allocate plant to departments.
3. Draw basic flow chart.
4. Determine the process sequence for each part.
5. Analyze the sequences by the process route number.
6. Study exceptions and eliminate them where possible.
7. Plan the inter-departmental flow system.

Steps 4, 5, and 6 were implemented because the objective of using the PFA method in this research was to form part families. The other steps were not implemented in the software because these steps are usually used to divide the plant into associated groups of machines.

The final stage, called also group analysis, considers each department in turn and seeks to find the best division of their parts into families and of the plant into associated groups of machines. Burbidge has suggested the following eight main steps for this analysis stage [5]:

1. Renumber operations on route cards.
2. Sort routes into packs.
3. Draw pack/machine chart.
4. Find families and groups.
5. Check load and allocate plant.

6. Investigate exceptional cases.
7. Specify groups and families.
8. Draw final flow system network and check.

Steps 4, 6, and 8 have been implemented because this research again addressed on the formation of part families. At step six of the group analysis, the "exceptional cases" included machine centers required by only a few parts or parts which required operations on two different identifiable machine centers. When these cases occurred after each application of clustering algorithms, the corresponding machines and parts were eliminated from the analysis. This is because a block diagonal form of final part-machine matrix did not exist for those machines and parts.

The following six steps were implemented in the PFA method in this research.

1. Determine the process sequence for each part.
2. Analyze the sequences by the process route number.
3. Study exceptions and eliminate them where possible.
4. Find part families and their corresponding groups of machine by using a clustering algorithm.
5. Investigate exceptional cases.
6. Specify groups and families.

The six steps comprised the four analysis stages in the PFA method. The implementation of those steps in the computer software is explained in the next section.

3. Implementation of PFA coding method

As discussed in the previous section, six steps were implemented to code the combined data set based on the process routing. The following six steps were considered in this research:

Step 1: Find all the machines involved in the manufacture of parts

Step 2: For each particular part, define a sequence of machines whose path represents the sequence of operations required for the manufacturing process.

Step 3: A Part-Machine incidence matrix is formed based on the following:

$$PMMAT_{ij} = \begin{cases} 1: \text{if part i requires machine j} \\ 0: \text{otherwise} \end{cases}$$

Step 4: Perform clustering algorithms (ROCA and CASC)

Step 5: Investigate the final incidence matrix to see if there are exceptional machines.
If there are no such machines, then stop
Otherwise, go to Step 6.

Step 6: Delete those machines and revise the Part-Machine incidence matrix. Go to Step 4.

At step 4, the part-machine incidence matrix is required to perform clustering analyses. The matrix contains the information on the process sequence of each part. If part i has an operation on a machine j, the element (i,j) of the part-machine is recorded as "1". Thus, in the development of the software for the PFA method, this research concentrated on generating this matrix. Figure 27 shows the flow diagrams for this method.

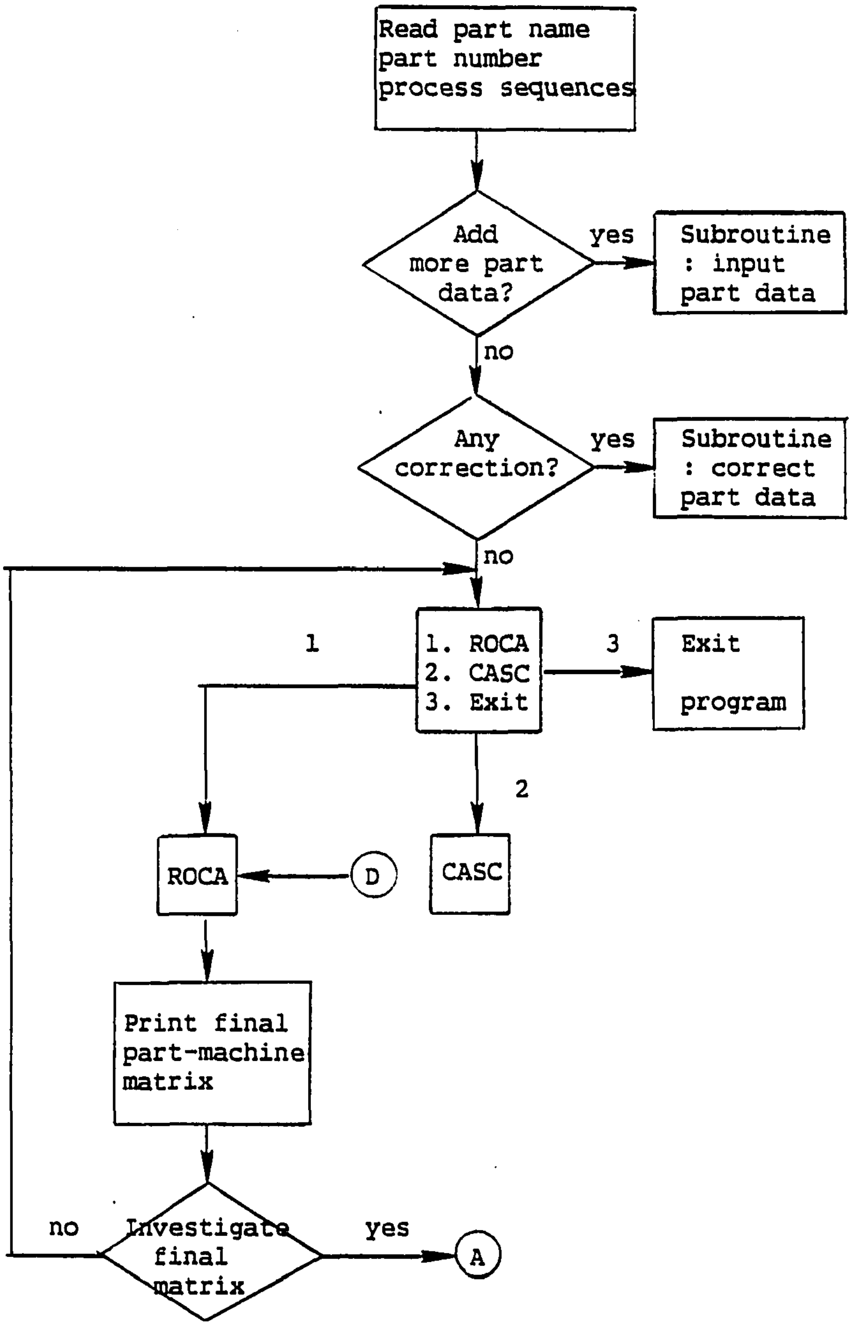


FIGURE 27. Flow diagram for the PFA method

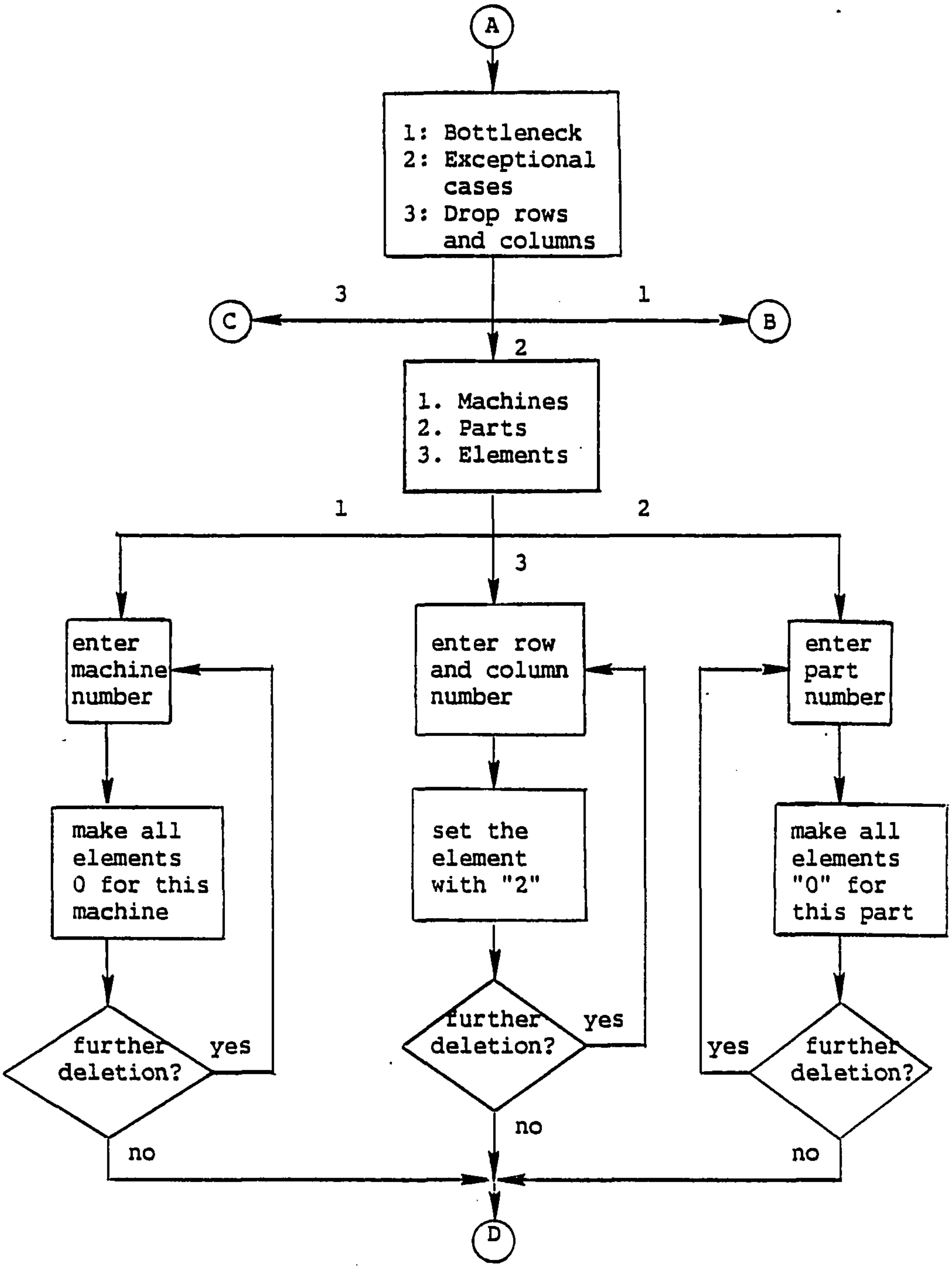


FIGURE 27. (Continued)

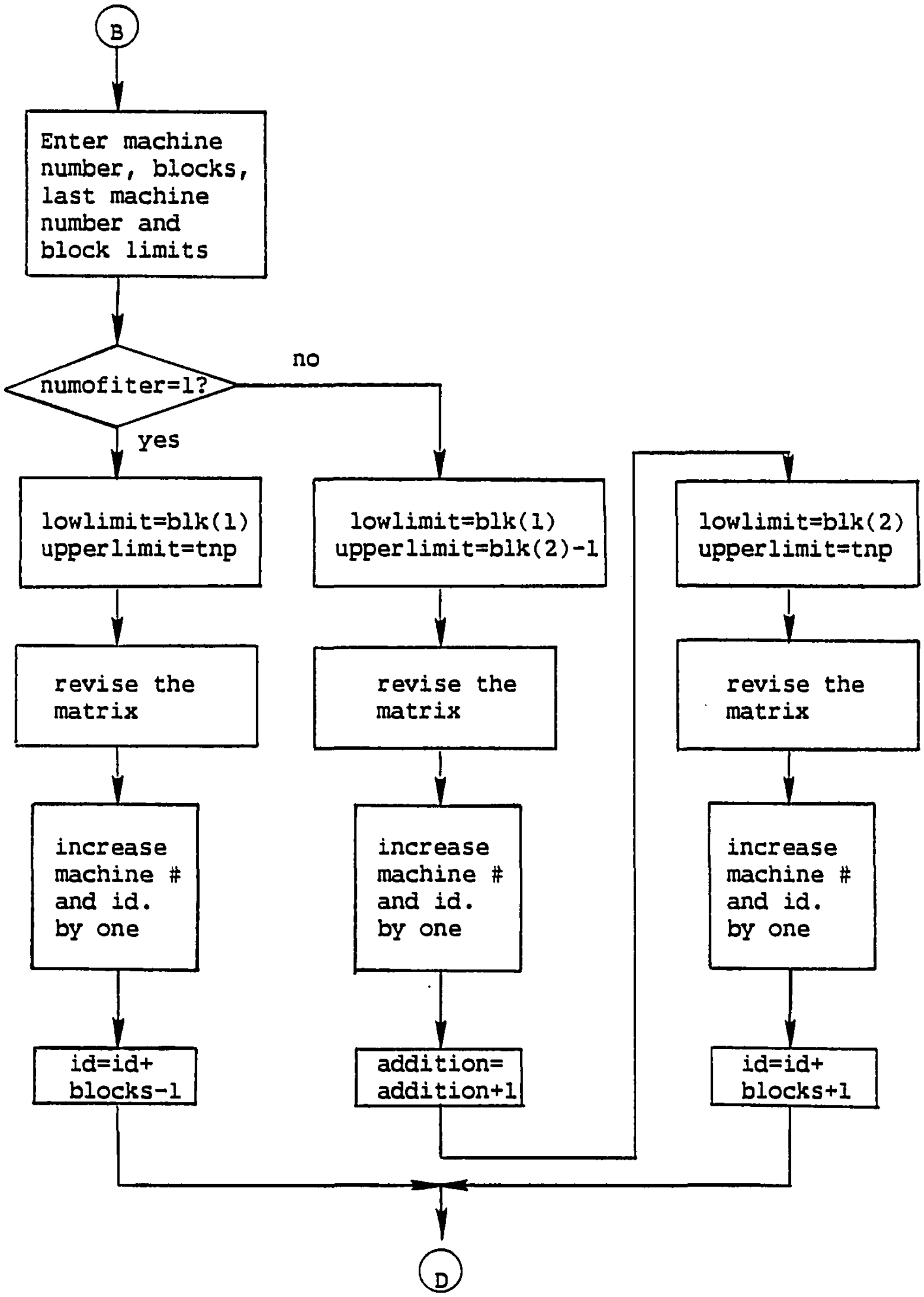


FIGURE 27. (Continued)

In addition to six main steps required for the PFA method, the following subroutines were also implemented to code the parts more efficiently:

1. Subroutine for data entry
2. Subroutine for reading data file
3. Subroutine for generating the Part-Machine matrix
4. Subroutine for generating the machine list

The coding of the PFA method is illustrated with parts shown in Figure 28(a). In order to use the PFA method, the data on the part name, the part number, the total number of processes, and the process sequence are required. In the subroutine for data entry, these data were entered interactively. The data were saved in the following arrays:

pname$(i) : Part name of part i
pnum$(i) : Part number of part i
tp(i) : Total number of processes of part i
route(i,j): Process route of part i and jth sequence

Once all the data required for the PFA method is entered, it is saved on the data file "PARTS.DAT". The list of machines used in all the parts is generated automatically by the program. The array mach(i) holds the list. The part-machine incidence matrix is formed based on the list. The machines used to manufacture the example parts are shown in Figure 28(b).

The part-incidence matrix formed for the example parts is shown in Figure 28(c). The columns of the incidence matrix represent the machines used. The rows of the incidence matrix represent the parts.

Part name	Part number	Total # of processes	Process sequences
AA	01	3	2 3 5
BB	02	2	1 4
CC	03	2	2 3
DD	04	2	1 4
EE	05	1	1
FF	06	2	1 4
GG	07	2	3 5

(a) The input data for the PFA method

Machine list	Machine name
1	Sandblast Plating
2	Horizontal Bandsaw
3	Lathe
4	Drill Press
5	Milling Machine

(b) The machine list obtained from the data.

$$\begin{array}{l}
\begin{array}{lccccc} \text{Part} \quad \text{Machine} & 1 & 2 & 3 & 4 & 5 \end{array} \\
\begin{array}{l} AA \\ BB \\ CC \\ DD \\ EE \\ FF \\ GG \end{array}
\left[\begin{array}{ccccc}
0 & 1 & 1 & 0 & 1 \\
1 & 0 & 0 & 1 & 0 \\
0 & 1 & 1 & 0 & 0 \\
1 & 0 & 0 & 1 & 0 \\
1 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 1 & 0 \\
0 & 0 & 1 & 0 & 1
\end{array}\right]
\end{array}$$

(c) The part-machine incidence matrix obtained for the data.

FIGURE 28. Results of the PFA coding method

The entry "1" in the matrix indicates that the part has an operation on the machine. The entry "0" indicates that the part has no operation on the machine. The two cluster analyses (ROCA and CASC) are applied on this matrix to define part families based on process routings. The results of this applications of the two cluster analyses are explained later in this chapter.

C. Software for the Opitz System

1. Overview

The Opitz system is a manual classification system which has been developed to classify parts into groups or families according to similar attributes. A code is associated with each individual family. The heart of the Opitz system is a coding program which is used to establish classification code numbers which identify each workpiece. The manual approach is often used to group families of drawings and codes for design retrieval purposes. This method is both labor and time intensive. The computer software developed in this research generates codes for a part in relation to its geometrical and technological characteristics; shape, dimensions, tolerances, etc. These codes are used to form the part-characteristic incidence matrix. The two clustering algorithms were applied on the matrix.

The logic sequence necessary to derive the specific codes of the Opitz system was computerized in the developed software. The software queries the user for part attributes used to select the geometrical and technological characteristics of a part. The software generates a specific codes of a part automatically after responding to the series of questions and making selection among the attributes.

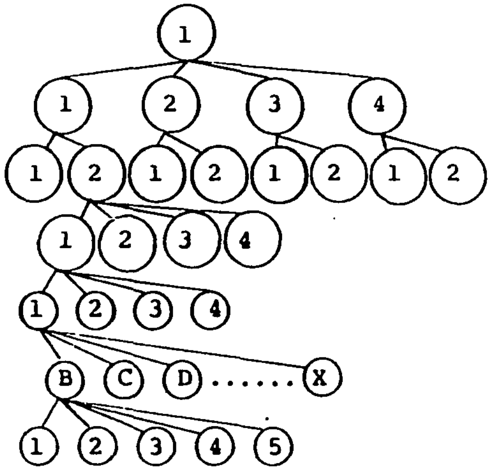
2. General overview of coding systems

There are basically two forms of coding and classification system structures. The first coding method uses monocodes that are integrated with the hierarchical classification. This coding method is the integrated, hierarchically oriented code from the less complex, simpler coding forms. The second coding method uses polycodes that are not integrated within hierarchy of the classification. Examples of these two coding methods are shown in Figure 29.

As shown in the Figure 29, the hierarchical tree structure can be formed in the monocode system. Each node represents a specific geometrical characteristic of the part. By starting at the main trunk of the tree structure and answering questions about a part, the specific codes can be obtained in a monocode system.

In the polycode system, the entire population of parts is presented in tabular form. Classification is performed based on a set of questions to be asked about each part in the collection. It is difficult to form a hierarchical tree structures with a polycode system because one code number includes many geometrical features which cannot be exclusively defined in this system. Thus, the list of geometrical features for each code number is usually presented as a menu in the polycode system. By selecting the corresponding geometrical features

Monocode



Polycode

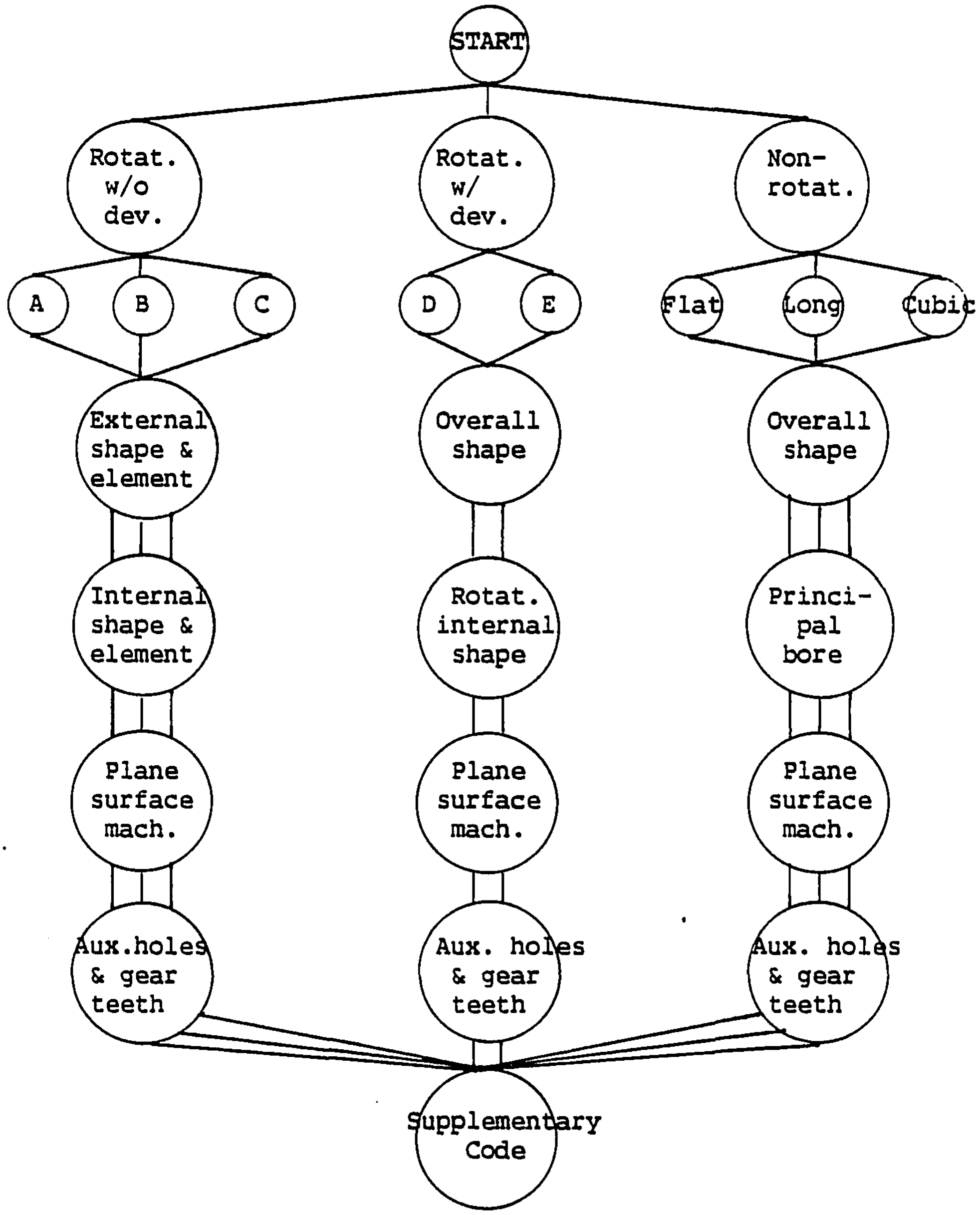
	Position						
	Ext. shape	Int. shape		Size		Material code	
	1	1	0	1	1	A	1
	2	2	1	2	2	B	2
	3	3	2	3	3	C	3
	4	4	3	4	4	D	4
	5	5	5	5	5	E	5
	6	6	8	6	6	F	6

FIGURE 29. Two coding methods

of a part from a given menu, the specific code of the part is then derived.

Most classification and coding systems in industrial use are hybrids of monocode and polycode systems. Hybrid systems, including the Opitz system, have been developed to capitalize on the benefits from both basic systems. Thus, hybrid systems use some digits arranged hierarchically. Others have a fixed significance, indicating the presence of particular attributes. The usual structure of the system is for the first one or two digits to divide the population of items into the main subgroups as in a monocode system. From this point on, each subgroup has its own attribute code or series of fixed-significance digits.

For example, in the Opitz system shown in Figure 30, parts are first classified into eight subgroups based on their basic shape and dimensional ratio. These subgroups are represented by the each nodes represented by the first digit of the Opitz system. One query leads to the one of these subgroups. The query corresponds the basic shape of a part and its corresponding dimensions. For the following four digits and four supplemental digits, the hierarchical tree structure cannot be formed entirely because several geometrical features are represented by one code number of the digits. Both a interactive series of questions and a menu for selection of geometrical characteristics can be used to computerize this hybrid aspect of the system.



A = L/D ≤ 0.5   B = 0.5 < L/D < 3   C = L/D ≥ 3
D = L/D ≤ 2   E = L/D > 2

where L = length of rotational part
D = largest diameter of rotational part

FIGURE 30. Tree structure of the Opitz system

3. Methods of programming

While a manual approach can be used with a small database, larger databases lend themselves to computerization. The basic idea is to computerize the logic sequence necessary to derive a specific code.

Because the Opitz system is hybrid of two basic systems, a tree structure of a series of questions is formed if a monocode system is used to define the codes of the Opitz system. If the polycode system is used, a list of significant attributes of geometrical and technological characteristics (a menu) is given to select a code number.

The first digit of the Opitz system represents a component class based on the overall shape. The Opitz system uses the monocode system for the first digit. There are three major component classes. These include a rotational component without deviation, a rotational component with deviation and a non-rotational component. Based on the their dimensional ratio, these major classes are divided to designate a component class. Thus, the major shape of a part and related dimensional information comprise the initial inputs required by the software. The digit of the class is next determined based on calculated dimensional ratio.

Once the component class is determined, the following codes are determined from either a interactive series of questions or a menu. If a hierarchical tree structure in a class can be formed, a series of questions is presented to users. Users can respond "yes" and "no" to the series of questions to reach a specific code number for the subclass. For example, the second digit of the Opitz system shows a external shape and shape elements. The hierarchical tree structure of this subclass, shown in Figure 31, can be formed within this class.

Based on the hierarchical structure, a series of questions can be structured to derive the code number within the class. The tree form of the series of questions is shown in Figure 32. The numbers shown in the square represent the code number of the second digit.

When a tree structure of a certain class cannot be formed, a menu for selection of attributes of the class is presented to users. For example, the fourth digit of a rotational component class with deviation shows the attributes of a plane surface machining. The hierarchical tree structure of attributes cannot be formed because many attributes are mixed in one classification number. Thus, the following menu is presented to users:

1: No surface machining

2: External plane surface and/or surface curved in one direction

3: External plane surfaces related to one another by graduation around circle

4: External groove and/or slot

5: External spline and/or polygon

6: External plane surface and/or slot and/or groove, spline

7: Internal plane surface and/or groove

8: Internal spline and/or polygon

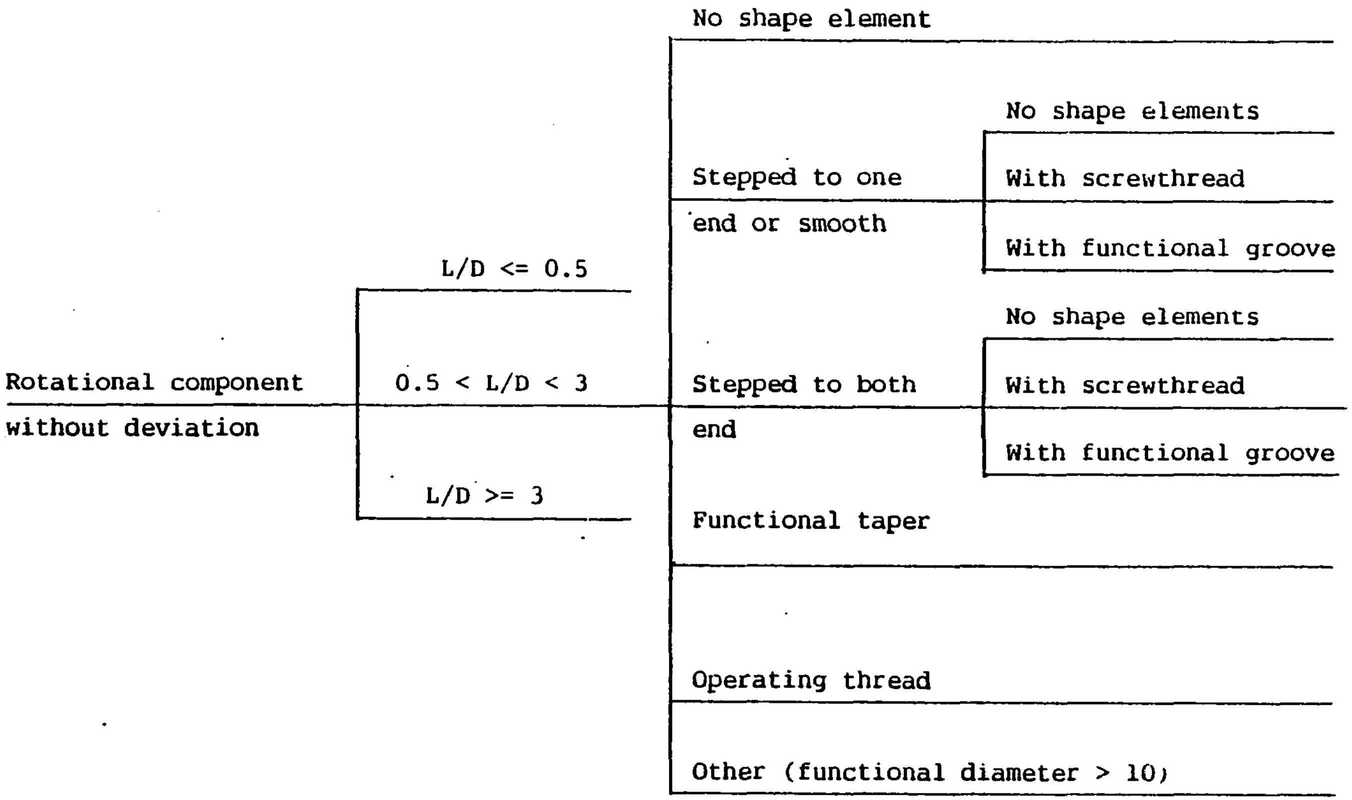
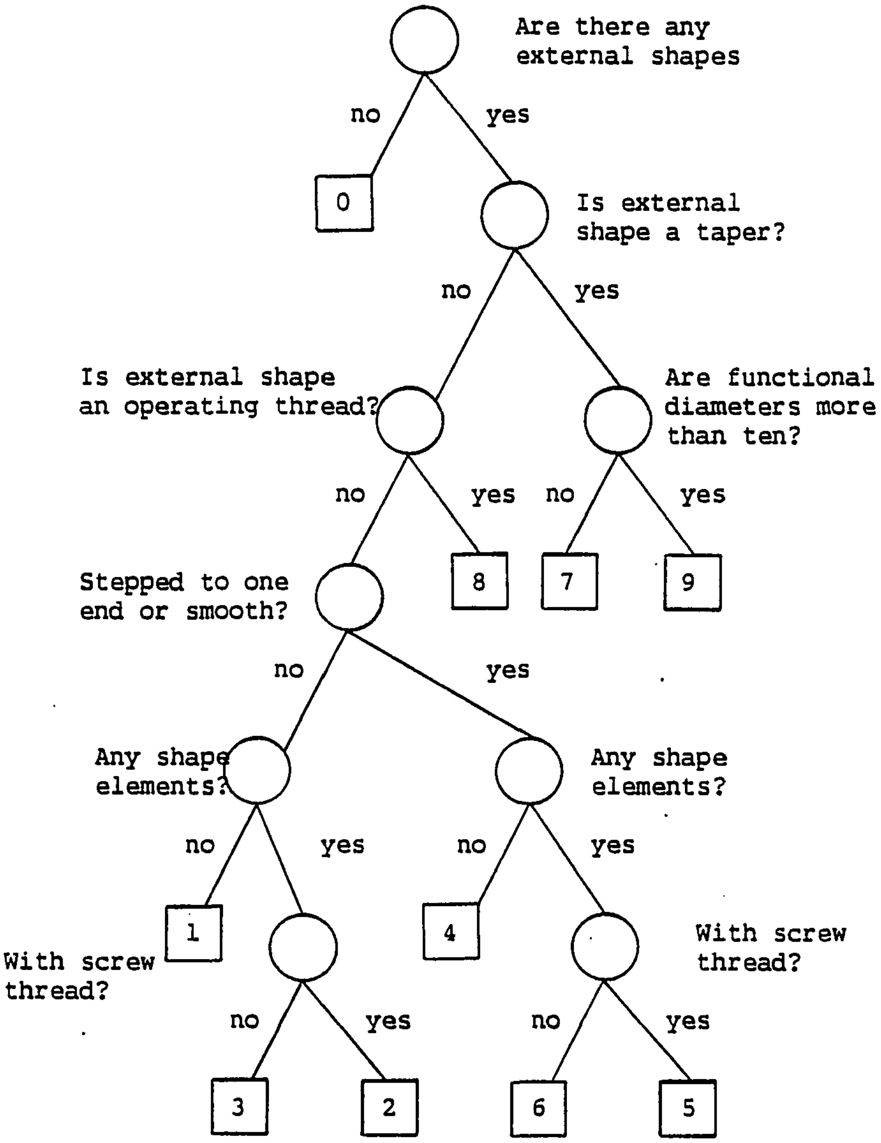


FIGURE 31. Hierarchical tree structure of the second digit class of rotational component without deviation



Shape elements: Grooves for V-belts, Sealing rings
Functional tapers and treads.

FIGURE 32. The hierarchical tree structure of questions

9: External and internal splines and/or slot and/or groove

10: Others

The choice from this menu determines the fourth digit of the code number.

4. An example using a rotational part

Coding with the Opitz system is illustrated with two examples. A part drawing is required to code a part with the Opitz system. The drawing for an example rotational part without deviation is shown in Figure 33. In addition to the drawing, the part name and part number are also required.

The overall shape of a part is first determined in the Opitz system. The shapes includes a rotational part without deviation, a rotational part with deviation, and a non-rotational part. For the rotational part without deviation and a rotational part with deviation, the largest diameter, denoted by D, and the length of the part, denoted by L, are required to determine the part's dimensional ratio. For a non-rotational part, the lengths of three edges, denoted by A, B, and C, are required to determine the part's dimensional ratio. Based on the dimensional ratio, the first digit of the part is determined.

For the part shown in Figure 33, the overall shape is a rotational part without deviation because the part satisfies the following conditions [47]:

1. There is only one axis of rotation.
2. The geometrical axis is identical with the axis of rotation.

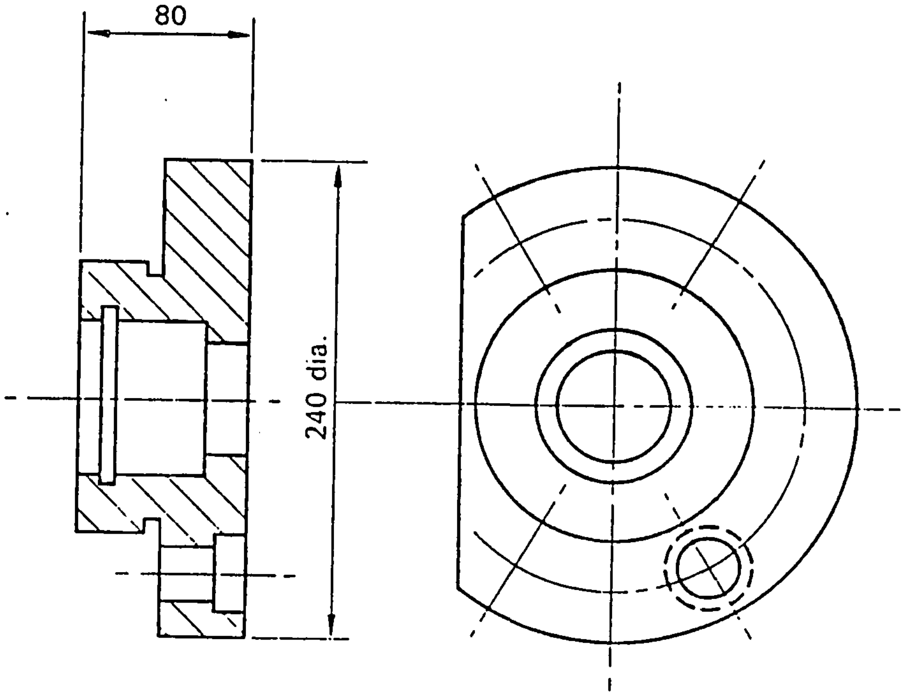


FIGURE 33. A part drawing of an example rotational part without deviation

3. The cross-section perpendicular to the axis of rotation is everywhere circular or angular, or a combination of the two.

The rotational parts without deviation are further classified into three classes based on the dimensional ratio: the length of the part/the largest diameter, L/D. The required dimensional ratio for each class is shown in Table 6.

TABLE 6. The required dimensional ratio for the rotational part without deviation

Component class	Dimensional ratio
0	$L/D \leq 0.5$
1	$0.5 < L/D < 3$
2	$L/D \geq 3$

The largest diameter and the length of the part were determined as D=240 mm and L=80 mm respectively for the part shown in 33. The dimensional ratio, L/D, was 0.33. Thus, the first digit of this part is "0" because the ratio is less than 0.5.

The following four digits of geometrical code are determined by either answering a series of questions or selecting the corresponding geometrical characteristics of a part. The geometrical codes for these digits of the rotational part without deviation are shown in Figure 34.

The second digit for the rotational part without deviation shows the external shape and external shape elements. The code number for

GEOMETRICAL CODE

1st Digit

		Component Class
0	Rotational Components	$\frac{L}{D} \leq 0.5$
1		$0.5 < \frac{L}{D} < 3$
2		$\frac{L}{D} \geq 3$

2nd Digit

			External Shape, external shape elements
0			Smooth, no shape elements
1	Stepped to one End		no shape elements
2		or smooth	with screwthread
3			with functional groove
4	Stepped to both Ends (Multiple increases)		no shape elements
5			with screwthread
6			with functional groove
7			functional taper
8			Operating thread
9			Others (> 10 functional diameters)

3rd Digit

		Internal Shape, internal shape elements
0		Without through bore blind hole
1	Smooth or Stepped to one End	no shape elements
2		with screwthread
3		with functional groove
4	Stepped to both Ends (Multiple increases)	no shape elements
5		with screwthread
6		with functional groove
7		functional taper
8		Operating thread
9		Others (> 10 functional diameters)

4th Digit

	Plane Surface Machining
0	No surface machining
1	External plane surface and/or surface curved in one direction
2	External plane surfaces related to one another by graduation around a circle
3	External groove and/or slot
4	External spline and/or Polygon
5	External plane surface and/or slot and/or groove, spline
6	Internal plane surface and/or groove
7	Internal Spline and/or Polygon
8	External and Internal splines and/or slot and/or groove
9	others

5th Digit

		Auxiliary Hole(s) and Gear Teeth
0	no gear teeth	No auxiliary hole(s)
1		axial hole(s) not related by a drilling pattern
2		axial holes related by a drilling pattern
3		radial hole(s) not related by a drilling pattern
4		holes axial and/or radial and/or in other directions, not related
5		holes axial, and/or radial and/in other directions related by drilling pattern
6	with gear teeth	spur gear teeth
7		bevel gear teeth
8		other gear teeth
9		others

FIGURE 34. The geometrical codes of rotational part without deviation

the digit can be determined by answering a series of questions. This is because a tree structure for the series of questions (shown in Figure 35) can be formed. For the part shown in Figure 33, the external shape is stepped to the left end. No shape elements are included in this part. Thus, the code number of second digit for this part is determined as "1". The decision processes to derive the code number are also shown in Figure 35.

The third digit of the rotational part without deviation shows an internal shape and internal shape elements. The code number for this digit can also be determined by answering a series of questions because a tree structure of the series of questions, shown in Figure 36 can be formed. For the part shown in Figure 33, the internal shape is also stepped to the right end. A functional groove is present in the internal shape. Thus, the code number of third digit of the part is determined as "2". The decision processes to derive the code number are also shown in Figure 36.

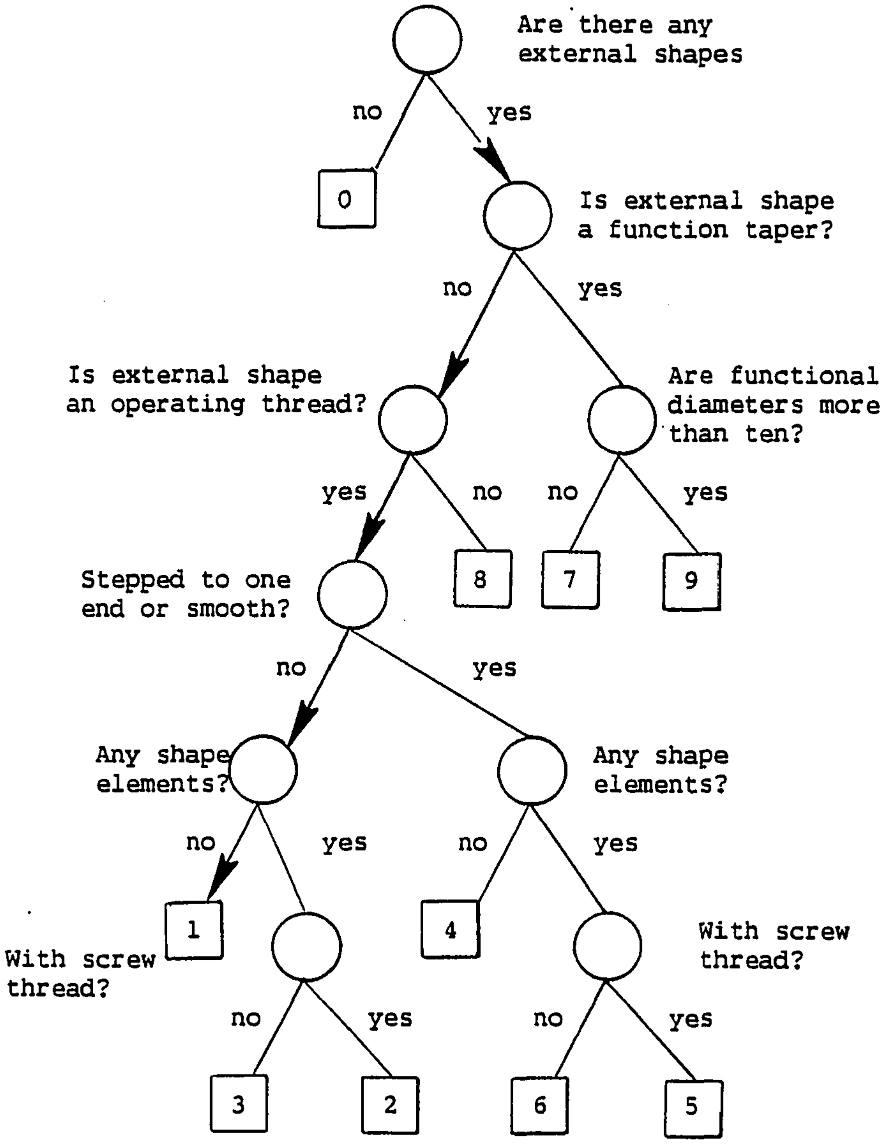
The fourth digit of the rotational part without deviation considers plane surface machining. A unique series of questions cannot be formed for this digit because several geometrical features are included in one code number as shown in Figure 34. Thus, the following menu of geometrical characteristics for each code number is provided:

0: No surface machining

1: External surface and/or surface curved in one direction.

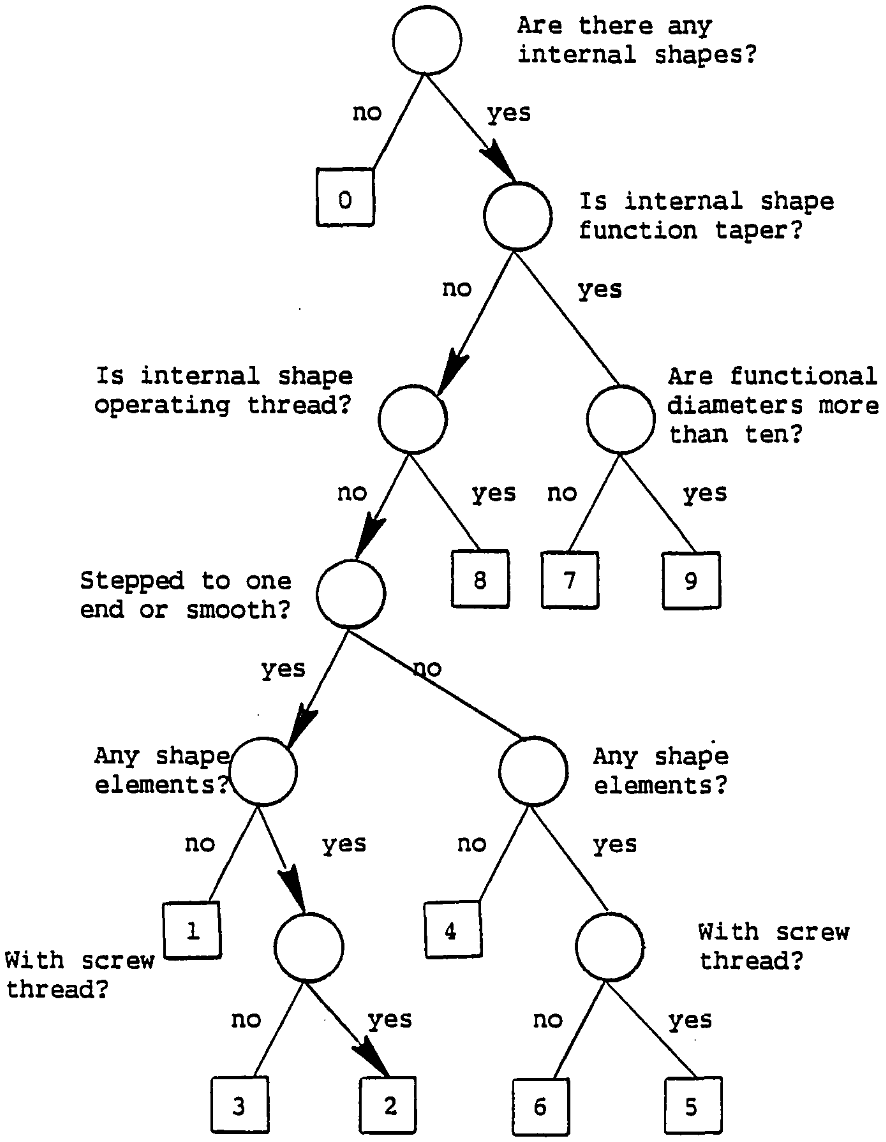
2: External plane surfaces related to one another by graduation around a circle.

3: External groove and/or slot.



Shape elements: Grooves for V-belts, Sealing rings Functional tapers and treads etc.

FIGURE 35. The hierarchical tree structure of questions for the second digit of the rotational part without deviation



Shape elements: Grooves for V-belts, Sealing rings
Functional tapers and treads etc.

FIGURE 36. The hierarchical tree structure of questions for the third digit of the rotational part without deviation

4: External spline and/or slot.

5: External plane surface and/or slot and/or groove, spline.

6: Internal plane surface and/or groove.

7: Internal spline and/or groove.

8: External and internal splines and/or slot and/or groove.

9: Others

For the part shown in Figure 33, an external plane surface machining is present. Thus, the code number of fourth digit of the part is determined as "1".

The fifth digit of the rotational part without deviation considers an auxiliary hole(s) and gear teeth machining. The geometrical characteristics of each code number are shown in Figure 37. A unique series of questions to derive a specific code number cannot be formed for this digit. The only question which can be structured for this digit is whether machining of gear teeth is involved. Based on the answer to the question, the following list of geometrical characteristics can be presented to the users [47]:

If the answer is "yes":

0: No auxiliary hole(s).

1: Axial hole(s) not related by a drilling pattern.

2: Axial hole(s) related by a drilling pattern.

3: Radial hole(s) not related by a drilling pattern.

4: Holes axial and/or radial and/or in other directions, not related.

5: Holes axial, and/or radial and/in other directions related by drilling pattern.

If the answer is "no":

6: Spur gear teeth.

7: Bevel gear teeth.

8: Other gear teeth.

9: Others.

For the part shown in Figure 33, no machining of gear teeth is involved. One axial hole which requires a drilling pattern is present. Thus, the code number of the fifth digit for the part can be selected as "2". The geometrical code of the part shown in Figure 33 can be "01212".

5. An example using a non-rotational part

The coding procedure is again illustrated with a non-rotational part. The part drawing for the example part is shown in Figure 38. The non-rotational part is defined as a rectangular prism in the Opitz system [47].

The non-rotational part is further classified into three different components. These include a flat part, a long part, and a cubic part based on dimensional ratios. The lengths of three edges are required to determine the dimensional ratio. These lengths are denoted by A, B, and C such that A > B > C. The dimensional ratios required for each component class are shown in Table 7.

For the part shown in Figure 38, the lengths of three edges are determined to be as A=425 mm, B=250 mm, and C=80 mm. Two dimensional ratios are A/B=1.7 and A/C=5.3125. The first dimensional ratio A/B is

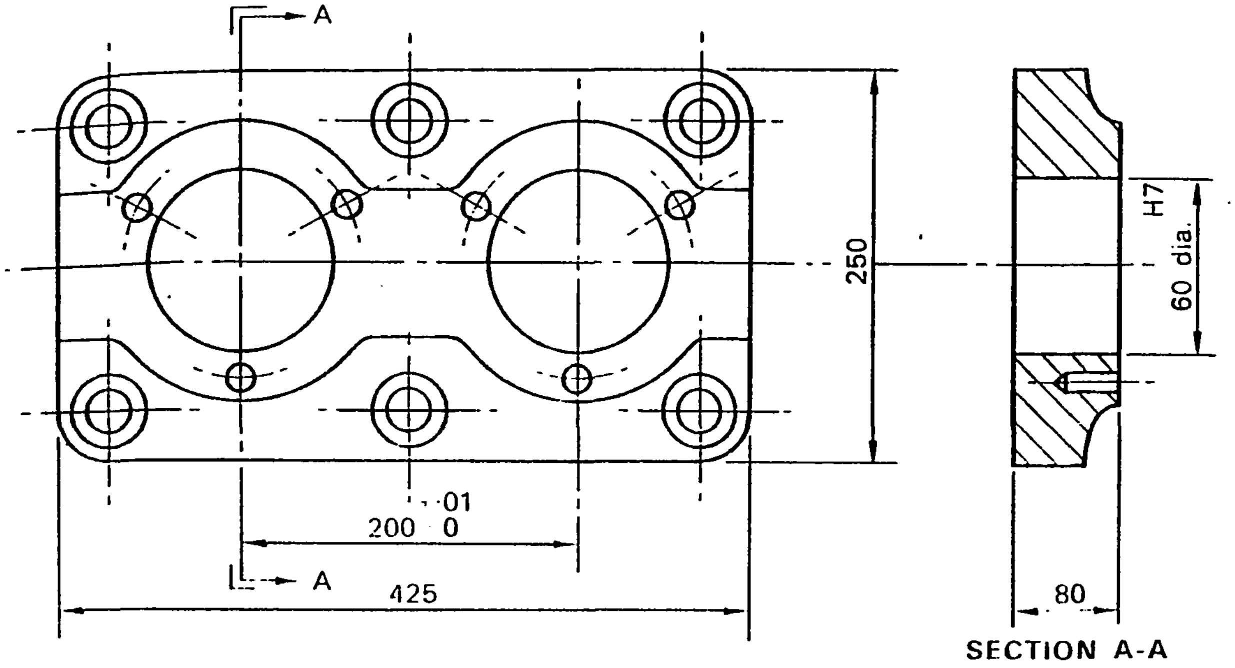


FIGURE 38. Example of the non-rotational part

TABLE 7. The dimensional ratio required for each component class for the non-rotational part

Component	Code number	Dimensional ratio
Flat	6	$A/B \le 3$, $A/C \ge 4$
Long	7	$A/B > 3$
Cubic	8	$A/B \le 3$, $A/C < 4$

less than 3. The second dimensional ratio is greater than 4. Thus, the part is classified as a flat component. The corresponding code number is "6".

The geometrical code of the following digits for flat part are shown in Figure 39. As shown in Figure 39, a unique series of questions to derive specific code number for the following digits cannot be formed. Thus, the lists of geometrical features of each code number (a menu) can be presented to users.

The second digit considers a part's overall shape. The hierarchical tree structure for this digit cannot be formed. Two basic shapes are included which include a plane shape and a flat shape [47]. Based on these two basic shapes, the geometrical features of each code number can be presented to users as a menu. The geometrical features of each code number are shown in Figure 39. For the part shown in Figure 38, the overall shape is flat and rectangular with small deviations. Thus, the code number "5" is selected as the second digit.

GEOMETRICAL CODE

	1st Digit	2nd Digit		3rd Digit	4th Digit	5th Digit		
	Component Class	Overall Shape		Principal bore, rotational surface machining	Plane Surface Machining	Auxiliary hole(s) Forming. Gear Teeth		
0		Plane	Rectangular	No rotational machining or bore(s)	No Surface *Machining*	No auxiliary holes, gear teeth and forming		
1			Rectangular, with one deviation (Right Angle or Triangular)	One principal bore, smooth	Functional Chamfers (e.g. welding prep.)	No gear teeth, no forming		Holes drilled in one direction only
2			Rectangular, with angular deviations	One principal bore stepped to one or both ends	One plane surface			Holes drilled in more than one direction
3			Rectangular with circular deviation	One principal bore with shape elements	Stepped plane surfaces		related by a drilling pattern	Holes drilled in one direction only
4			Any flat shape other than 0 to 3	Two principal bores, parallel	Stepped plane surfaces *at right angles, inclined* and/or opposite			Holes drilled *in more than* one direction
5			Flat components, rectangular or right angled with small deviations due to casting, welding, forming	Several principal bores, parallel	Groove and/or Slot	Forming, no *Gear Teeth*		Formed, *no auxiliary* holes
6	Flat Components $\frac{A}{B} \cdot 3$, $\frac{A}{C} \cdot 4$		Flat Components, round or of any shape other than position 5	*Several principal bores,* other than parallel	*Groove and/or Slot* and 4			Formed, with auxiliary holes
7			Flat Components regularly arched or dished	Machined *annular* surfaces, annular grooves	Curved Surface	Gear teeth, no auxiliary hole(s)		
8			*Flat Components* irregularly arched or dished	7 + principal bore(s)	Guide Surfaces	Gear teeth, with auxiliary hole(s)		
9			Others	Others	Others	Others		

FIGURE 39. Geometrical codes of the flat component class

The third digit considers whether the part has a principal bore and a rotational surface machining. It is not possible to form a unique series of questions which leads to a specific code number for this digit. The geometrical features of each code number of the digit are presented to users as a menu. These features are shown in Figure 39. For the part shown in Figure 38, two parallel principal bores are shown. Thus, the code number "4" is selected as the third digit.

The fourth digit considers plane surface machining. The geometrical features of each code number are presented to users as a menu for this digit. For the part shown in Figure 38, a plane surface machining at right angle is present. The code number "4" is selected as the fourth digit.

The fifth digit considers whether an auxiliary hole(s), and gear teeth, with or without forming are present. The geometrical features shown in Figure 39 were presented to users as a menu. For the part shown in Figure 38, holes which are related by drilling pattern in one direction are present in the drawing. The code number "3" is selected as the fifth digit. The Opitz codes for the example part are thus "65443".

The software that evolved from this research was developed such that users can either respond to a series of questions or selecting geometrical features from given menu to derive geometrical codes of a part. By using the software, the parts collected for this research were coded. The code numbers for all parts analyzed are presented in Appendix B.

6. Data requirements for clustering algorithms

In order to use two clustering algorithms to define families based on geometrical characteristics of parts, the part-characteristic matrix must be formed. This matrix represents the geometrical characteristics which each part possesses. The columns of this matrix represent geometrical characteristics. The rows of this matrix represent the parts. The matrix was formed based on the geometrical codes of the Opitz system.

The formation of this matrix is illustrated with a new set of example parts shown in Table 8. Table 8 contains the part name, the part number, and the Opitz code numbers. In order to form the part-characteristic matrix, the geometrical characteristics that all the parts possess are determined first. These geometrical characteristics obtained for the example parts are shown in Table 9. The geometrical characteristics are used to form the incidence matrix. The part-characteristic incidence matrix (denoted by $PCMAT_{ij}$) was formed based on the following:

$$PCMAT_{ij} = \begin{cases} 1 & \text{if a part i has geometrical characteristic j} \\ 0 & \text{otherwise} \end{cases}$$

The part-characteristic incidence matrix obtained for the example parts is shown in Figure 40. Two clustering algorithms were applied to this matrix to define part families based on the geometrical characteristics of a part. This defines the two coding and classification methods; OPITZ/ROCA and OPITZ/CASC.

TABLE 8. The geometrical codes of selected parts

Part name	Part number	Opitz codes
Bus bar	370452703	6 0 0 5 3
HD. Copper	126460138	6 0 1 0 3
Stud	370401009	2 2 0 0 0
Contact	687004001	2 4 0 0 0
Rod	687006001	2 4 0 0 0

TABLE 9. The geometrical characteristics obtained for the example parts

Digit	Characteristics description
Digit 1	x_1 - rotational parts w/o deviations ($0.5 < L/D < 3$) x_2 - flat parts ($A/B \leq 3$, $A/C \geq 4$)
Digit 2	x_3 - cylindrical with no shape elements x_4 - stepped cylindrical with no shape elements x_5 - rectangular
Digit 3	x_6 - without through bore x_7 - no rotational machining x_8 - one principal bore
Digit 4	x_9- no surface machining x_{10} - groove and/or slot
Digit5	x_{11} - holes drilled in one direction related by drilling pattern x_{12} - no auxiliary hole(s) and gear teeth

$$\begin{array}{l|cccccccccccc|}
\text{characteristic} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \\
\text{Part} & & & & & & & & & & & & \\
\text{Bus-bar} & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\
\text{HD-copper} & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
\text{Stud} & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 \\
\text{Contact} & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 \\
\text{Rod} & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0
\end{array}$$

FIGURE 40. The part-characteristic incidence matrix obtained for the example parts

D. Implementation of the ROCA Clustering Algorithm

1. Overview

The rank order clustering algorithm (ROCA), developed by King [30], was implemented in this procedure to define families of parts. The part-machine matrix from the PFA analysis and the part-characteristic matrix from the Opitz system are used as input matrices for the ROCA algorithm. The ranking algorithm is programmed according to the steps which will be described in the following section. The incidence matrix which is formed from the PFA coding method example is used to illustrate this clustering algorithm. This matrix represents the part and the machine requirements in the process routings. The matrix is shown in Figure 41.

$$\begin{array}{cc}
\text{Part} \quad \text{Machine} & \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\
\begin{array}{c} \text{AA} \\ \text{BB} \\ \text{CC} \\ \text{DD} \\ \text{EE} \\ \text{FF} \\ \text{GG} \end{array} &
\begin{bmatrix}
0 & 1 & 1 & 0 & 1 \\
1 & 0 & 0 & 1 & 0 \\
0 & 1 & 1 & 0 & 0 \\
1 & 0 & 0 & 1 & 0 \\
1 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 1 & 0 \\
0 & 0 & 1 & 0 & 1
\end{bmatrix}
\end{array}$$

FIGURE 41. The part-machine incidence matrix obtained for the data

The following variables are used in implementation of the ROCA:

tnp:	Total number of parts
id:	Total number of machines
col:	Index of machine of a part-machine matrix
row:	Index of part of a part-machine matrix
mach(i):	list of machines
pmmat(i,j):	Incidence matrix
atp(i):	Total number of machines used for part i
route(i,j):	Process sequence for part i and machine j
y:	Row number with entry
z:	Row number with no entry

2. Clustering procedure

The rows of the part-machine matrix are used to represent parts collected for this study. The columns indicate machines used to manufacture the parts. The ranking processes consist of sorting procedures of rows and columns. The basic steps involved in both row and column reordering procedures are the same. The steps of row reordering procedure are as follows:

Step 1: Start sorting procedure with last column

Step 2: Make two lists for this column
List 1: row numbers which have an entry
List 2: row numbers which have no entry

Step 3: Combine two lists by putting the list 1 ahead of the list 2

Step 4: Determine whether the ranking procedure is done for all columns.
If no, decrement current column number by 1
If yes, goto step 5

Step 5: Rearrange the part-machine matrix according to the new ranking.

The flow chart for the reordering procedure is shown in Figure 42.

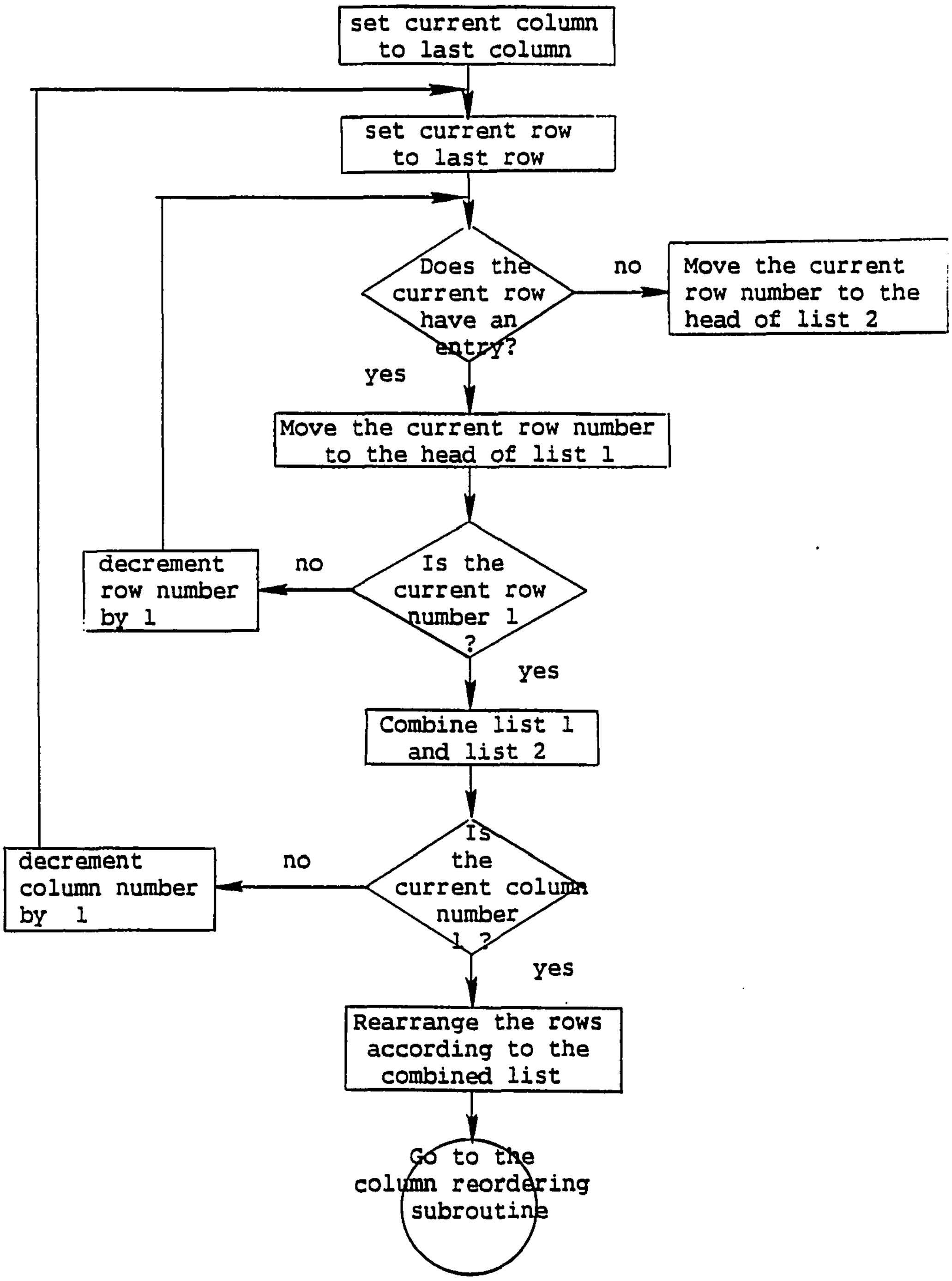


FIGURE 42. Flow chart for sorting procedure

The reordering procedure for columns is exactly the same as one for rows. Thus, the following ROCA algorithm can be described by the following sequence of code:

ROCA Algorithm:

```
REPEAT
  FROM the last column TO the first column
  DO          (*row reordering*)
      locate the rows (*machines*) with entries;
      move the rows with entries to the head of the
      row list, maintaining the previous order of the
      entries
  END DO;     (*row reordering*)
  FROM the last row TO the first row
  DO          (*column reordering*)
      locate the columns (*part*) with entries;
      move the columns with entries to the head of the
      column list, maintaining the previous order of
      the entries
  END DO      (*column reordering*)
UNTIL (no change AND inspection required)
```

The algorithm can be illustrated with the matrix presented in Figure 41. The stages involved in row ordering of the matrix are shown in Figure 43(a). The first line shows the initial row list. For the last column (5) the underlined entries 1 and 7 are the machines for this column. They are moved in this order to the front of the list, as indicated in line 2 of Figure 43(a). For the next column of the matrix (column 4), the machines entries are 2, 4, and 6. They are underlined in line 2 of Figure 43(a). These entries are moved to the front of the list to form line 3 of Figure 43(a). This process is repeated for the remaining columns of the matrix. The matrix is rearranged according to the ranks determined by this row reordering operation. The matrix is shown in right hand side of Figure 43(a).

$$
\begin{array}{llccccccc}
 & & \multicolumn{7}{c}{\text{Row list}} \\
\text{Column no.} & 5 & \underline{1} & 2 & 3 & 4 & 5 & 6 & \underline{7} \\
 & 4 & 1 & 7 & \underline{2} & 3 & \underline{4} & 5 & \underline{6} \\
 & 3 & 2 & 4 & 6 & \underline{1} & \underline{7} & \underline{3} & 5 \\
 & 2 & \underline{1} & 7 & \underline{3} & 2 & 4 & 6 & 5 \\
 & 1 & 1 & 3 & 7 & \underline{2} & \underline{4} & \underline{6} & \underline{5} \\
 & & 2 & 4 & 6 & 5 & 1 & 3 & 7
\end{array}
\qquad
\begin{array}{ll}
 & \text{Machines} \\
 & \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\
\text{Parts} & \begin{array}{c|ccccc|}
2 & 1 & 0 & 0 & 1 & 0 \\
4 & 1 & 0 & 0 & 1 & 0 \\
6 & 1 & 0 & 0 & 1 & 0 \\
5 & 1 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 1 & 0 & 0 \\
3 & 0 & 1 & 1 & 0 & 0 \\
7 & 0 & 0 & 1 & 0 & 1
\end{array}
\end{array}
$$

(a) Stages involved in the row reordering
and the result matrix

$$
\begin{array}{llccccc}
 & & \multicolumn{5}{c}{\text{Column list}} \\
\text{Row no.} & 7 & 1 & 2 & \underline{3} & 4 & \underline{5} \\
 & 6 & \underline{3} & 5 & 1 & \underline{2} & 4 \\
 & 5 & \underline{3} & \underline{2} & 5 & 1 & 4 \\
 & 4 & 3 & 2 & 5 & \underline{1} & 4 \\
 & 3 & \underline{1} & 3 & 2 & 5 & \underline{4} \\
 & 2 & \underline{1} & \underline{4} & 3 & 2 & 5 \\
 & 1 & \underline{1} & \underline{4} & 3 & 2 & 5 \\
 & & 1 & 4 & 3 & 2 & 5
\end{array}
\qquad
\begin{array}{ll}
 & \text{Machines} \\
 & \begin{array}{ccccc} 1 & 4 & 2 & 3 & 5 \end{array} \\
\text{Parts} & \begin{array}{c|ccccc|}
2 & 1 & 1 & 0 & 0 & 0 \\
4 & 1 & 1 & 0 & 0 & 0 \\
6 & 1 & 1 & 0 & 0 & 0 \\
5 & 1 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 1 & 1 & 1 \\
3 & 0 & 0 & 1 & 1 & 0 \\
7 & 0 & 0 & 1 & 0 & 1
\end{array}
\end{array}
$$

(b) Stages involved in the column reordering
and the result matrix.

FIGURE 43. The results obtained from the ROCA

Column reordering is carried out in a similar way but starting with the current column order 1,2,3,4,5, and the current row order 2,4,6,5,1,3,7. The stages involved are shown as the successive underlined entries of Figure 43(b). The new column order is determined to be 1,4,2,3,5. The result matrix is also shown in the right hand side of the Figure 43(b). In this example, the algorithm stops after column reordering operation because no "exceptional" elements exist in this example. Two part families are formed in this example as presented in Figure 43(b). The first family includes parts 2, 4, 6, and 5. The second family includes parts 1, 3, and 7.

Output obtained by executing ROCA software developed in this research is shown in Figure 44. The initial matrix shown in the figure was the input data for the ROCA algorithm. The algorithm stopped after first iteration because no further row or column exchanges occurred. The final matrix after first iteration was investigated whether exceptional parts or machines were existed. The exceptional parts are those parts which require some of their operations to be performed on the machines belonging to other groups. The exceptional machines are those machines which are required by a relatively large number of parts [29]. There are no such elements with the example. Thus, two part families; (2,4,6,5) and (1,3,7) are defined.

The algorithm is applied to both the PFA and the Opitz coding methods. After each run, the final matrix is inspected to determine whether exceptional elements exist. If so, such elements are

```
                              Result of ROCA


***** The initial Part-Machine *****


Iteration    0

  part/  mach       ABCDE

  1    01           01101
  2    02           10010
  3    03           01100
  4    04           10010
  5    05           10000
  6    06           10010
  7    07           00101


***** The matrix after row reordering ****

Iteration    1

  part/  mach       ABCDE

  2    02           10010
  4    04           10010
  6    06           10010
  5    05           10000
  1    01           01101
  3    03           01100
  7    07           00101
```

FIGURE 44. The actual output of ROCA algorithm obtained for the example parts

```
***** The incidence matrix after column reordering *****

Iteration   1

  part/  mach      ADCBE

  1    02          11000
  2    04          11000
  3    06          11000
  4    05          10000
  5    01          00111
  6    03          00110
  7    07          00101


***** The matrix after row reordering ****

Iteration   2

  part/  mach      ADCBE

  1    02          11000
  2    04          11000
  3    06          11000
  4    05          10000
  5    01          00111
  6    03          00110
  7    07          00101



***** Number of machine usage *****

Number        Machine No.  Machine id.   num. of usage
 1               1            A              4
 2               4            D              3
 3               3            C              3
 4               2            B              2
 5               5            E              2
```

FIGURE 44. (Continued)

eliminated from the analysis, and the matrix is rearranged because those elements may limit the formation of block-diagonalized matrix. The ROCA algorithm is again applied until there is no change of rows and columns. Thus, the main program of the ROCA algorithm can be summarized by the following procedure:

```
IF (start afresh)
   THEN read data from file
   ELSE add more data
END IF:
REPEAT (*the whole loop*)
   IF (information about machines and components required)
      THEN print as much as requested
   END IF:
   REPEAT (*interactive*)
   CASE
      1: Selecte part of current matrix for detailed
         inspection.
      2: specify exceptional elements
      3: return exceptional elements to normal status
      4: specify or remove bottleneck status of particular
         machines
      5: increase the number of machines of specified type
      6: merge machines of the same type
   END CASE:
   UNTIL (no further action required);
   (*end of interaction*)
   implement ROCA:
   print current matrix and other data as requested
UNTIL (block diagonal form OR time off to consider next move);
(*end of the whole loop*)
```

E. Implementation of CASC Clustering Algorithm

1. Overview

Minimum spanning trees (MST) and single linkage cluster analysis (SLCA) are used to implement the CASC algorithm. The SLCA uses similarity coefficients between pairs of parts. Pairs are formed by selecting another parts which has the largest degree similarity. In order to apply SLCA in this research, the the similarity coefficient matrix whose dimension is 233x233 is calculated and saved in computer memory. By constructing of MST's of the similarity matrix, there is no need to save such a large matrix in memory. This is because all the information required for the SLCA of a set of points is contained in their MST [19]. Many algorithms for finding the MST are known. Prim's algorithm was adopted in constructing the MST because it is an efficient algorithm in terms of both computation time and memory requirements [19].

The following variables are defined to implement the CASC clustering algorithm:

n: The number of points = the order of similarity coefficient matrix.
dlarge: The arbitrary value less than the minimum of of the similarity coefficient matrix.
D : The lower triangular similarity matrix with bound [1:nx(n-1)/2].
A(i) : If i is already assigned to the tree (initially consisting of no. 1 only), or 0 otherwise.
B(i) : The index of a part to which i is jointed.
C(i) : Similarity coefficient between i and B(i).
ifault: Set to 1 if n less than 2, 0 otherwise.
delta : The amount by which the clustering threshold is raised at each iteration.

2. The data array

Figure 45 shows an example of raw data array which could be used in the CASC cluster analysis. From the Figure 45 it can be seen that each row of the array consists of description of a single part or processing machine in terms of presence or absence of a machining operation. For the program, the convention 1 = 'operation required' and 0 = 'operation not required' was adopted.

		machines				
		1	2	3	4	5
parts	AA	0	1	1	0	1
	BB	1	0	0	1	0
	CC	0	1	1	0	0
	DD	1	0	0	1	0
	EE	1	0	0	0	0
	FF	1	0	0	1	0
	GG	0	0	1	0	1

FIGURE 45. Example of an incidence matrix

3. Construction of the similarity coefficient matrix

The SLCA algorithm was performed based on the similarity coefficient matrix. Three variables, denoted by A, B and C, are used to calculate the similarity coefficient between part i and part j. The variable A contains the number of elements which both parts have as attributes. The variable B contains the number of elements for which part i has an attribute, but part j has not. The variable C contains the number of elements for which part j has an attribute, but part i has not. For the example shown in Figure 45, both part AA and part CC require two machines 2 and 3. Part AA requires machine 5, but part CC does not. Thus, A, B, and C are 2, 1, and 0 respectively for part AA and part CC. The similarity coefficient between the part AA and the part CC is then calculated as A/(A+B+C) which is 2/3 [16].

By repeating the above procedure, the similarity coefficients were calculated for every two parts collected for this research. The similarity coefficient matrix obtained for the example represented by the part-machine incidence matrix, shown in Figure 45, is shown in Figure 46. The entries in the matrix show the similarity coefficients between two parts. The entries in upper triangular portion of the matrix are the same as those in lower part which is shown. Based on this matrix, the minimal spanning tree of the matrix can be constructed. The construction of the MST is explained in the following section.

		Part						
		AA	BB	CC	DD	EE	FF	GG
Part	AA	0						
	BB	0	0					
	CC	2/3	0	0				
	DD	0	1	0	0			
	EE	0	1/2	0	1/2	0		
	FF	0	1	0	1	1/2	0	
	GG	1/2	0	1/3	0	0	0	0

FIGURE 46. The similarity coefficient matrix obtained for the example

4. Construction of the MST

The SLCA algorithm starts with constructing the minimal spanning (MST) tree of the similarity coefficient matrix. The Prim's algorithm is used to find the MST because it is faster and requires each similarity coefficient between two parts only once. The similarity coefficient matrix therefore need not be stored in the memory.

The flow chart for constructing the MST is shown in Figure 47. The following variables were used to construct the MST of similarity coefficient matrix:

rowl: indicates the part i of part-machine matrix
row2: indicates the part j of part-machine matrix
A: number of machines visited by both parts i and j
B: number of machines visited by part i but not by part j
C: number of machines visited by part j but not by part i
dist: used to store the similarity coefficient between part i and part j
min: indicate the current largest similarity coefficient of part j
nex: indicate next candidate part j

The other variables were defined in the beginning of this chapter. In order to compute the MST, three lists are formed. They are described below:

List 1: An indicator which is 1 if P belongs to group A, and 0 otherwise.

List 2: For members of group A, the reference number of the point to which P was linked when it joined group A. For members of group B, the reference number of the point in group A nearest to P

List 3: For all points the distance between P and the point referred to in list 2.

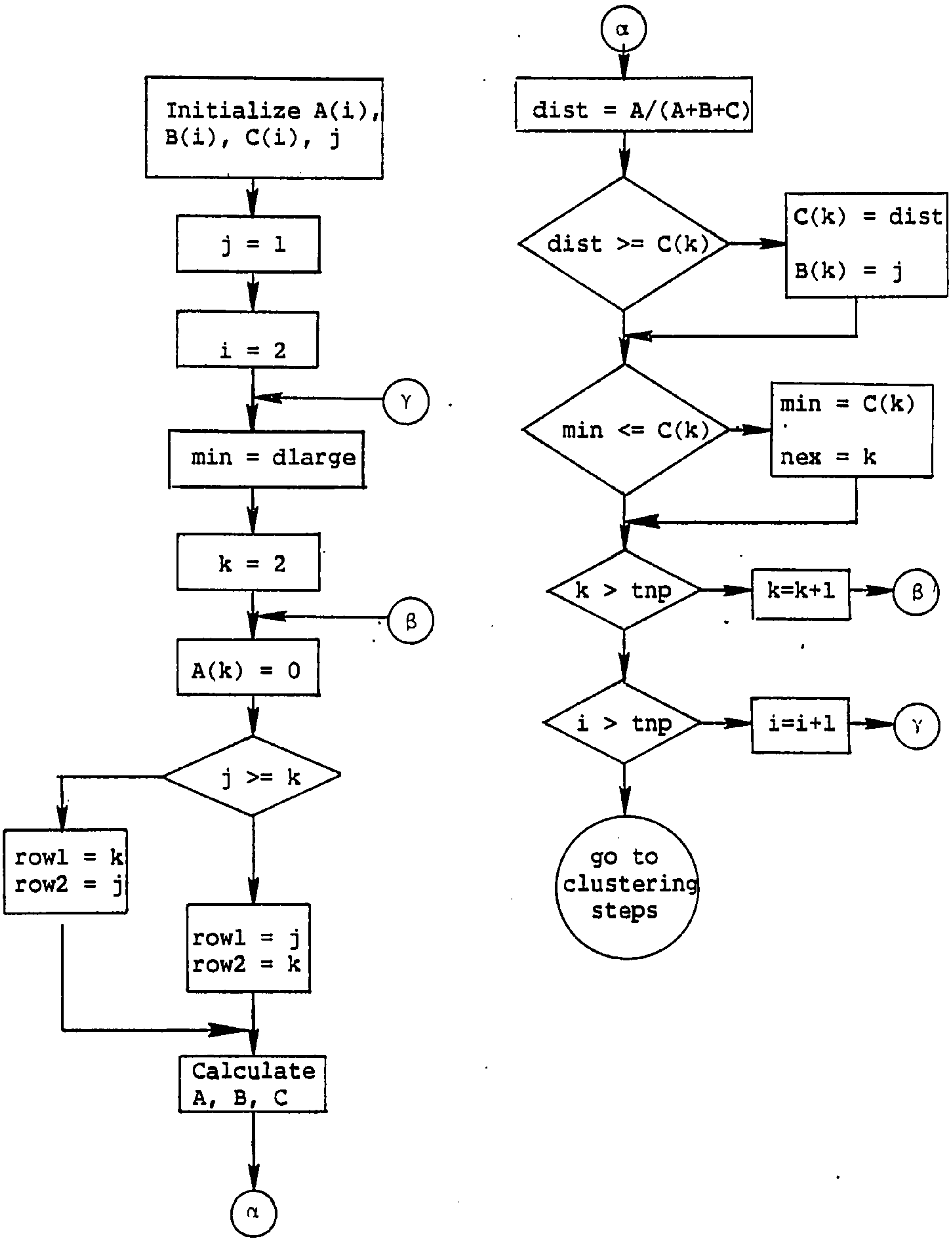


FIGURE 47. Flow chart for constructing the MST

Initially point 1 is assigned to group A. Let Q be the latest addition to A. Then the distance PQ is calculated for each member of B. If it is less than the value recorded in list 3, Q and the new distance are substituted for the values in lists 2 and 3. Simultaneously the minimum value of the distances recorded in list 3 for members of B is found, and the next point Q is determined. The new point Q is then assigned to A. The process terminates when all points belong to group A. The minimal spanning tree obtained from the example is shown in Table 10.

TABLE 10. The minimal spanning tree obtained from the example

From part	To part	Distance (similarity coefficient)
BB	DD	1
CC	AA	2/3
DD	FF	1
EE	BB	1/2
FF	CC	0
GG	AA	2/3

5. Single linkage cluster analysis

Single Linkage Cluster Analysis was developed by Sneath and Sokal [65]. The distance threshold δ is given as data. The maximum similarity coefficient d_{max} is computed because the sorting begins at L_0; the largest multiple of δ which is less than d_{max}. A list H is formed of all links whose lengths lie between L and $L+\delta$.

A list G containing the group members is then formed, marking the final member of each group with an indicator. The list G consists initially of all points as single groups.

At the beginning of the procedure, the minimal spanning tree is created from the similarity coefficient matrix. The next procedure consists of a sorting scheme that determines clusters at a series of decreasing distance thresholds $(d_1, d_2, \ldots.)$.

The clusters at level d_i are constructed according to the following steps:

Step 1: Find maximum similarity coefficient (D_{max})

Step 2: Set all the points as single groups

Step 3: Set starting cluster level to integral multiple
of δ which is greater than d_{min}, the
shortest link of the minimum similarity coefficient

Step 4: For each link in array C that is greater than the
level, amalgamate two clusters

Step 5: Decrease all links of jointed points to zero to
prevent re-use

Step 6: All the points are clustered in a single group?
If no, Go to Step 7
If yes, Stop

Step 7: Decrease the cluster level by δ and go to
Step 4

The SLCA algorithm is illustrated with the minimal spanning tree shown in Table 10. The distance threshold δ is set to 0.01 for the example. The maximum similarity coefficient D_{max} can be found easily in the Table 10 which is 1.00. The clustering starts at the level 1.00. At this level, all parts are in separate group. At the level of similarity coefficient 0.99, parts (2,4,6) are in one family because their coefficients are greater than 0.99. At the level 0.66, (1,3,7) is another family because their coefficients are greater than 0.66. The number of families and their part members are shown in Table 11 at different similarity coefficient levels. Two part families with same members which are also obtained by ROCA algorithm are formed at similarity coefficient 0.49. The two families are parts (1,3,7) and (2,4,6,5).

TABLE 11. The result of SLCA for the example

Similarity coefficient	Number of family	Part numbers
1.00	7	(1) (2) (3) (4) (5) (6) (7)
0.99	5	(1) (2,4,6) (3) (5) (7)
0.66	3	(1,3,7) (2,4,6) (5)
0.49	2	(1,3,7) (2,4,6,5)
0.00	1	(1,3,7,2,4,6,5)

The actual output for the example is also shown in Figure 48. The last member of each family is indicated by * in the actual output. Prim's tree structure of similarity coefficients and the results of the SLCA are shown in the figure. The results obtained correspond with those shown in Tables 10 and 11.

```
                         Results of CASA


                      Prim's Tree Structure


02             2              4              1
03             3              1              .6666667
04             4              6              1
05             5              2              .5
06             6              3              0
07             7              1              .6666667


          Result of Single Linkage Cluster Analysis

level =  1.01

number of clusters =  7

 1 *
 2 *
 3 *
 4 *
 5 *
 6 *
 7 *
```

FIGURE 48. The actual output of CASC algorithm obtained for the example parts

```
level =  .99

number of clusters =  5

 1 *
 2  4  6 *
 3 *
 5 *
 7 *


level =  .6600003

number of clusters =  3

 1  3  7 *
 2  4  6 *
 5 *


level =  .4900005

number of clusters =  2

 1  3  7 *
 2  4  6  5 *


level = -9.999329E-03

number of clusters =  1

 1  3  7  2  4  6  5 *
```

FIGURE 48. (Continued)

VII. RESULTS OF ANALYSIS

A. Introduction

Many industrial robots used in industry today are inefficient because they lack the ability to handle different part geometries. One goal of this research has been to design X-change robotic gripper sets to handle different part geometries. The part families were formed by using group technology techniques to utilize the geometrical similarities of parts within families in the design of the gripper sets. Actual manufacturing data including part drawings and process routings were collected from four manufacturing organizations.

Altogether, 233 parts were involved in the analysis. In part coding, it was necessary to analyze all drawings and route sheets for the parts to be coded. This is because the codes were formed from the parts' geometrical characteristics and process routes. Computerized coding and classification systems were applied on the combined data base to define part families for the design of robotic gripper sets. In this chapter, the part families and their characteristics from each coding and classification system used are identified and discussed.

B. Formation of Part Families

1. Overview

The data from four manufacturing organizations were combined into one database in Chapter V. This database was used to form part families by using the computer software developed and described in the preceding chapter. Individual sets of part families were obtained for the four different coding and classification methods.

Two coding methods and two classification algorithms, discussed in Chapter III, were applied to define part families. Thus, four coding and classification methods; PFA/CASC, PFA/ROCA, Opitz/CASC and Opitz/ROCA were applied. The families and their component parts for each method are identified and discussed in the following section.

2. Part families of the PFA/CASC method

This method uses process sequences of parts as a basis for coding and similarity coefficients between parts for classification. The only data used were the number of machines and the parts which visited each machine, in effect, the part-machine matrix. This means that neither the process sequence nor the loading on each machine were taken into account. The sequence in which the parts visited the machines did not affect the definition of part families.

The clustering procedure was performed iteratively as the clustering level was lowered. The similarity coefficient calculated based on the process routings was used to represent the clustering level. The clustering procedure started at the similarity coefficient 1.00 in this method. Families were combined to form a new family as the level of clustering was lowered. The level of similarity coefficient was lowered by increments 0.01. The amalgamation of families took place when the similarity coefficients of the families were greater than a certain clustering level. The clustering process was continued until the level of similarity coefficient reached to 0.00.

The number of part families depends on the clustering level represented by similarity coefficient in this method. The number of families formed at various levels of similarity coefficients are shown in Table 12. As can be seen in Table 12, one family is formed at the similarity coefficient level 0.00 where the clustering algorithm stops. It can also be seen that 233 families were formed at the similarity coefficient level of 1.00.

TABLE 12. Number of families at each level of similarity coefficient

Level of similarity coefficient	Number of families
1.00	233
0.99	150
0.87	149
0.85	147
0.83	138
0.79	123
0.74	91
0.71	87
0.66	46
0.59	36
0.57	33
0.49	6
0.42	5
0.39	3
0.33	2
0.00	1

Five major part families out of a total of 91 were formed at the similarity coefficient 0.74. The level was selected because the 91 families at this level was approximately midway between two extremes 233 and 1. At this level of coefficient many families had one part member. Only families which had ten or more parts as members were selected. Five major part families were obtained as a result. The part families and their members formed with the PFA/CASC coding and classification method are shown in Table 13. These families were defined at the similarity coefficient 0.74.

3. Part families of the PFA/ROCA method

This method is a coding and classification system in which process routes are used as a basis for a ranking process for rows and columns in a part-machine matrix. The objective of the ROCA algorithm is to generate diagonal groupings of the part-machine matrix entries. If the part-machine matrix can be divided into such diagonalized groups, the ROCA algorithm will generate the families of parts and groups of corresponding machines.

With the data collected for this research, it was not possible to divide the matrix into mutually exclusive families of parts and groups of machines. This was because of two cases discussed by King [29] which occurred with the data. The first case corresponded to some parts which required some of their operations to be performed on the machines belonging to other identifiable groups. The second case corresponded to "bottleneck" machines which were required by a relatively large number of parts in the data base.

TABLE 13. Part families formed by PFA/CASC method (Similarity coefficient = 0.74)

Family	Members (part number)			
1 (17 members)	0W019819012	2J496219012	1J1277000B2	2E4085000A2
	2L373522012	3N698122012	2E542919042	2L416322012
	3C780819042	3N698322012	2L342619012	2L339519012
	4E397919012	1R125624092	1R124835072	2F143224092
	2R124724092			
2 (10 members)	6870008005	6870008006	6870092001	6870093001
	6870239001	7578887003	7578887004	7578887010
	7578887009	7578889004		
3 (10 members)	6870112001	6874139001	7576591001	7610167002
	7576896001	7578887005	7578887006	7578887007
	7610014003	7574570001		
4 (46 members)	7J1025	4J4571	5J9110	5J0766
	5J1553	4J1091	4J2696	4J3291
	5J8793	8J5875	8J1917	3G0650
	9J3441	2J8069	4J6485	4T1014
	1U4010	9J4077	9T4097	9J4941
	5J8774	4T9165	3J7807	8J8660
	3S7445	9J1234	9J4847	9M5550
	7J8308	4T9151	4T0958	6J0433
	6J0434	8J0130	8J0444	6J9992
	8J1701	3T2321	7J5928	8J9257
	8J0084	5J8773	3G2842	7J3897
	8J8661	9J3453		
5 (20 members)	3J0601	5J1340	1U0488	3G2840
	3G2841	4T4632	6P5391	7J8056
	8J8573	8J2308	9J0752	5J0899
	9T1495	1U2083	7J2266	9J2382
	9T2887	9J3382	8J3554	8J3665

To overcome the problem, two relaxation methods suggested by King [29] were adopted. If "case #1" parts existed after each application of the clustering algorithm, the part's operations to be performed on the other groups of machines were ignored. If the bottleneck machines were found (case #2), the matrix was revised by decomposition that provided duplication of these machines to the extent each component operation was performed by one such machine.

A series of relaxation procedures was performed interactively until diagonal groupings of the parts-machines were obtained. The ROCA algorithm was applied on the revised matrix after each relaxation procedure. An investigation of the initial matrix showed that machines existed which were used less than 10 times to perform necessary operations. Those machines were excluded to permit the ROCA algorithm to produce a diagonalized block matrix.

Nine machines were excluded, and the initial matrix was revised. The ROCA algorithm was performed sequentially after revising the matrix with each relaxation method. The families which had ten or more part members were selected. Seven major part families were obtained in this method. The families and their component parts are shown in Table 14.

4. Coding parts with the Opitz system

The computer software for the Opitz system discussed in Chapter VI was used to code geometrical characteristics of parts. The Opitz codes for all the parts collected for this research are presented in Table 30 in Appendix B. The manual for the Opitz system [47] was also used

TABLE 14. Part families formed by PFA/ROCA method

Family	Members (Part number)			
1 (31 members)	3N698122012	2E542919042	2L416322012	3C780819042
	2E4085000A2	2L373522012	1J1277000B2	3N698322012
	1E3943000A2	2L339519012	2L342619012	4E397919012
	2N698722012	0W019819012	2J496219012	3E5210000A2
	1R124835072	11A5216X012	2F1428000A2	10A7182X012
	11A5214X022	1K586935162	1R250935162	4J3291
	3P786933092	3V708322012	6874216002	7610504001
	7575875001	7619594002	7575872002	
2 (45 members)	11A5324X012	11A5326X012	2F143224092	2R124724092
	3R124624092	5J1553	8J1917	7J1025
	4J4571	5J9110	5J8793	4J1091
	3J2973	5J2438	7J7674	3J1970
	2J5143	8J8829	4J2696	7J5928
	8J9257	5J0766	8J5875	2J8069
	4J6485	3J7807	8J8660	5J8773
	3G2842	7J3897	8J8661	9J3453
	6J0433	6J0434	8J0130	8J0444
	6J9992	8J1701	3T2321	1E501208012
	28A2514X012	38A2508X012	38A2511X012	8J2045
	1U2764			
3 (22 members)	6870003001	15A6470X012	6870174001	28A2519X012
	6870008004	15A6503X012	2R2617X0012	7575863006
	1U222646172	4T1889	6870092001	6870008005
	6870008006	6870093001	6870239001	7578887003
	7578887004	7578887009	7578887010	7578889004
	6870005001	7610493001		
4 (32 members)	6870181001	6870020002	6870027002	6870026002
	6870167003	6870021002	7575872001	6870112001
	6870007001	7576896001	7578889002	7578887002
	7578887001	6870364001	7578889001	7576591001
	7610167002	7574570001	7575955002	7578614001
	6870060001	6870341001	6870444001	7578677001
	6870148002	6874139001	6874008002	6870043001
	6870110001	6870407001	6874098001	6870127001
5 (31 members)	9J1234	9J4847	9M5550	4T1014
	1U4010	9J4077	9J4097	9J4941
	5J8774	4T9165	2R331019022	3J0601
	5J1340	1U0488	3G2840	3G2841
	4T4632	6P5391	7J8056	8J8573

TABLE 14. (Continued)

Family	Members (Part number)			
5	8J2308 1U2083 9J3382	9J0752 7J2266 8J3554	5J0899 9J2382 8J3665	9T1495 9T2887

whenever references about the conditions of classification were required.

There are 10^5 geometrical features in the Opitz system. It is impossible to include all the geometrical features in the cluster analyses because of computer memory limitations. Thus, major geometrical features were selected to perform the cluster analyses. The frequencies of each code number are shown in Table 15. The entries in this table show the frequencies of code numbers used in all the parts collected for this research. A total of 63.1 % of all parts were a rotational component with or without deviation.

The parts were first classified into three major classes to select the geometrical features. The major classes are based on the overall shape. The first class is rotational parts without deviation. The second class is rotational parts with deviation. The third class is non-rotational parts.

There are other geometrical features of a part which affect the design of a robotic gripper. The major three classes were further refined to determine the geometrical features other than the overall

TABLE 15. Frequencies of code number used in part data

Major class	Code number	Digit 1	Digit 2	Digit 3	Digit 4	Digit 5
Rotational parts without deviation	0	31	28	31	38	44
	1	31	22	24	11	15
	2	22	2	18	21	2
	3		2	1	4	0
	4		9	0	0	6
	5		5	0	0	3
	6		4	0	0	3
	7		2	0	0	0
	8		0	0	0	1
	9		0	0	0	0
Rotational parts with deviation	0		1	1	12	11
	1		16	0	2	32
	2		26	2	22	15
	3	40	9	8	22	1
	4	30	0	57	2	7
	5		12	1	10	0
	6		0	1	0	1
	7		1	0	0	2
	8		5	0	0	1
	9		0	0	0	0
Non-Rotational parts	0		25	41	32	27
	1		22	10	1	31
	2		7	12	7	9
	3		21	0	16	2
	4		3	6	1	1
	5		3	7	30	10
	6	41	0	12	1	10
	7	15	0	2	2	0
	8	34	1	0	0	0
	9		8	0	0	0

shape. Those features included the contour of component's external shape, internal shape, component's surface condition etc. Thus, the component classes were determined by not only the part's overall shape, but also those features which affect the design of robotic grippers.

After all the parts were coded, the code numbers with high frequencies were selected and combined to define the geometrical characteristics. Thirty-six geometrical characteristics were selected from the Opitz system. The selected geometrical characteristics are shown in Table 16. These characteristics were used to form the part-characteristic matrix. This matrix was used as a basis to perform the ROCA and CASC clustering algorithms with the Opitz coding system.

5. Part families of the Opitz/CASC method

This method uses geometrical characteristics of parts as a basis for coding and similarity coefficients between parts for classification. The similarity coefficients were calculated based on the geometrical characteristics. Thus, the similarity coefficients showed the geometrical relationships of parts. Procedures for calculating these similarity coefficients were presented in Section E of Chapter VI. The data used in this method were the geometrical characteristics represented by the Opitz codes, the part name, and the part number, in effect, the part-characteristic matrix.

The numbers of part families formed at different similarity coefficient levels are shown in Table 17. Five major part families were obtained at the similarity coefficient 0.74 with this method. The level was selected because the part families defined at this level was a approximately midway between two extremes 233 and 1. At this level of similarity coefficient, many families had only one part member. Only families which had ten or more part members were selected. Four

TABLE 16. Selected geometrical characteristics from the Opitz system

Main Group	Characteristics description
Basic Shape	x_1 - rotational parts w/o deviations ($L/D \leq 0.5$)
	x_2 - rotational parts w/o deviations ($0.5 < L/D < 3$)
	x_3 - rotational parts w/o deviations ($L/D \geq 3$)
	x_4 - rotational parts with deviations ($L/D \leq 2$)
	x_5 - rotational parts with deviations ($L/D > 2$)
	x_6 - flat parts ($A/B \leq 3$, $A/C \geq 4$)
	x_7 - long parts ($A/B > 3$)
	x_8 - cubic parts ($A/B \leq 3$, $A/C < 4$)
Main shape outside	x_9 - smooth, no shape elements
	x_{10} - stepped to one end with no shape elements
	x_{11} - stepped to both ends with no shape elements
	x_{12} - square or other regular polygonal section
	x_{13} - symmetrical cross-section producing no unbalance
	x_{14} - segments after rotational machining
	x_{15} - rectangular
	x_{16} - rectangular with one deviation
	x_{17} - rectangular with circular deviations
Internal shape and shape elements	x_{18} - without through bore, blind hole
	x_{19} - smooth or stepped to one end with no shape elements
	x_{20} - smooth or stepped to one end with screwthread
	x_{21} - stepped to both ends with functional groove
	x_{22} - no rotational machining
	x_{23} - external machined shape
	x_{24} - external shape with screwthread(s)
	x_{25} - one principal bore with shape elements
	x_{26} - two parallel principal bores
Plane surface machining	x_{27} - no surface machining
	x_{28} - external plane surface and/or surface curved in one direction
	x_{29} - external plane surfaces related to one another by graduation around a circle
	x_{30} - stepped plane surfaces
	x_{31} - groove and/or slots
Auxiliary holes and gear teeth	x_{32} - no auxiliary holes, gear teeth and forming
	x_{33} - holes drilled in one direction
	x_{34} - holes drilled in more than one direction
	x_{35} - formed with no auxiliary holes and gear teeth
	x_{36} - formed with auxiliary holes and no gear teeth

major part families were obtained in this method. The families and corresponding component parts of this method are shown in Table 18.

TABLE 17. Number of clusters at each level of coefficient

Level of similarity coefficient	Number of families
1.00	233
0.99	175
0.79	120
0.74	86
0.66	37
0.59	14
0.49	7
0.42	5
0.39	3
0.00	1

<u>6. Part families of the Opitz/ROCA method</u>

This method is a coding and classification method in which geometrical characteristics of parts are used as a basis for a ranking process for rows and columns in part-characteristic matrix. The matrix after the first iteration was reviewed to investigate those geometrical characteristics or parts which might limit the formation of a block diagonalized matrix.

Three disjoint classes were formed after first ROCA algorithm iteration. These classes represented each major groups representing the overall part shapes. The block diagonalized matrices were not formed in each major group. This was because two cases discussed by

TABLE 18. Part families formed by Opitz/CASC method (similarity coefficient = 0.74)

Families	Members (part number)			
1 (63 members)	20A3382X022	1C899514022	2R124724092	2R331019022
	7J5928	7J1025	5J1340	8J9259
	3J0601	8J8661	5J1553	5J2438
	4J4571	4T4632	9J3453	3T2321
	4J6485	3G0650	8J3554	4T0958
	4J3291	0W019819012	1E501208012	8J0444
	1U4010	9J4077	4T4636	9J3441
	9J4097	9J4847	1E3943000A2	5J9110
	7575875001	3J7807	7J8308	8J8573
	6J7908	8J5875	7J7674	6F4350
	3P786933092	1C477219012	4T1014	1R124835072
	4T1014	1R124835072	4J2696	2R2617X0012
	2U223433272	2U740448932	2U741048932	36A2065X012
	2U223733272	3G2842	7J3897	6J9992
	3V708322012	2E542919042	9M5550	5J8774
	4T9156	3R124624092	6874138001	
2 (26 members)	1U0488	2J5143	8J0084	1U2177
	8J1701	5J8793	8J2308	7575955002
	4J1137	8J2045	7J2266	3J1970
	5J0899	1U2083	8J2305	9J1234
	4T1889	8J3665	3G2840	2G2841
	1E944223072	8J8829	8J0510	8J1917
	9J3382	6870007001		
3 (37 members)	8J5618	9T2887	7578431001	6870008002
	6870148002	6870112001	6870127001	6870092001
	6870093001	6874139001	6870239001	7578677001
	6874008002	7576896001	6874216002	6870407001
	7578887010	7578612001	7578887001	7578889001
	7578889002	6870043001	7578887002	7578889006
	6870060001	7574570001	6870167002	6870167004
	6870167005	7578887005	7578887006	7578887007
	6870364001	7578887003	7578887004	7578887009
	7578889004			
4 (58 members)	8J8660	7575872002	6870173002	6870174001
	6870181001	9T2382	1R250935162	1K586935162
	6870005001	7575872001	7575863006	10A7182X012
	2F1428000A2	2N5532000A2	6870004001	6870006001
	2R2454000A2	15A1288X012	7575872003	15A6470X012
	15A6480X012	15A6490X012	3N698122012	3N698322012

TABLE 18. (Continued)

Families	Members (part number)			
4 (Continued)	1H830814012	1J1277000B2	2L416322012	2L342619012
	2L373522012	15A6503X012	1B883119012	28A2514X012
	2E4085000A2	3C780819042	1L432314012	25A6687X012
	25A1289X012	6870007003	2J496219012	4E397919012
	T1095224102	1B169135012	7575863002	6870327001
	6870341001	6870444001	7575872004	7576591001
	1A510735072	38A2508X012	7575863004	38A2511X012
	1D228235072	6870008004	7610014003	7610493001
	7575863005	6870003001		

King [29] were occurred with the data collected for this research. The first case corresponded to some parts which had geometrical characteristics possessed by other identifiable groups. The second case corresponded to some geometrical characteristics which were possessed by a large number of parts. These two cases corresponds to the "case #1" and "case #2" discussed in the PFA/ROCA method. Thus, the ROCA algorithm was further applied for each major group.

The relaxation procedures suggested by King [29] were applied to eliminate those geometrical characteristics and parts which limited the formation of the block diagonalized matrix. The geometrical characteristics which were possessed by the parts in other identifiable groups of parts were ignored because they limited the formation of block diagonalized matrix. The geometrical characteristics which were possessed by a relatively large number of parts were divided such that they belong to each identifiable groups.

The families which had ten or more part members were selected. Nine part families were obtained in this method. The part families and their members are presented in Table 19.

7. Summary

Part families identified by each coding and classification procedure have been described in this chapter. Each method yielded a different number of part families. The number of parts within each family also varied. Table 20 shows the number of families, the total number of parts grouped in families, and the percentage of grouped parts for each method.

The Opitz coding method showed higher percentages of grouped parts than the PFA coding method. This was because the coding of a part for each of the two methods was based on different attributes. The Opitz coding method was based on the geometrical characteristics of a part. The PFA coding method was based on the process routings in which a variety of different machines were used in the data collected for this research. The Opitz coding method with the ROCA classification showed largest number of parts grouped in families. The geometrical characteristics of each part family are described in the following section.

8. Justification of the exclusion of small part families

There were many families which consisted of only one part member for each method. In order to keep the size of number of families

TABLE 19. Part families formed by Opitz/ROCA method

Families	Members (Part number)			
1 (21 members)	6870444001	7575872004	6870327001	6870341001
	6870173002	6870174001	6870181001	1R125624092
	6870110001	7576591001	7575863004	7575872003
	1R126335072	1C794935032	1U222646172	T1173614012
	38A2508X012	38A2511X012	28A2514X012	1A510735072
	1D228235072			
2 (17 members)	1B169135012	7575863002	1K586935162	6870005001
	7575872001	7575863006	9T2382	1R250935162
	7575872002	8J8660	6870007003	7575863005
	2L339519012	T1095224102	7610014003	7610493001
	6870008004			
3 (11 members)	6870004001	6870006001	2N5532000A2	15A1288X012
	10A7182X012	2F1428000A2	2R2454000A2	1B883119012
	3S7445	11A5214X022	11A5216X012	
4 (12 members)	15A6490X012	3N698122012	3N698322012	15A6503X012
	15A6470X012	15A6480X012	2E4085000A2	3C780819042
	2L416322012	28A2519X012	1H830814012	1J1277000B2
5 (40 members)	9M5550	9J3441	9J4097	9J4847
	3G2842	5J8774	4T9156	7575875001
	6P5391	8J0444	1U4010	9J4077
	4T4636	4T1014	7J3897	6J9992
	3V708322012	3R124624092	6F4350	3P786933092
	1C477219012	20A3382X022	5J9110	7J8308
	8J8573	1E3943000A2	6J7908	1C899514022
	2R2617X0012	2U223433272	2U740448932	2U741048932
	36A2065X012	2U223733272	1R124835072	2R124724092
	2R331019022	3J7807	4J2696	2E542919042
6 (16 members)	8J8661	5J2438	4J4571	8J3554
	8J9257	5J1553	3T2321	6874138001
	3J2975	3B186522012	8J5875	7J7674
	4T0958	3G0650	7J1025	7J5928
7 (41 members)	6870407001	7578887010	6874008002	7576896001
	6870239001	7578887001	7578889001	7578889002
	7578431001	7578677001	6870060001	9T2887
	8J5618	5J8773	8J0130	2J8069
	6870008002	6874216002	6870112001	6870127001
	7578612001	6870148002	6874098001	6870092001

TABLE 19. (Continued)

Families	Members (Part number)			
	6870093001	6874139001	6874140002	7610167002
	7610464001	7578614001	6870007001	6J0433
	9T1495	9J4941	7J8056	6870027002
	6870026002	6870020002	6870021002	8J2302
	6J0434			
8 (11 members)	6870167004	6870167005	7578887005	7578887006
	7578887007	6870364001	6870167002	7578424001
	6870148001	6870167003	7610463001	
9 (15 members)	8J2305	5J0899	3J1970	1U0488
	2J5143	5J8793	1U2083	4J1137
	8J2045	7J2266	9J1234	1U2177
	8J1701	8J2308	6870008006	

TABLE 20. Summary of four methods

	PFA/CASC	PFA/ROCA	Opitz/CASC	Opitz/ROCA
Number of familes	5	5	4	9
Total number of parts grouped	103	161	184	184
% of grouped parts	0.442	0.692	0.781	0.790

manageable, the families which had ten or more part members were selected for each method. This selection was arbitrary. In order to justify this selection, a sensitivity analysis was performed. The coding and classification was repeated for families which had five or more part members. The results are presented in Table 54 in Appendix D. As can be seen from this table, the results have not changed significantly except that the percentages of number of parts successfully grasped has increased slightly. Performance of this coding and classification methods relative to each other is relatively unchanged.

C. Characteristics of Part Families

1. Overview

The geometrical and other relevant characteristics of part families for the design of grippers are presented and discussed in this section. The geometrical characteristics of a part were represented in terms of the geometrical code of the Opitz system. The other relevant characteristics of a part included part dimensions and weight.

The first five digits of Opitz system code represent the geometrical characteristics of a part. Each digit represents the following geometrical characteristics:

- 1st Digit: Part class
- 2nd Digit: Overall or main shape
- 3rd Digit: Rotational surface machining
- 4th Digit: Plane surface machining

- 5th Digit: Auxiliary holes, gear teeth, and forming

The most frequently used code numbers of each digit were selected to represent the geometrical characteristics of the family. The maximum and minimum dimensions were selected to represent the dimensional characteristics of the family. The maximum weight of the part within family was selected to represent the weight to be handled by the designed gripper. The following dimensional notation has been used in the tables presented in this section:

L: a length of a rotational part (inches)
D: a largest diameter of a rotational part (inches)
A,B,C: lengths of three edges of a non-rotational part (inches)
M: a weight of a part (lbs)
D_{min}: a smallest diameter selected for a family (inches)
D_{max}: a largest diameter selected for a family (inches)
L_{min}: a minimum length of L selected for a family (inches)
L_{max}: a maximum length of L selected for a family (inches)
A_{min}: a minimum length of A selected for a family (inches)
A_{max}: a maximum length of A selected for a family (inches)
B_{min}: a minimum length of B selected for a family (inches)
B_{max}: a maximum length of B selected for a family (inches)
C_{min}: a minimum length of C selected for a family (inches)
C_{max}: a maximum length of C selected for a family (inches)
M_{max}: a maximum weight selected for a family (lbs)

2. Characteristics of part families with the PFA/CASC method

Five major part families were obtained with this method. The Opitz codes along with dimensions and weight of each part within each family are shown in Tables 30-34 in Appendix C. The summaries of part families are presented in Table 21.

The parts within families showed different geometrical characteristics. Thus, the most frequently used code numbers of each

TABLE 21. Characteristics of part families of PFA/CASC method

Family	Geometrical characteristics	Dimensions	Weight
1	.Rotational part without deviation ($L/D \leq 0.5$) .External: stepped to one end or smooth with no shape elements. .Internal: smooth or stepped to one end with screwthread. .External plane surface and/or surface curved in one direction. .No auxiliary holes.	$L_{max}=7.438$ $L_{min}=0.5$ $D_{max}=10.188$ $D_{min}=1.372$	$M_{max}=7.00$
2	.Cubic parts ($A/B \leq 3$, $A/C \leq 4$) .Overall shape: rectangular prism. .No rotational machining or bores .No surface machining .No auxiliary holes, gear teeth and forming.	$A_{max}=0.78$ $A_{min}=0.4$ $B_{max}=0.5$ $B_{min}=0.203$ $C_{max}=0.428$ $C_{min}=0.2$	$M_{max}=2.0$
3	.Long parts ($A/B \geq 3$) .Shape Axis is straight, uniform cross section, and rectangular shape .No rotational machining or bores .No surface machining .No auxiliary holes, gear teeth and forming	$A_{max}=1.89$ $A_{min}=0.796$ $B_{max}=0.422$ $B_{min}=0.155$ $C_{max}=0.03$ $C_{min}=0.005$	$M_{max}=1.5$
4	.Rotational parts with deviation ($L/D \leq 2$). .Segments before rotational machining. .Internal rotational machining with no shape. .External plane surface and/or slot and/or groove, spline. .No forming, no gear teeth, and axial holes not related by drilling pattern.	$L_{max}=4.12$ $L_{min}=1.062$ $D_{max}=2.48$ $D_{min}=1.00$	$M_{max}=7.00$
5	.Cubic parts ($A/B \leq 3$, $A/C \geq 4$). .Block like parts with components with a mounting or locating surface. .Several principal bores, parallel. .Stepped plane surfaces at right angle, inclined and/or opposite. .No gear teeth, no forming, holes drilled in one direction.	$A_{max}=6.875$ $A_{min}=3.25$ $B_{max}=4.00$ $B_{min}=2.125$ $C_{max}=3.09$ $C_{min}=1.1$	$M_{max}=14.00$

digit of Opitz system were selected to represent the geometrical characteristics of this family. Two part families (1 and 4) were classified as rotational parts in this method. Family 1 was classified as rotational parts without deviation. Family 4 was classified as rotational parts with deviation. Three families were classified as non-rotational parts. The three families represented flat, long and cubic parts respectively. The maximum and minimum dimensions are shown for each family to represent the size of a part. The maximum weight is also shown in the table for each family.

This method yielded the smallest percentage of grouped parts. Each family contained some parts which were different from the selected basic overall shape in this method because the coding of this method was based on the process routings. For example, there were some non-rotational parts in Family 1 which was classified as a rotational part without deviation.

3. Characteristics of part families with the PFA/ROCA method

Five major part families were obtained with this method. The geometrical codes along with part dimensional features and weight of are presented in Tables 35-39 in Appendix C. The summaries of part families for this method are shown in Table 22.

Four families were classified as rotational parts in this method. One family was classified as non-rotational and represented flat parts. This method used processing routings as a basis for coding a part. The ROCA algorithm was used to classify parts into families. The

TABLE 22. Characteristics of part families of PFA/ROCA method

Family	Geometrical characteristics	Dimensions	Weight
1	.Rotational parts without deviation ($0.5 \le L/D \le 3$). .External shape: stepped to one end or smooth with no shape elements. .Internal shape: smooth or stepped to one end with screwthread. .External plane surfaces related to one another by graduation around a circle. .No auxiliary holes	$L_{max}=7.5$ $L_{min}=2.125$ $D_{max}=10.1875$ $D_{min}=1.119$	$M_{max}=7.00$
2	.Rotational parts w/ deviation ($L/D > 2$). .Overall shape: around one axis with no segment and symmetrical cross-section. .Internal rotational machining with stepped towards one or both ends. .External plane surface and/or slot and/or groove, spline. .No auxiliary holes, gear teeth, and forming.	$L_{max}=6.8125$ $L_{min}=2.46$ $D_{max}=2.625$ $D_{min}=0.812$	$M_{max}=9.00$
3	.Rotational parts w/o dev. ($L/D \ge 3$). .External: smooth, no shape elements. .Internal: stepped to one end with no shape elements. .No surface machining. .No auxiliary holes.	$L_{max}=27.0$ $L_{min}=0.04$ $D_{min}=1.25$ $D_{min}=0.375$	$M_{max}=4.00$
4	.Flat parts ($A/B \le 3$, $A/C \ge 4$). .Overall shape: rectangular plane. .No rotational machining or bores. .No surface machining. .No auxiliary holes, gear teeth and forming.	$A_{max}=8.756$ $A_{min}=0.125$ $B_{max}=5.795$ $B_{min}=0.09$ $C_{max}=2.00$ $C_{min}=0.025$	$M_{max}=4.00$
5	.Rotational parts w/o dev. ($L/D \le 2$). .Overall shape: segments before rotational machining. .Internal rotational machining with stepped towards one or both ends. .External plane surface and/or slot and/or groove, spline. .No auxiliary holes, gear teeth, and forming.	$L_{max}=5.0625$ $L_{min}=1.062$ $D_{max}=5.875$ $D_{min}=1.0$	$M_{max}=5.00$

geometrical relationships between parts within each family were not stronger than for the PFA/CASC method. However, more parts than the PFA/CASC method were classified in various part families.

4. Characteristics of part families with the Opitz/CASC method

Four part families were obtained with this method. Geometrical characteristics, dimensions, and weight for each family are shown in Tables 40-43 in Appendix C. Summaries of part families for this method are shown in Table 23.

The codes of the Opitz system were the basis for coding. Classification was performed using the similarity coefficients. Two families were classified as rotational parts in this method. Two families were classified as non-rotational and represented cubic and flat parts respectively.

Members within each family were related to each other by the geometrical characteristics; not by the process routings. The smallest number of part families were obtained with this method. However, a strongest geometrical relationships between parts within families were achieved with this method. This was because the classification was performed based on the similarity coefficients.

5. Characteristics of part families with the Opitz/ROCA method

Nine part families were obtained with this method. The geometrical characteristics and dimensions of each part within each family are shown in Tables 44-52 in Appendix C. A summary of part families for this method are shown in Table 24.

TABLE 23. Characteristics of part families of Opitz/CASC method

Family	Geometrical characteristics	Dimensions	Weight
1	.Rotational parts with deviation (L/D ≤ 2). .Overall shape: around one axis with square or other regular polygonal. .Smooth internal rotational machining. .External spline and/or slot. .Axial holes not related by drilling pattern and no forming and gear teeth.	L_{max}=7.25 L_{min}=1.062 D_{max}=8.375 D_{min}=0.3	M_{max}=16.5
2	.Cubic parts (A/B ≤ 3, A/C < 4). .Overall shape: block like parts with with mounting or locating surface. .Several principal bores, other than parallel. .Stepped plane surfaces. .Holes drilled in one direction only.	A_{max}=5.00 A_{min}=0.7188 B_{max}=15.00 B_{min}=0.6875 C_{max}=3.09 C_{min}=0.375	M_{max}=20.0
3	.Flat parts (A/B > 3). .Overall shape: plane rectangular. .No rotational machining or bores. .No surface machining. .No auxiliary holes, gear teeth and forming.	A_{max}=19.245 A_{min}=0.375 B_{max}=6.463 B_{min}=0.155 C_{max}=1.75 C_{min}=0.005	M_{max}=8.0
4	.Rotational parts without deviation (0.5 < L/D < 3). .External shape: smooth, no shape elements. .Without through bore blind hole. .No surface machining. .No auxiliary holes.	L_{max}=27.9 L_{min}=0.032 D_{max}=10.875 D_{min}=0.031	M_{max}=8.5

TABLE 24. Characteristics of part families of Opitz/ROCA method

Family	Geometrical characteristics	Dimensions	Weight
1	.Rotational parts without deviation ($L/D \leq 0.5$). .External shape: round, smooth, no shape elements. .Without through bore, blind hole. .No surface machining. .No auxiliary holes.	$L_{max}=2.6875$ $L_{min}=0.0002$ $D_{max}=6.37$ $D_{min}=0.125$	$M_{max}=6.0$
2	.Rotational parts without deviation ($0.5 < L/D < 3$). .External shape: round, smooth, no shape elements. .Without through bore, blind hole. .No surface machining. .No auxiliary holes.	$L_{max}=3.69$ $L_{min}=0.04$ $D_{max}=3.69$ $D_{min}=0.031$	$M_{max}=8.5$
3	.Rotational parts without deviation ($0.5 < L/D < 3$). .External shape: stepped to both ends with no shape elements. .Without through bore, blind hole. .No surface machining. .No auxiliary holes.	$L_{max}=14.9$ $L_{min}=0.718$ $D_{max}=4.875$ $D_{min}=0.2813$	$M_{max}=5.0$
4	.Rotational parts without deviation ($L/D \geq 3$). .External shape: stepped to one end or smooth with no shape elements. .Internal shape: smooth or stepped to one end with no shape elements. .External plane surfaces related to one another by graduation around circle. .No auxiliary holes.	$L_{max}=7.5$ $L_{min}=0.625$ $D_{max}=7.125$ $D_{min}=0.869$	$M_{max}=7.0$
5	.Rotational with deviation ($L/D \leq 2$). .Overall shape: symmetrical cross-section producing no unbalance. .Internal shape: stepped toward one or both ends. .External plane surfaces related to one another by graduation around a circle. .Axial holes ot related by drilling pattern.	$L_{max}=7.25$ $L_{min}=1.062$ $D_{max}=8.375$ $D_{min}=0.4688$	$M_{max}=7.00$

TABLE 24. (Continued)

Family	Geometrical characteristics	Dimensions	Weight
6	.Rotational part with deviation .Overall shape: symmetrical cross-section producing no unbalance. .Internal shape: stepped towards one or both ends. .External plane surface and/or slot and/or groove, spline. .Axial hole(s) not related by drill pattern.	$L_{max}=8.25$ $L_{min}=1.03$ $D_{max}=3.011$ $D_{min}=0.3$	$M_{max}=16.5$
7	.Flat parts (A/B ≤ 3, A/C ≥ 4). .Overall shape: plane rectangular. .No rotational machining or bore(s). .No surface machining. .No gear teeth, no forming, and holes drilled in one direction only.	$A_{max}=24.0$ $A_{min}=0.125$ $B_{max}=10.875$ $B_{min}=0.09$ $C_{max}=2.0$ $C_{min}=0.005$	$M_{max}=12.0$
8	.Long parts (A/B > 3). .Shape axis-straight and rectangular with uniform cross-section. .No rotational machining or bore(s). .No surface machining. .No auxiliary holes, gear teeth and forming.	$A_{max}=25.593$ $A_{min}=1.068$ $B_{max}=7.488$ $B_{min}=0.325$ $C_{max}=3.272$ $C_{min}=0.03$	$M_{max}=7.0$
9	.Cubic parts (A/B ≤ 3, A/C < 4). .Shape axis straight and rectangular with varying cross-section. .Several principal bores, parallel. .Groove and/or slot. .Holes drilled in one direction only no gear teeth and forming.	$A_{max}=5.94$ $A_{min}=3.5$ $B_{max}=4.813$ $B_{min}=0.75$ $C_{max}=2.86$ $C_{min}=0.124$	$M_{max}=11.0$

Six part families were classified as rotational parts in this method. Three families were classified as non-rotational and represented flat, long, and cubic parts respectively. Each family was well represented each of class of the Opitz coding and classification system in which eight classes were defined based on the overall shape and the dimensional ratio of a part.

The largest number of parts were classified into nine groups with this method. The largest number of part families was obtained with this method. Certain families had very similar geometrical characteristics with other families. Those families can be combined if one gripper set can grasp parts from both groups successfully.

6. Summary

The geometrical characteristics, dimensions and weight of each family were obtained and described in this chapter. A gripper set will be configured for each family in the chapter that follows. Two families can be combined if one gripper set can successfully grip parts from both families.

The percentage of parts which can be successfully grasped by the configured gripper set will also be determined for each family. This will yield expected percentages of parts which can be grasped successfully with the selected gripper set for each method. The coding and classification method which shows the largest percentage of successful grips can be also determined as result of the above analysis.

VIII. GRIPPER CONFIGURATIONS AND EVALUATIONS

A. Introduction

A wide variety of conventional grippers are available for workpieces of different shapes and sizes. In order to select a suitable gripper, the exterior geometry of the workpiece to be grasped must be known. It is apparent that different grippers are required to grasp a solid cylindrical part as opposed to a thin, flat, workpiece. Rimmed edges or flanges on workpieces may be utilized to advantage for gripping. Workpieces of large size and odd shape may require specially designed grippers. It is also obvious that the material properties of the workpiece, such as the specific weight, modulus of elasticity, surface conditions, roughness, contamination, fragility, etc., are equally important factors that must be considered in gripper design.

In this research, the Opitz coding and classification system was used to select the geometrical and other features of parts related to the configuration of a gripper. In order to obtain these features, the the frequencies of each geometrical characteristic present in all the parts were determined. The geometrical characteristics were used in configuring specific gripper sets for part families.

A gripper was configured for each part family defined by the four different coding and classification methods previously described. The "best" coding and classification method was selected based on the number of parts which could be grasped successfully by the gripper set.

B. Configurations of Grippers

1. Overview

Different gripper types can be applied to physically constrain a part based on its geometry. In this research, four different jaw shapes of two finger mechanical gripper were considered. These included "C-C", "V-V", "V-P", and "P-P" types of jaw shapes. Figures illustrating these jaw shapes were presented in Chapter V. Vacuum and magnetic grippers were also considered as possible gripper types to handle flat parts.

The first five digits of the Opitz system specify the geometrical characteristics of a part. The gripper type was determined based on the selected geometrical characteristics of each part family. The dimensions of the selected gripper type were then determined. The number of parts which can be grasped by the configured gripper were then determined.

2. Determination of gripper types

The families obtained in the previous chapter showed various geometrical characteristics and part dimensions. Each family contained the geometrical characteristics in terms of the part's class, overall or main shapes, shapes of rotational surface machining, shapes of plane surface machining, and auxiliary features. The auxiliary features included holes, gear teeth, and forming. In this section, the gripper types are determined for each family based on the family's geometrical characteristics.

For part families with cylindrical external shape, the "C-C", "V-V", and "V-P" jaw shapes were selected. The "P-P" jaw was selected for the part whose external shape was rectangular. Vacuum and magnetic grippers were used to handle flat parts.

A vacuum gripper was selected for handling flat parts which was made of light metal and had the auxiliary holes on its gripping surface. A magnetic gripper was selected for the flat parts made of steel and had no auxiliary holes on its gripping surface. Table 25 shows the selected gripper types for each part family defined by the four different coding and classification systems used in this research.

3. Determination of gripper dimensions

The gripper types were selected based on the geometrical characteristics of part families defined by the four coding and classification systems in the previous section. The dimensions of part's overall shape selected for each part family were also presented along with the geometrical characteristics in Chapter VII.

The dimensions of the selected gripper types were determined by using the criteria for successful grips. These criteria were previously described in Chapter V. For example, part family 1 of the PFA/CASC method had the following geometrical and dimensional characteristics:

- Overall shape: cylindrical
- External shape: stepped to one end or smooth with no shape elements
- Internal shape: smooth or stepped to one end with screwthread
- Plane surface machining: plane surface and/or surface curved in one direction
- No auxiliary holes

TABLE 25. The part families and their selected jaw shapes

Method	Family	Gripper types	Jaw shape
PFA/CASC	1	Mechanical gripper	"C-C" "V-V" "V-P"
	2	Mechanical gripper	"P-P"
	3	Mechanical gripper	"P-P"
	4	Mechanical gripper	"P-P"
	5	Mechanical gripper	"P-P"
PFA/ROCA	1	Mechanical gripper	"C-C" "V-V" "V-P"
	2	Mechanical gripper	"P-P"
	3	Mechanical gripper	"P-P"
	4	Vacuum gripper	
	5	Mechanical gripper	"P-P"
Opitz/CASC	1	Mechanical gripper	"P-P"
	2	Mechanical gripper	"P-P"
	3	Magnetic gripper	
	4	Mechanical gripper	"C-C" "V-V" "V-P"
Opitz/ROCA	1	Mechanical gripper	"C-C" "V-V" "V-P"
	2	Mechanical gripper	"C-C" "V-V" "V-P"
	3	Mechanical gripper	"C-C" "V-V" "V-P"
	4	Mechanical gripper	"C-C" "V-V" "V-P"
	5	Mechanical gripper	"P-P"
	6	Mechanical gripper	"P-P"
	7	Vacuum gripper	
	8	Mechanical gripper	"P-P"
	9	Mechanical gripper	"P-P"

- Dimensions: D_{max}=10.188, D_{min}=1.372, L_{max}=7.438, L_{min}=0.5 (inches)
- Weight: M_{max}=10.00 (lbs)

The "C-C", "V-V", and "V-P" jaw shapes were selected because the overall shape of this part family was cylindrical. The dimensions for each jaw shape were calculated based on the maximum and minimum diameters of the part family. The dimensional conditions of successful grips were derived in Chapter V. By using these conditions, the parameters of the selected jaw shape were determined. These parameters were illustrated in Chapter V along with diagrams of the jaw shapes. The following equations were used to calculate the dimensions of the jaw shapes selected for the family of the PFA/CASC method:

"C-C" jaw shape:

$$r_o = D_{max}/2 = 5.094$$

$$\lambda_o = D_{min}/2 = 0.686$$

$$B_{open} = D_{max} + 2\lambda_o = 10.188$$

"V-V" jaw shape:

$$\epsilon_t = \cos^{-1}(\sqrt{D_{min}/D_{max}}) = 68.47°$$

$$\lambda_t = D_{min}/2*\sin\epsilon_t = 0.738$$

$$B_{open} = D_{max} + 2\lambda_t = 11.663$$

"V-P" jaw shape:

$$\epsilon_p = \sin^{-1}((D_{max} - D_{min})/D_{max}) = 59.92°$$

$$\lambda_p = ((1 + \sin\epsilon_p)*D_{min})/2*\sin\epsilon_p = 1.479$$

$$B_{open} = D_{max} + \lambda_p = 10.188$$

where: D_{max} = 10.188 in
D_{min} = 1.372 in

The dimensions of other gripper types were calculated in a similar fashion. Table 26 shows the determined dimensions of the selected gripper type for each part family.

C. Gripper Evaluation

1. Overview

The configured gripper was evaluated by using the conditions for successful grips presented in Chapter V. The "best" gripper configuration was selected based on the number of parts which were grasped successfully. A robotic gripper set was also determined for each coding and classification method. The percentage of parts which could be successfully grasped by the gripper set was next ascertained. The best coding and classification system was determined based on this percentage.

2. Gripper evaluation within a part family

A gripper was configured for each part family based on the geometrical characteristics and dimensions obtained. Each configured gripper could handle only limited part geometries and dimensions. By using the three conditions discussed in the Chapter V, each part within a family was tested to determine whether it could be grasped successfully by the configured gripper. The three conditions are as follows:

Condition 1: If a gripper is configured with a jaw shape other than "P-P", the contour of the part must be enclosed within the shape of the jaw.

Condition 2: The maximum dimension of the part must be in the

TABLE 26. The dimensions of the selected gripper type

Method	Family	Gripper type	Dimensions		
PFA/CASC	1	C-C	$r_o=5.094$	$\lambda_o=0.686$	$B_{open}=11.560$
		V-V	$\epsilon_t=68.47$	$\lambda_t=0.738$	$B_{open}=11.663$
		V-P	$\epsilon_p=59.92$	$\lambda_p=1.479$	$B_{open}=11.667$
	2	P-P			$B_{open}=0.428$
	3	P-P			$B_{open}=0.030$
	4	P-P			$B_{open}=2.480$
	5	P-P			$B_{open}=4.790$
PFA/ROCA	1	C-C	$r_o=5.094$	$\lambda_o=0.560$	$B_{open}=11.308$
		V-V	$\epsilon_t=70.64$	$\lambda_t=0.593$	$B_{open}=11.374$
		V-P	$\epsilon_p=62.89$	$\lambda_p=1.188$	$B_{open}=11.376$
	2	P-P			$B_{open}=2.860$
	3	P-P			$B_{open}=1.250$
	4	Vacuum			
	5	P-P			$B_{open}=5.875$
Opitz/CASC	1	P-P			$B_{open}=8.375$
	2	P-P			$B_{open}=3.090$
	3	Magnetic			
	4	C-C	$r_o=5.438$	$\lambda_o=0.016$	$B_{open}=10.906$
		V-V	$\epsilon_t=86.93$	$\lambda_t=0.016$	$B_{open}=10.906$
		V-P	$\epsilon_p=85.67$	$\lambda_p=0.031$	$B_{open}=10.906$
	1	C-C	$r_o=3.185$	$\lambda_o=0.063$	$B_{open}=6.496$
		V-V	$\epsilon_t=81.95$	$\lambda_t=0.063$	$B_{open}=6.496$
		V-P	$\epsilon_p=78.63$	$\lambda_p=0.126$	$B_{open}=6.496$
	2	C-C	$r_o=1.845$	$\lambda_o=0.016$	$B_{open}=3.722$
		V-V	$\epsilon_t=84.74$	$\lambda_t=0.016$	$B_{open}=3.722$
		V-P	$\epsilon_p=82.57$	$\lambda_p=0.032$	$B_{open}=3.722$
	3	C-C	$r_o=2.438$	$\lambda_o=0.141$	$B_{open}=5.156$
		V-V	$\epsilon_t=76.10$	$\lambda_t=0.145$	$B_{open}=5.166$

TABLE 26. (Continued)

Method	Family	Gripper type	Dimensions		
		V-P	$\epsilon_p=70.44$	$\lambda_p=0.290$	$B_{open}=5.166$
Opitz/ROCA		C-C	$r_o=3.563$	$\lambda_o=0.435$	$B_{open}=7.995$
	4	V-V	$\epsilon_t=69.56$	$\lambda_t=0.464$	$B_{open}=8.053$
		V-P	$\epsilon_p=61.41$	$\lambda_p=0.929$	$B_{open}=8.054$
	5	P-P			$B_{open}=8.375$
	6	P-P			$B_{open}=3.011$
	7	Vacuum			
	8	P-P			$B_{open}=3.272$
	9	P-P			$B_{open}=2.860$

Notation:

r_o = Radius of semi-circular notch (inches)

λ_o = Depth of the notch of "C-C" jaw shape (inches)

λ_t = Depth of the notch of "V-V" jaw shape (inches)

λ_p = Depth of the notch of "V-P" jaw shape (inches)

B_{open} = Maximum opening range (inches)

ϵ_t = Notch angle of "V-V" jaw shape (°)

ϵ_p = Notch angle of "V-P" jaw shape (°)

range of the maximum opening distance, B_{open}. The minimum dimension of the part must be greater than the length of the notch.

Condition 3: The weight of a part must be less than or equal the maximum weight determined by the part family.

Table 27 shows the gripper types and the corresponding geometrical shapes to be handled. The Opitz codes of each part were used to checked if their geometrical shapes conformed to the shapes shown in Table 27. If the geometrical shapes conformed, the first condition was satisfied. The second condition was checked based on the dimensions of the part. Finally, the third condition was tested by checking the weight of each part.

TABLE 27. The gripper types and corresponding geometrical shapes which satisfy the first condition

Gripper type	Jaw shape	Geometrical shapes
Mechanical gripper	C-C	Overall shape: cylindrical External shape: round
	V-V	Overall shape: cylindrical External shape: round or hexagonal
	V-P	Overall shape: cylindrical External shape: round
	P-P	Overall shape: long and cubic External shape: rectangular
Vacuum gripper		Overall shape: flat External shape: no holes and light weight
Magnetic gripper		Overall shape: flat Material: Ferrous metal

By using the three conditions, each part was evaluated to determine whether it could be grasped successfully by the configured gripper. Table 28 shows the total number of parts of each part family and number of parts that were successfully grasped by the configured gripper.

3. Determination of gripper sets

A gripper set was determined for each coding and classification method. If the same grippers were configured for a certain two families, the gripper with larger dimensions was selected for overall use. Table 29 shows the gripper set determined for each coding and classification method. The dimensions of the configured gripper and the number of parts which were grasped by the gripper set are also presented in this table.

Results of an identical analysis for families of five or more parts are presented in Appendix D. The results are consistent with those presented in Table 29.

4. Summary

The gripper configured for each part family was evaluated by using the three conditions for successful grips. The gripper set was also defined based on the number of parts which could grasped successfully by the configured grippers. The percentage of parts which could be successfully grasped by the gripper set was ascertained from the number of parts grasped successfully by the gripper configured for each family of each coding and classification method.

TABLE 28. Results of gripper evaluation within family

Methods	Part family	Total number of parts	Gripper type	Number of parts grasped successfully
PFA/CASC	1	17	C-C	12
			V-V	12
			V-P	10
	2	10	P-P	5
	3	10	P-P	4
	4	46	P-P	25
	5	20	P-P	14
PFA/ROCA	1	31	C-C	12
			V-V	14
			V-P	10
	2	45	P-P	28
	3	22	P-P	9
	4	32	Vacuum	12
	5	30	P-P	22
Opitz/CASC	1	63	P-P	42
	2	25	P-P	24
	3	37	Magnetic	11
	4	58	C-C	53
			V-V	56
			V-P	50
Opitz/ROCA	1	21	C-C	20
			V-V	20
			V-P	18
	2	17	C-C	14
			V-V	16
			V-P	13
	3	11	C-C	10
			V-V	11
			V-P	10
	4	12	C-C	9
			V-V	11
			V-P	5
	5	40	P-P	37
	6	16	P-P	16
	7	41	Magnetic	22
	8	11	P-P	10
	9	15	P-P	15

TABLE 29. Result of gripper evaluation for each coding and classification method

Method	Part family	Gripper type	Dimensions			Number of parts grasped
PFA/CASC	1	C-C	r_o=5.094	λ_o=0.686	B_{open}=11.560	12
		V-V	ϵ_t=68.47	λ_t=0.738	B_{open}=11.663	12
	2	P-P			B_{open}=0.428	5
	3	P-P			B_{open}=0.030	4
	4	P-P			B_{open}=2.480	25
	5	P-P			B_{open}=4.790	14
					Total	60
PFA/ROCA	1	V-V	ϵ_t=70.64	λ_t=0.593	B_{open}=11.374	14
	2	P-P			B_{open}=2.860	28
	3	P-P			B_{open}=1.250	9
	4	Vacuum				12
	5	P-P			B_{open}=5.875	22
					Total	85
Opitz/CASC	1	P-P			B_{open}=8.375	42
	2	P-P			B_{open}=3.090	24
	3	Magnetic				11
	4	V-V	ϵ_t=86.93	λ_t=0.031	B_{open}=10.906	56
					Total	133
Opitz/ROCA	1	C-C	r_o=3.185	λ_o=0.063	B_{open}=6.496	20
		V-V	ϵ_t=81.95	λ_t=0.063	B_{open}=6.496	20
	2	V-V	ϵ_t=84.74	λ_t=0.016	B_{open}=3.721	16
	3	V-V	ϵ_t=76.10	λ_t=0.145	B_{open}=5.165	11

TABLE 29. (Continued)

Method	Part family	Gripper type	Dimensions			Number of parts grasped
Opitz/ROCA	4	V-V	$\epsilon_t=69.56$	$\lambda_t=0.464$	$B_{open}=8.053$	11
	5	P-P			$B_{open}=8.375$	37
	6	P-P			$B_{open}=3.011$	16
	7	Vacuum				22
	8	P-P			$B_{open}=3.272$	10
	9	P-P			$B_{open}=2.860$	15
					Total	158

The Opitz/ROCA method yielded the highest percentage of parts which were grasped successfully by the gripper set. The PFA/CASC method showed the lowest percentage of successfully grasped parts. The Opitz coding method yielded the better percentage than the PFA coding method. This was because the coding of the Opitz system was based on the geometrical characteristics parts. The coding of the PFA method was based on the process routings of a part. Inspection of Table 29 shows only small differences in the percentages associated with the ROCA and CASC classification methods. Thus, the method of coding is more important than the method of classification in defining part families.

IX. CONCLUSIONS

This study has been conducted to use part coding and classification systems in the design of robotic gripper sets. The purpose of this study was first to determine a part coding classification system based on common gripping characteristics and part geometries. A second purpose was to conceptually design a set of robotic grippers that can manipulate the respective families of parts within a given size and weight range. Production sequences and part geometries have been analyzed to determine common gripping characteristics. A third purpose was to estimate the reasonable percentage of parts which can be grasped successfully by the defined robotic gripper set.

Four coding and classification systems were used to define the part families. These systems included the PFA/CASC, the PFA/ROCA, the Opitz/CASC, and the Opitz/ROCA. Computer software for each of the four systems was developed in this research. By using this software, the part families were defined for each system.

A gripper set was configured for each part family. The gripper features included in this study were the gripping mechanism and the jaw shapes. The gripper mechanisms adopted in this research were two finger mechanical gripper, a magnetic gripper, and a vacuum gripper. These gripper types have been most widely used in manufacturing environments. The jaw shapes included in this research were a twin semi-circular notch ("C-C"), a twin V-shaped notch ("V-V"), a combination of V-shaped notch and plane shape ("V-P"), and a twin plane shapes ("P-P").

Each part within part families was tested to determine whether it could be successfully grasped by the gripper configured for the part family. Based on the number of parts which were grasped successfully, the robotic gripper set was defined for each method. The reasonable percentage of parts which could be grasped by the robot gripper set was obtained for each coding and classification method.

Based on the analyses performed in this study, the following conclusions are apparent:

- The Opitz/ROCA method yielded the highest percentage of parts which were successfully grasped by the defined the robotic gripper set.
- Two finger mechanical grippers with "V-V" and "P-P" jaw shapes were included in the gripper set for all four methods.
- The Opitz coding method was the better than the PFA coding method in terms of percentages of parts grasped. This is because the coding of the Opitz system is based on geometrical characteristics.
- The "V-V" jaw shapes was performed better than "C-C" and "V-P" jaw shapes in terms of the number of parts grasped successfully.
- With the defined robotic gripper set, two coding methods showed the high percentages of parts which were grasped successfully. This indicated that the coding was important in defining part families than the classification methods.

Assembly is the most advanced, complex and sophisticated application of robots at the present time. However, to reduce the time and cost occupied by assembly tasks to a minimum, it is necessary to devote attention to the design of grippers. It is desirable to design and build a set of grippers that can be used in a manufacturing environments. Current technology restricts robots to special purpose or single part tasks. Use of a standard set of grippers may considerably reduce tooling costs for job shops, small manufacturers, and assembly operations. This is because grippers, at present, are usually custom designed and fabricated for one, and only one, production task. In addition, developing a standard robotic gripper set would convert single-purpose, machine-tending robots into flexible manufacturing cells. This is valuable in a job shop or assembly environment or in small manufacturing facilities.

The commercial availability of a standard set of grippers will help make robots more economically and technically feasible for small and medium-sized production organizations. Finally, a standard set of grippers will open the door to enable robotics to be used in a wider range of manufacturing applications.

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APPENDIX A: PROGRAM LISTINGS

```
1000 '*********************************************************************
1010 '*                                                                   *
1020 '*          Computer Aided Opitz Coding System                       *
1030 '*                                                                   *
1040 '*        Digit1 - Digit9: Save the coding digit                     *
1050 '*                                                                   *
1060 '*                                                                   *
1061 '*        c: Array to store the code digits of a part                *
1062 '*        l: Largest dimension for a rotational part                 *
1063 '*        d: Largest diameter for a rotational part                  *
1070 '*                                                                   *
1080 '*                                                                   *
1090 '*********************************************************************
1100 dim arrypnames$(300),arrypnum$(300),c(300,8),tol(300)
1110 key off
1120 space1$="     "
1130 cls:locate 5,10
1140 print "**********  MENU **********"
1150 locate 7,10
1160 locate 8,10:print "1.  Read the code data file"
1170 locate 9,10:print "2.  Correction"
1180 locate 10,10:print "3.  Coding"
1190 locate 11,10:print "4.  Exit"
1200 print
1210 locate 13,10:input "Enter the choice ";slect
1220 if slect = 1 then gosub 1300:goto 1130
1230 if slect = 2 then gosub 1500:goto 1130
1240 if slect = 3 then gosub 1715:goto 1130
1250 if slect = 4 then 1251    .
1251 lprint using "                          ";"Part Name",
     lprint using "                ";"Part Number"
     lprint
1252 for i = 1 to j-1
1253   lprint using "                             ";arrypnames$(i);
       lprint arrypnum$(i),
       lprint c(i,1);c(i,2);c(i,3);c(i,4);c(i,5);c(i,6);
       lprint c(i,7);c(i,8);tol(i)
1254 next
1255 end
1260 '
1270 '------------------------- Read in opitz code
1280 '
1290 '
1300 open "program  code.dat" for input as #2
1310 j=1
1320 if eof(2) then  1360
1330    input #2,pnames$,pnum$,dig1,dig2,dig3,dig4,dig5,dig6,dig7,dig8,t
```

FIGURE 49. The program listing of the Opitz system

```
        arrypname$(j)=pname$:arrypnum$(j)=pnum$
        c(j,1)=dig1:c(j,2)=dig2:c(j,3)=dig3
        c(j,4)=dig4:c(j,5)=dig5:c(j,6)=dig6
        c(j,7)=dig7:c(j,8)=dig8:tol(j)=t
1340    j=j+1
1350    goto 1320
1360 close #2
1370 for k=1 to j-1
1380    cls:locate 10
1390    print "Part ";k
1400    print
1410    print "Part Name: ";arrypname$(k)
1420    print "Part Number: ";arrypnum$(k)
1430    print
1440    print "Code: ";c(k,1);c(k,2);c(k,3);c(k,4);c(k,5);
        print c(k,6);c(k,7);c(k,8);tol(k)
1450    print
1460    print "Press any key to continue"
1470    a$=inkey$:if a$="" then 1470
1480 next
1490 return
1500 '
1510 '--------------------------- Correction is made on the code
1520 '--------------------------- of the part
1530 '
     shell "copy program code.dat program    code.bak"
1531 open "program  code.dat" for input as #2
1532 j=1:m=1:cls
1533 if eof(2) then  1537
1534    input #2,pname$,pnum$,dig1,dig2,dig3,dig4,dig5,dig6,dig7,dig8,t
        arrypname$(j)=pname$:arrypnum$(j)=pnum$
        c(j,1)=dig1:c(j,2)=dig2:c(j,3)=dig3
        c(j,4)=dig4:c(j,5)=dig5:c(j,6)=dig6
        c(j,7)=dig7:c(j,8)=dig8:tol(j)=t
1535    j=j+1
1536    goto 1533
1537 close #2
1538 for k = 1 to j-1
1539    print k,arrypname$(k),arrypnum$(k),c(k,1);c(k,2);c(k,3);c(k,4);
        print c(k,5);c(k,6);c(k,7);c(k,8);tol(k)
1540    if k    15*m and k   j-1 then goto 1661
1541       locate 18
1550       input "Do you want correct any code of a part (y/n) ";ans$
1560       if ans$ = "n" then goto 1660
1570          input "Enter the part number you want to correct ";cornum
1580          gosub 1724:cls
1590          arrypname$(cornum)=pname$
```

FIGURE 49. (Continued)

```
1600          arrypnum$(cornum)=pnum$
1610          c(cornum,1)=dig1:c(cornum,2)=dig2:c(cornum,3)=dig3
1620          c(cornum,4)=dig4:c(cornum,5)=dig5:c(cornum,6)=dig6
1630          c(cornum,7)=dig7:c(cornum,8)=dig8:tol(cornum)=tolerance
1660    m=m+1:cls
1661 next
     open "program  code.dat" for output as #1
     for n = 1 to j-1
     write #1,arrypnames$(n),arrypnum$(n),c(n,1),c(n,2),c(n,3),c(n,4),c(n,5),
              c(n,6),c(n,7),c(n,8),tol(n)
     next
     close #1
1670 return
1680 '
1690 '--------------------------- Start of coding or correction of
1700 '--------------------------- existing code
1710 '
1715 n=j
1716 gosub 1724
1717 cls:locate 5
1718 open "program  code.dat" for append as #1
1719 write #1, pname$,pnum$,dig1,dig2,dig3,dig4,dig5,dig6,dig7,dig8,tolerance
1720 close #1
     open "program  dimen.dat" for append as #3
     write #3, dig1,dig2,dig3,l,d,a,b,c,weight,tolerance
     close #3
     l=0:d=0:a=0:b=0:c=0:weight=0:tolerance=0
1721 input "Do you want to code another part (y/n) ";ans$
1722 if ans$ = "y" then n=n+1:goto 1716
1723 return
1724 '
1725 '
1726 cls:locate 5
1727 input "Enter the part name ";pname$
1728 print
1729 print pname$
1730 print
1731 input "Is this correct part name (y/n) ";ans$
1732 if ans$ = "y" then goto 1737
1733 locate 5
1734 input "Enter the part name again ";pname$
1735 print:print pname$:print
1736 goto 1731
1737 cls:locate 5
1738 input "Enter the part number ";pnum$
1739 print
```

FIGURE 49. (Continued)

```
1740 print pnum$
1741 print
1742 input "Is this correct part number (y/n) ";ans$
1743 if ans$ = "y" then goto 1748
1744 locate 5
1745 input "Enter the part number again ";pnum$
1746 print:print pnum$:print
1747 goto 1742
1748 print
1749 print "Press any key to continue"
1750 a$=inkey$:if a$="" then 1750
1970 '
1980 '
2010 cls:locate 5
2020 print space1$;"***** Basic Shape *****"
2030 print
2040 print "1.  Rotational without deviation"
2050 print "2.  Rotational with deviation"
2060 print "3.  Non-Rotational"
2070 print
2080 input "Choose basic shape of component";choice
2090 if choice = 1 then gosub 2142:goto 2131
2100 if choice = 2 then gosub 2210:goto 2131
2110 if choice = 3 then gosub 2271:goto 2131
2120 locate 11:input "Incorrect choice, enter the choice again";choice
2130 goto 2090
2131 return
2140 '
2141 '
2142 gosub 2320
2150 gosub 2440
2160 gosub 3090
2170 gosub 3740
2180 gosub 3970
2190 gosub 4250
2191 gosub 9170
2200 return
2201 '
2202 '
2210 gosub 5130
2220 gosub 5240
2230 gosub 5640
2240 gosub 6040
2250 gosub 6280
2260 gosub 4250
2261 gosub 9170
2262 return
```

FIGURE 49. (Continued)

```
2263 '
2264 '
2271 gosub 6730
2272 on dig1-5 gosub 6840,8310,8720
2273 gosub 7190
2274 gosub 7610
2275 gosub 7850
2276 gosub 4250
2277 gosub 9170
2278 return
2280 '
2290 ' -------------------------- Digit 1 of Rotational without deviation
2300 '
2310 '
2320 cls:locate 5
2330 print space1$;"***** Rotational without deviation *****"
2340 print
2350 input "Enter L (Largest Dimension) and D (Largest Diameter): L,D";L,D
2360 if L/D  .5 then dig1 = 0:goto 2390
2370 if L/D >= 3  then dig1 = 2:goto 2390
2380 dig1= 1
2390 return
2400 '
2410 ' -------------------------- Digit 2 of Rotational without deviation
2420 '
2430 '
2440 cls:locate 5
2450 print space1$;"***** Rotational without deviation *****"
2460 print
2470 print space1$;" 2nd Digit: External shape, external shape elements "
2480 print
2490 print space1$;"***** External shape *****"
2500 print
2510 print "1.  Smooth"
2520 print "2.  Stepped to one end"
2530 print "3.  Stepped to both ends"
2540 print "4.  Functional Taper"
2550 print "5.  Operating Thread"
2560 print "6.  Others ( > 10 functional diameters)"
2570 print
2580 input "Enter the choice";choice
2590 if choice = 1 then dig2=0:goto 2670
2600 if choice = 2 then gosub 2720:goto 2670
2610 if choice = 3 then gosub 2820:goto 2670
2620 if choice = 4 then dig2=7:goto 2670
2630 if choice = 5 then dig2=8:goto 2670
2640 if choice = 6 then dig2=9:goto 2670
```

FIGURE 49. (Continued)

```
2650 locate 18:input "Incorrect choice, enter the choice again";choice
2660 goto 2590
2670 return
2680 '
2690 '
2700 '
2710 '
2720 gosub 2920
2730 if choice = 1 then dig2=1:goto 2770
2740 if choice = 2 then dig2=2:goto 2770
2750 if choice = 3 then dig2=3:goto 2770
2760 locate 15:input "Incorrect choice, enter the choice again";choice:goto 2730
2770 return
2780 '
2790 '
2800 '
2810 '
2820 gosub 2920
2830 if choice = 1 then dig2=4:goto 2870
2840 if choice = 2 then dig2=5:goto 2870
2850 if choice = 3 then dig2=6:goto 2870
2860 locate 15:input "Incorrect choice, enter the choice again";choice:goto 2830
2870 return
2880 '
2890 '--------------------------- Shape elements
2900 '
2910 '
2920 cls:locate 5
2930 print space1$;"***** Rotational without deviation *****"
2940 print
2950 print space1$;" 2nd dig: External shape, external shape elements "
2960 print
2970 print space1$;"***** Shape elements *****"
2980 print
2990 print "1. No shape elements"
3000 print "2. With screwthread"
3010 print "3. With functional groove"
3020 print
3030 input "Enter the choice";choice
3040 return
3050 '
3060 '--------------------------- Digit 3 of Rotational without deviation
3070 '
3080 '
3090 cls:locate 5
3100 print space1$;"***** Rotational without deviation *****"
3110 print
```

FIGURE 49. (Continued)

```
3120 print space1$;" 3rd Digit: Internal shape, internal shape element "
3130 print
3140 print space1$;"***** Internal shape *****"
3150 print
3160 print "1.  Without through bore, blind hole"
3170 print "2.  Stepped to one end"
3180 print "3.  Stepped to both ends"
3190 print "4.  Functional taper"
3200 print "5.  Operating thread"
3210 print "6.  Others ( > 10 functional diameters )"
3220 print
3230 input "Enter the choice";choice
3240 if choice = 1 then dig3=0:goto 3320
3250 if choice = 2 then gosub 3370:goto 3320
3260 if choice = 3 then gosub 3370:goto 3320
3270 if choice = 4 then dig3=7:goto 3320
3280 if choice = 5 then dig3=8:goto 3320
3290 if choice = 6 then dig3=9:goto 3320
3300 locate 18:input "Incorrect choice, enter the choice again";choice
3310 goto 3240
3320 return
3330 '
3340 '
3350 '
3360 '
3370 gosub 3530
3380 if choice = 1 then dig3=1:goto 3420
3390 if choice = 2 then dig3=2:goto 3420
3400 if choice = 3 then dig3=3:goto 3420
3410 locate 15:input "Incorrect choice, enter the choice again";choice:goto 3380
3420 return
3430 '
3440 '
3450 '
3460 '
3470 gosub 3530
3480 if choice = 1 then dig3=4:goto 3520
3490 if choice = 2 then dig3=5:goto 3520
3500 if choice = 3 then dig3=6:goto 3520
3510 locate 15:input "Incorrect choice, enter the choice again";choice:goto 3480
3520 return
3530 '
3540 '
3550 '
3560 '
3570 cls:locate 5
3580 print space1$;"***** Rotational without deviation *****"
```

FIGURE 49. (Continued)

```
3590 print
3600 print space1$;" 3rd Digit: Internal shape,external shape elements "
3610 print
3620 print space1$;"***** Internal shape elements *****"
3630 print
3640 print "1.  No shape elements"
3650 print "2.  With screwthread"
3660 print "3.  With functional groove"
3670 print
3680 input "Enter the choice";choice
3690 return
3700 '
3710 '--------------------------- Digit 4 of Rotational without deviation
3720 '
3730 '
3740 cls:locate 5
3750 print space1$;"***** Rotational without deviation *****"
3760 print
3770 print space1$;" 4th Digit: Plane Surface Machining "
3780 print
3790 print "1.  No surface machining"
3800 print "2.  External plane surface and/or surface curved in one direction"
3810 print "3.  External plane surfaces related to one another by graduation";
     print " around a circle"
3820 print "4.  External groove and/or slot"
3830 print "5.  External spline and/or slot"
3840 print "6.  External plane surface and/or slot and/or groove,spline"
3850 print "7.  Internal plane surface and/or groove"
3860 print "8.  Internal spline and/or polygon"
3870 print "9.  External and internal splines and/or slot and/or groove"
3880 print "10. others"
3890 print
3900 input "Enter the choice";choice
3910 dig4=choice-1
3920 return
3930 '
3940 '------------------------- Digit 5 of Rotational without deviation
3950 '
3960 '
3970 cls:locate 5
3980 print space1$;"***** Rotational without deviation *****"
3990 print
4000 print space1$;" 5th Digit: Auxiliary Hole(s) and Gear Teeth "
4010 print
4020 input "Is the component with gear teeth (y/n) ";ans$
4030 if ans$ = "y" then goto 4160
4040 if ans$ = "n" then goto 4070
```

FIGURE 49. (Continued)

```
4050 locate 9:input "Incorrect answer, enter the answer again (y/n) ";ans$
4060 goto 4030
4070 print:print "1.  No auxiliary hole(s)"
4080 print "2.  Axial hole(s) not related by a drilling pattern"
4090 print "3.  Axial holes related by a drilling pattern"
4100 print "4.  Radial hole(s) not related by a drilling pattern"
4110 print "5.  Holes axial and/or radial and/or in other directions, not related"
4120 print
4130 input "Enter the choice";choice
4140 dig4=choice-1
4150 return
4160 print
4161 print "1.  Holes axial, and/or radial and/in other directions related by "
4162 print "drill pattern"
4170 print "2.  Spur gear teeth"
4180 print "3.  Bevel gear teeth"
4190 print "4.  Other gear teeth"
4200 print "5.  Other"
4210 print
4220 input "Enter the choice";choice
4230 dig4=choice-1
4240 return
4250 '
4260 '-------------------------- Supplementary code
4270 '
4280 '
4290 cls:locate 5
4300 print space1$;"*****  Supplementary Code *****"
4310 print
4320 print space1$;" 1st Digit: Diameter D or Edge length A "
4330 print
4340 input "Enter the diameter D or Edge length A ";dimedge
4350 if dimedge  .8 then dig6=0:goto 4460
4360 if dimedge  2 then dig6=1:goto 4460
4370 if dimedge  4 then dig6=2:goto 4460
4380 if dimedge  6.5 then dig6=3:goto 4460
4390 if dimedge  10 then dig6=4:goto 4460
4400 if dimedge  16 then dig6=5:goto 4460
4410 if dimedge  25 then dig6=6:goto 4460
4420 if dimedge  40 then dig6=7:goto 4460
4430 if dimedge  80 then dig6=8:goto 4460
4440 dig6=9
4450 goto 4460
4460 '
4470 '
4480 '
4490 '
```

FIGURE 49. (Continued)

```
4500 cls:locate 5
4510 print space1$;"*****  Supplementary Code *****"
4520 print
4530 print space1$;" 2nd Digit: Material "
4540 print
4550 print "1.  Cast Iron "
4560 print "2.  Modular graphitic cast iron and malleable cast iron "
4570 print "3.  Stee‡26.5 tonf/in square, Not heat treated "
4580 print "4.  Steel > 26.5 tonf/in square, Heat treatable low carbon and case"
4590 print "    hardening steel, not heat treated"
4600 print "5.  Steels 2 and 3, Heat treated "
4610 print "6.  Alloy steel (Not heat treated) "
4620 print "7.  Alloy steel (Heat treated) "
4630 print "8.  Non-ferrous metal "
4640 print "9.  Light Alloy "
4650 print "10. Other material "
4660 print
4670 input "Enter the choice ";choice
4680 dig7=choice-1
4690 '
4700 '
4710 '
4720 '
4730 cls:locate 5
4740 print space1$;"*****  Supplementary Code *****"
4750 print
4760 print space1$;" 3rd Digit: Initial Form "
4770 print
4780 print "1.  Round Bar, clack "
4790 print "2.  Round bar, bright drawn "
4800 print "3.  Bar-triangular, square, hexagonal, other "
4810 print "4.  Tubing ",
4820 print "5.  Angle, U-, T-, and similar sections "
4830 print "6.  Sheet "
4840 print "7.  Plate and slabs "
4850 print "8.  Cast or forged components "
4860 print "9.  Welded assembly "
4870 print "10. Pre-machined components "
4880 print
4890 input "Enter the choice ";choice
4900 '
4910 '
4920 '
4930 '
4940 cls:locate 5
4950 print space1$;"*****  Supplementary Code *****"
4960 print
```

FIGURE 49. (Continued)

```
4970 print space1$;" 4th Digit: Accuracy in coding digit "
4980 print
5100 input "Enter the tolerance ";tolerance
5101 print
5102 input "Enter the weight ";weight
5120 return
5130 '
5140 '
5150 '
5160 '
5170 cls:locate 5
5180 print "     ";"***** Rotational with deviation *****"
5190 print
5200 input "Enter L(Largest Dimension and D(Largest Diameter): L,D";L,D
5210 if L/D  2 then dig1=3: goto 5230
5220 dig1=4
5230 return
5240 '
5250 '
5260 '
5270 '
5280 cls:locate 5
5290 print space1$;"***** Rotational with deviation *****"
5300 print
5310 print space1$;" 2nd Digit: Overall shape "
5320 print
5330 input "Is the component around one axis (y/n) ";ans$
5340 if ans$ = "y" then goto 5420
5350 input "The component must be with segments (y/n) ";ans$
5360 if ans$ = "n" then goto 5540
5370 input "Do segments occur after rotational machining (y/n) ";ans$
5380 if ans$ = "y" then dig2=4:goto 5631
5390 if ans$ = "n" then dig2=5:goto 5631
5400 dig2=9
5410 goto 5631
5420 print
5430 print "1.  Hexagonal bar "
5440 print "2.  Square or other regular polygonal section "
5450 print "3.  Symmetrical cross-section producing no unbalance "
5460 print "4.  Cross-sections other than 1 to 3 "
5470 print
5480 input "Enter the choice ";choice
5490 if choice  4 then goto 5520
5500 locate 18:input "Incorrect choice, enter the choice again ";choice
5510 goto 5490
5520 dig2=choice-1
5530 goto 5631
```

FIGURE 49. (Continued)

```
5540 print
5550 print "1.  Rotational components with curved axis "
5560 print "2.  Rotational components with two or more parallel axes "
5570 print "3.  Rotational components with intersecting axes "
5580 print
5590 input "Enter the choice ";choice
5600 if choice  3 then goto 5630
5610 locate 17:input "Incorrect choice, enter the choice again ";choice
5620 goto 5600
5630 dig2=choice+5
5631 return
5640 '
5650 '
5660 '
5670 '
5680 cls:locate 5
5690 print space1$;"***** Rotational with deviation *****"
5700 print
5710 print space1$;" 3rd Digit: Rotational machining "
5720 print
5730 print "1.  No rotational machining"
5740 print "2.  External shape"
5750 print "3.  Internal shape"
5760 print "4.  External and internal shape"
5770 print "5.  External shape elements"
5780 print "6.  Other shape elements"
5790 print
5800 input "Enter the choice ";choice
5810 if choice = 1 then dig3=0:goto 6031
5820 if choice = 2 then goto 5890
5830 if choice = 3 then goto 5920
5840 if choice = 4 then goto 6010
5850 if choice = 5 then dig3=8:goto 6031
5860 if choice = 6 then dig3=9:goto 6031
5870 locate 16:input "Incorrect choice, enter the choice again ";choice
5880 goto 5810
5890 input "Is the external shape machined (y/n) ";ans$
5900 if ans$ = "y" then dig3=1:goto 6031
5910 if ans$ = "n" then dig3=2:goto 6031
5920 print
5930 print "1.  Smooth"
5940 print "2.  Stepped towards to one or both ends (Multiple increases)"
5950 print "3.  With screwthreads"
5960 print
5970 input "Enter the choice ";choice
5980 if choice  3 then dig3=choice+2:goto 6031
5990 locate 22:input "Incorrect choice, enter the choice again ";choice
```

FIGURE 49. (Continued)

```
6000 goto 5980
6010 input "Is the external and internal shape machined ";ans$
6020 if ans$ = "y" then dig3=6:goto 6031
6030 if ans$ = "n" then dig3=7:goto 6031
6031 return
6040 '
6050 '
6060 '
6070 '
6080 cls:locate 5
6090 print space1$;"***** Rotational with deviation *****"
6100 print
6110 print space1$;" 4th Digit: Plane surface machining "
6120 print
6130 print "1.  No surface machining "
6140 print "2.  External plane surface and/or surface curved in one direction"
6150 print "3.  External plane surfaces related to one another"
6160 print "4.  External groove and/or slot"
6170 print "5.  External spline and/or polygon"
6180 print "6.  External plane surface and/or slot and/or groove, spline"
6190 print "7.  Internal plane surface and/or groove"
6200 print "8.  Internal spline and/or polygon"
6210 print "9.  External and internal spline and/or slot and/or groove"
6220 print "10. Other"
6230 print
6240 input "Enter the choice ";choice
6250 if choice  10 then dig4=choice-1:goto 6271
6260 locate 20:input "Incorrect choice, enter the choice again ";choice
6270 goto 6250
6271 return
6280 '
6290 '
6300 '
6310 '
6320 cls:locate 5
6330 print space1$;"***** Rotational with deviation *****"
6340 print
6350 print space1$;" 5th Digit: Auxiliary hole(s), gear teeth, forming "
6360 print
6370 print "1.  No auxiliary holes, gear teeth and forming"
6380 print "2.  Auxiliary holes, no forming, no gear teeth"
6390 print "3.  Forming, no gear teeth"
6400 print "4.  Gear teeth, no auxiliary hole(s)"
6410 print "5.  Gear teeth, with auxiliary hole(s)"
6420 print "6.  Other"
6430 print
6440 input "Enter the choice ";choice
```

FIGURE 49. (Continued)

```
6450 if choice = 1 then dig5=0:goto 6721
6460 if choice = 2 then goto 6530
6470 if choice = 3 then goto 6680
6480 if choice = 4 then dig5=7:goto 6721
6490 if choice = 5 then dig5=8:goto 6721
6500 if choice = 6 then dig5=9:goto 6721
6510 locate 17:input "Incorrect choice, enter the choice again ";choice
6520 goto 6450
6530 input "Are the hole(s) related by a drilling pattern (y/n)";ans$
6540 if ans$ = "y" then goto 6630
6550 if ans$ = "n" then goto 6580
6560 locate 19:input "Incorrect answer, answer again ";ans$
6570 goto 6540
6580 input "Are they axial holes (y/n) ";ans$
6590 if ans$ = "y" then dig5=3:goto 6721
6600 if ans$ = "n" then dig5=4:goto 6721
6610 locate 21:input "Incorrect answer, answer again (y/n) ";ans$
6620 goto 6590
6630 input "Are they axial holes (y/n) ";ans$
6640 if ans$ = "y" then dig5=1:goto 6721
6650 if ans$ = "n" then dig5=2:goto 6721
6660 locate 21:input "Incorrect answer,  answer again (y/n) ";ans$
6670 goto 6640
6680 input "Is the component formed with auxiliary holes (y/n)";ans$
6690 if ans$ = "y" then dig5=6:goto 6721
6700 if ans$ = "n" then dig5=5:goto 6721
6710 locate 21:input "Incorrect answer, answer again (y/n)";ans$
6720 goto 6690
6721 return
6730 '
6740 '
6750 '
6760 '
6770 cls:locate 5
6780 print "     ";"***** Non-Rotational *****"
6790 print
6800 input "Enter three Dimensions A,B,C (A>B>C>) ";A,B,C
6810 if A/B  3 AND A/C >= 4 then dig1=6:goto 6831
6820 if A/B > 3                then dig1=7:goto 6831
6830 dig1=8
6831 return
6832 '
6833 '
6834 '
6835 '
6840 cls:locate 5
6850 print space1$;"***** Non-Rotational *****"
```

FIGURE 49. (Continued)

```
6860 print
6870 print space1$;" 2nd Digit: Overall shape "
6880 print
6890 input "Is the overall shape plane or flat or other (p/f/o) ";ans$
6900 if ans$ = "p" then goto 6950
6910 if ans$ = "f" then print:print "The overall shape must be flat ":goto 7080
6920 if ans$ = "o" then dig2=9:goto 7181
6930 locate 11:input "Incorrect answer, enter the answer again ";ans$
6940 goto 6900
6950 print
6960 print "The overall shape is plane"
6970 print
6980 print "1.  Rectangular"
6990 print "2.  Rectangular, with one deviation (right angle or triangular)"
7000 print "3.  Rectangular, with angular deviations"
7010 print "4.  Rectangular with circular deviation"
7020 print "5.  Any flat shape other than 1 to 4"
7030 print
7040 input "Enter the choice ";choice
7050 if choice  5 then dig2=choice-1:goto 7181
7060 locate 19:input "Incorrect choice, enter the choice again ";choice
7070 goto 7050
7080 print
7090 print "1.  Rectangular or right angled with small deviations due to"
7100 print "    casting, welding, forming"
7110 print "2.  Round or of any shape other than 1"
7120 print "3.  Regularly arched or dished"
7130 print "4.  Irregularly arched or dished"
7140 print
7150 input "Enter the choice ";choice:goto 7181
7160 if choice  4 then dig2=choice+4
7170 locate 19:input "Incorrect choice, enter the choice again ";choice
7180 goto 7160
7181 return
7190 '
7200 '
7210 '
7220 '
7230 cls:locate 5
7240 print space1$;"***** Non-Rotational *****"
7250 print
7260 print " 3rd Digit: Principal bore, rotational surface machining "
7270 print
7280 print "1.  No rotational machining or bore(s)"
7290 print "2.  One principal bore"
7300 print "3.  Two principal bores, parallel"
7310 print "4.  Several principal bores"
```

FIGURE 49. (Continued)

```
7320 print "5.  Machined angular surfaces, angular grooves"
7330 print "6.  5+principal bore(s)"
7340 print "7.  Others"
7350 print
7360 input "Enter the choice ";choice
7370 if choice = 1 then dig3=0:goto 7601
7380 if choice = 2 then goto 7460
7390 if choice = 3 then dig3=4:goto 7601
7400 if choice = 4 then goto 7550
7410 if choice = 5 then dig3=7:goto 7601
7420 if choice = 6 then dig3=8:goto 7601
7430 if choice = 7 then dig3=9:goto 7601
7440 locate 17:input "Incorrect choice, enter the choice again";choice
7450 goto 7370
7460 print
7470 print "1.  Smooth"
7480 print "2.  Stepped to one or both ends"
7490 print "3.  With shape elements"
7500 print
7510 input "Enter the choice ";choice
7520 if choice  3 then dig3=choice:goto 7601
7530 locate 23:input "Incorrect choice, enter the choice again ";choice
7540 goto 7520
7550 print
7560 input "Is it parallel (y/n) ";ans$
7570 if ans$ = "y" then dig3=5:goto 7601
7580 if ans$ = "n" then dig3=6:goto 7601
7590 locate 19:input "Incorrect choice, enter the answer again (y/n) ";ans$
7600 goto 7570
7601 return
7610 '
7620 '
7630 '
7640 '
7650 cls:locate 5
7660 print space1$;"***** Non-Rotational *****"
7670 print
7680 print " 4th Digit: Plane surface machining "
7690 print
7700 print "1.  No surface machining"
7710 print "2.  Functional chamfers (e.g. welding prep.)"
7720 print "3.  One plane surface"
7730 print "4.  Stepped plane surfaces"
7740 print "5.  Stepped plane surfaces at right angles, inclined and/or opposite"
7750 print "6.  Groove and/or slot"
7760 print "7.  Groove and/or slot and 5"
7770 print "8.  Curved surface"
```

FIGURE 49. (Continued)

```
7780 print "9.  Guide surfaces"
7790 print "10. Others"
7800 print
7810 input "Enter the choice ";choice
7820 if choice  10 then dig4=choice-1:goto 7841
7830 locate 20:input "Incorrect choice, enter the choice again ";choice
7840 goto 7820
7841 return
7850 '
7860 '
7870 '
7880 '
7890 cls:locate 5
7900 print space1$;"***** Non-Rotational *****"
7910 print
7920 print space1$;" 5th Digit: Auxiliary hole(s), forming, gear teeth "
7930 print
7940 print "1.  No auxiliary holes, gear teeth and forming"
7950 print "2.  Auxiliary holes, no forming, no gear teeth"
7960 print "3.  Forming, no gear teeth"
7970 print "4.  Gear teeth, no auxiliary hole(s)"
7980 print "5.  Gear teeth, with auxiliary hole(s)"
7990 print "6.  Other"
8000 print
8010 input "Enter the choice ";choice
8020 if choice = 1 then dig5=0:goto 8300
8030 if choice = 2 then goto 8100
8040 if choice = 3 then goto 6680
8050 if choice = 4 then dig5=7:goto 8300
8060 if choice = 5 then dig5=8:goto 8300
8070 if choice = 6 then dig5=9:goto 8300
8080 locate 17:input "Incorrect choice, enter the choice again ";choice
8090 goto 8020
8100 input "Are the auxiliary hole(s) related by a drilling pattern (y/n) ";ans$
8110 if ans$ = "y" then goto 8200
8120 if ans$ = "n" then goto 8150
8130 locate 19:input "Incorrect answer, enter the answer again ";ans$
8140 goto 8110
8150 input "Are the holes drilled in one direction (y/n) ";ans$
8160 if ans$ = "y" then dig5=3:goto 8300
8170 if ans$ = "n" then dig5=4:goto 8300
8180 locate 21:input "Incorrect answer, enter the answer again (y/n) ";ans$
8190 goto 8160
8200 input "Are the holes drilled in one direction (y/n) ? ";ans$
8210 if ans$ = "y" then dig5=1:goto 8300
8220 if ans$ = "n" then dig5=2:goto 8300
8230 locate 21:input "Incorrect answer, enter the answer again (y/n) ";ans$
```

FIGURE 49. (Continued)

```
8240 goto 8210
8250 input "Is the component formed with auxiliary holes (y/n) ";ans$
8260 if ans$ = "y" then dig5=6:goto 8300
8270 if ans$ = "n" then dig5=5:goto 8300
8280 locate 21:input "Incorrect answer, enter the answer again (y/n) ";ans$
8290 goto 8260
8300 return
8310 '
8320 '
8321 '
8330 '
8340 cls:locate 5
8350 print space1$;"***** Non-Rotational *****"
8360 print
8370 print space1$;" 2nd Digit: Overall shape "
8380 print
8390 input "Is the shape axis straight (y/n) ";ans$
8400 if ans$ = "y" then goto 8440
8410 if ans$ = "n" then goto 8620
8420 locate 10:input "Incorrect answer, enter the answer again ";ans$
8430 goto 8400
8440 print
8450 input "Is the cross-section uniform or curved (u/c) ";ans$
8460 if ans$ = "u" then goto 8500
8470 gosub 8530
8480 dig2=choice+2
8490 goto 8520
8500 gosub 8530
8510 dig2=choice-1
8520 return
8521 '
8522 '
8523 '
8524 '
8530 print
8540 print "1.  Rectangular"
8550 print "2.  Rectangular with one deviation"
8560 print "3.  Any cross-section other than 1 and 2"
8570 print
8580 input "Enter the choice ";choice
8590 if choice 3 then return
8600 locate 17:input "Incorrect choice, enter the choice again ";choice
8610 goto 8590
8611 '
8612 '
8613 '
8614 '
```

FIGURE 49. (Continued)

```
8620 print
8630 print "1.  Rectangular, angular and other cross-sections"
8640 print "2.  Formed component"
8650 print "3.  Formed component with deviations in the main axis"
8660 print "4.  others"
8670 print
8680 input "Enter the choice ";choice
8690 if choice  4 then dig2=choice+5:goto 8520
8700 locate 16:input "Incorrect choice, enter the choice again ";choice
8710 goto 8690
8720 '
8730 '
8740 '
8750 '
8760 cls:locate 5
8770 print space1$;"***** Non-Rotational *****"
8780 print
8790 print space1$;" 2nd Digit: Overall shape "
8800 print
8810 input "Is the overall shape block-like or box-like (block/box) ";ans$
8820 if ans$ = "block" then goto 8860
8830 if ans$ = "box"   then goto 8990
8840 locate 10: input "Incorrect answer, answer again (block/box) ";ans$
8850 goto 8820
8860 print
8870 print "1.  Rectangular prism "
8880 print "2.  Rectangular with deviations (right angle or triangular)"
8890 print "3.  Compounded of rectangular prisms"
8900 print "4.  Components with a mounting or locating surface and principal bore"
8910 print "5.  Components with a mounting or locating surface, principal"
8920 print "    bore with dividing surface"
8930 print "6.  Others"
8940 print
8950 input "Enter the choice ";choice
8960 if choice  6 then dig2=choice-1:goto 9161
8970 locate 20:input "Incorrect choice, enter the choice again ";choice
8980 goto 8960
8990 print
9000 input "Is the component split (y/n) ";ans$
9010 if ans$ = "y" then goto 9050
9020 if ans$ = "n" then goto 9110
9030 locate 13:input "Incorrect answer, enter the answer again (y/n) ";ans$
9040 goto 9010
9050 print
9060 print "Is the component approximate";
9061 input " or compounded of rectangular prisms (y/n) ";ans$
9070 if ans$ = "y" then dig2 =6 :goto 9161
```

FIGURE 49. (Continued)

```
9080 if ans$ = "n" then dig2=7:goto 9161
9090 locate 16:input "Incorrect answer, enter the answer again (y/n) ";ans$
9100 goto 9070
9110 print
9120 print "Is the component approximate";
9121 input " or compounded of rectangular prisms (y/n) ";ans$
9130 if ans$ = "y" then dig2=8:goto 9161
9140 if ans$ = "n" then dig2=9:goto 9161
9150 locate 16:input "Incorrect answer, enter the answer again (y/n) ";ans$
9160 goto 9130
9161 return
9170 '
9180 '
9190 '
9200 '
9210 cls:locate 5
9220 print "Part Name is ";pname$
9230 print "Part Number is ";pnum$
9240 print
9250 print "Opitz code is ";dig1;dig2;dig3;dig4;dig5;dig6;dig7;dig8;dig9
9320 return
```

FIGURE 49. (Continued)

```
100 '*-------------------------------------------------------------*
110 '|                                                             |
120 '|    Computer Aided Coding and Classification                 |
130 '|                                                             |
150 '|    Opitz Coding Method                                      |
160 '|    Rank Order Cluster Analysis (ROCA)                       |
170 '|    Cluster Analysis with Similarity Coefficients (CASC)     |
180 '|                                                             |
190 '|                                                             |
191 '|    Definitions of Variables                                 |
192 '|                                                             |
193 '|    tnp: Total Number of Parts in the data file              |
194 '|    tp:  Total Number of Process of a part                   |
195 '|    id:  Total number of machines                            |
196 '|                                                             |
197 '*-------------------------------------------------------------*
198 '
203    dim pname$(100),pnum$(100),pmmat(100,50),mach$(50)
220 '
221 '*-------------------------------------------------------------*
222 '*            Opitz                                            |
223 '*-------------------------------------------------------------*
224 '
226    cls:locate 10,40
227    print "1=";"ROCA"
228    locate 11,40
229    print "2=";"CASC"
230    locate 12,40
231    print "3=";"Exit"
232    locate 14,32:input "Enter the number ";method
233    if method = 1 then gosub 5400:gosub 1300 :' ROCA
234    if method = 2 then gosub 5400:gosub 2750 :' CASA
235    if method = 3 then end   : ' End of program
236    locate 14,32:input"Enter the number again";method:goto 233
1300 '
1310 '*-----------------------------------------------------------*
1320 '|                 Initialization                            |
1330 '*-----------------------------------------------------------*
1331 '
1340    dim rlist(tnp,2),clist(id,2),ylist(tnp),nlist(tnp),tlist(tnp,id)
1350    dim ytlist(tnp),ntlist(tnp),rtemp(tnp),ctemp(id),tmach$(id)
1360    dim tpnum$(tnp)
1361    for i = 1. to 56
1362        if (i > 27 and i 33) then 1364
            ii = i
            if i > 32 then ii  = i-6
1363        mach$(ii) = chr$(i+64)
```

FIGURE 50. The program listing of the Opitz coding method with the CASA and ROCA classification methods

```
1364    next
1491    iteration=0
1492    gosub 5080    :' print the initial p-m matrix
1500    crit=0
1510    for I = 1 to tnp
1520       rlist(I,1) = I
1530    next
1540    for j = 1 to id
1550       clist(j,1) = j
1560    next
1570    iteration=iteration+1
1580    gosub 2590
1581 '
1590 '*-----------------------------------------------------------*
1600 '|                   Rowwise sorting                         |
1610 '*-----------------------------------------------------------*
1611 '
1620    for j = id to 1 step -1
1630       y=0:z=0
1640       for I = tnp to 1 step -1
1650          if pmmat(I,j) = 1 then y=y+1:ylist(y)=I:goto 1670
1660          z=z+1:nlist(z)=I
1670       next
1680       for I = 1 to tnp:rlist(I,2)=0:next:I=1
1690       for l = y to 1 step -1
1700          if I > tnp then goto 1760
1710          if rlist(I,1) = ylist(l) then 1720 else 1740
1720          rlist(I,2)=1
1730          goto 1760
1740          I = I + 1
1750          goto 1700
1760       I=1:next
1770       y=0:z=0
1780       for I = 1 to tnp
1790          if rlist(I,2) = 1 then 1800 else 1830
1800          rlist(I,2)=0:y=y+1
1810          ytlist(y)=rlist(I,1)
1820          goto 1850
1830          z=z+1
1840          ntlist(z)=rlist(I,1)
1850       next
1860       for l= 1 to y: rlist(l,1)=ytlist(l): next
1870       for l=y+1 to tnp: rlist(l,1)=ntlist(l-y): next
1880       for l=1 to tnp-1: print rlist(l,1);: next: print rlist(tnp,1)
1890    next
1900    for i = 1 to tnp: tpnum$(i) = "": next
1910    for i = 1 to tnp
```

FIGURE 50. (Continued)

```
1920        index = rlist(i,1)
1930        tpnum$(i) = pnum$(index)
1940        for j = 1 to id
1950            tlist(i,j) = pmmat(index,j)
1960        next
1970    next
1980    for i = 1 to tnp: pnum$(i) = "": next
1990    for i = 1 to tnp
2000        pnum$(i) = tpnum$(i)
2010        for j = 1 to id
2020            pmmat(i,j) = tlist(i,j)
2030        next
2040    next
2060    gosub 2590
2061 '
2070 '*------------------------------------------------------------*
2080 '|                Colummwise sorting                            |
2090 '*------------------------------------------------------------*
2091 '
2100    for I = 1 to tnp:rlist(I,1)=I:next
2110    for j = 1 to id:clist(j,1)=j:next
2120    for I = tnp to 1 step -1
2130       y=0:z=0
2140       for j = id to 1 step -1
2150          if pmmat(I,j) = 1 then y=y+1:ylist(y)=j:goto 2170
2160          z=z+1:nlist(z)=j
2170       next
2180       for j = 1 to id:clist(j,2)=0:next:j=1
2190       for l = y to 1 step -1
2200           if j > id then 2260
2210           if clist(j,1)=ylist(l) then 2220 else 2240
2220           clist(j,2) = 1
2230           goto 2260
2240           j=j+1
2250           goto 2200
2260           j=1
2261       next
2270       y=0:z=0
2280       for j = 1 to id
2290           if clist(j,2) = 1 then 2300 else 2330
2300           clist(j,2)=0:y=y+1
2310           ytlist(y)=clist(j,1)
2320           goto 2350
2330           z=z+1
2340           ntlist(z)=clist(j,1)
2350       next
2360       for l=1 to y:clist(l,1)=ytlist(l):next
```

FIGURE 50. (Continued)

```
2370       for l=y+1 to id:clist(l,1)=ntlist(l-y):next
2380       for l = 1 to id-1:print clist(l,1);:next:print clist(id,1)
2390    next
2431    for j = 1 to id: tmach$(j) = "": next
2440    for j = 1 to id
2450        index = clist(j,1)
2460        tmach$(j) = mach$(index)
2470        for i = 1 to tnp
2480            tlist(i,j) = pmmat(i,index)
2490        next
2500    next
2501    for i=1 to tnp
2502       for j=1 to id
2503          if tlist(i,j) = pmmat(i,j) then goto 2505
2504          crit = crit+1
2505       next
2506   next
2497   if crit = 0 then 2581
2510   for j = 1 to id: mach$(j) = "": next
2520   for j = 1 to id
2530       mach$(j) = tmach$(j)
2540       for i = 1 to tnp
2550           pmmat(i,j) = tlist(i,j)
2551       next
2552   next
2560   gosub 2590
2580   goto 1500
2581   return
2590 '
2600 '
2610 '
2620    lprint "Iteration  ";iteration:lprint:lprint
2621    lprint using "                   ";"          list";
2622    for j=1 to id-1:lprint using "###";clist(j,1);:next
2623    lprint using "###";clist(id,1)
2630    lprint using "                   ";"list  part/mach ";
2640    for j = 1 to id-1:lprint USING "&"; mach$(j);:next
2650    lprint using "&"; mach$(id):lprint
2660    for I = 1 to tnp
2670       lprint using "###    "; rlist(I,1);
2671       lprint using "                   "; pnum$(i);
2680       for j = 1 to id-1
2690          lprint using "#"; pmmat(I,j);
2700       next
2710       lprint using "#"; pmmat(I,id)
2720    next
2730    lprint:lprint:lprint
```

FIGURE 50. (Continued)

```
2740    return
2741 '
2750 '*----------------------------------------------------------*
2760 '|          Cluster Analysis with Similarity Coefficient     |
2770 '*----------------------------------------------------------*
2790 dim B(tnp),C(tnp),A(tnp)
2921 '
2930 '*----------------------------------------------------------*
2940 '|          Calculation of Similarity Coefficient Matrix     |
2950 '*----------------------------------------------------------*
2951 '
2960    cls:locate 10,18
2961    print "Cluster Analysis with Similarity Coefficient"
2970    locate 11,20
2971    print "Calculating similarity coefficient matrix"
2980    locate 12,31
2981    print "Please  wait ......"
2982 '*
3131 '
3140 '*----------------------------------------------------------*
3150 '|             Prim Tree Data Structure                      |
3160 '*----------------------------------------------------------*
3161 '
3170    DLARGE=0:a=0:b=0:c=0
3180    if tnp  1 then ifAULT=1:end
3190    IFAULT=0
3200    for I=2 to tnp
3210       A(I)=0:B(I)=0:C(I)=DLARGE
3220    next
3230    j=1:
3240    for I=2 to tnp
3250       MIN=DLARGE
3260       for K=2 to tnp
3270          if A(K) = 0 then 3280 else 3320
3280          if j >= K then row1=j:row2=k  else row1=k:row2=j
3281          for col = 1 to id
3282              if pmmat(row1,col)=1 and pmmat(row2,col)=1 then a=a+1
3283              if pmmat(row1,col)=1 and pmmat(row2,col)=0 then b=b+1
3284              if pmmat(row1,col)=0 and pmmat(row2,col)=1 then c=c+1
3285          next
3290          DIST=a/(a+b+c)
3291          a=0:b=0:c=0
3300          if DIST >= C(K) then  C(K)=DIST:B(K)=j
3310          if MIN  C(K)  then  MIN=C(K):NEX=K
3320       next
3330       j=NEX:A(j)=1:print "next = ";nex
3340    next
```

FIGURE 50. (Continued)

```
3360    lprint "                          Results of CASC"
3370    lprint:lprint:lprint
3371    lprint "                       Prim's Tree Structure"
3380    lprint:lprint
3390    for i=2 to tnp:lprint pnum$(i),i,b(i),c(i):next:lprint:lprint
3391 '
3400 '*------------------------------------------------------------*
3410 '|               printing Minimal Spanning Tree               |
3420 '*------------------------------------------------------------*
3421 '
3430 dim ROUT(tnp),HIST(tnp)
3440    for I= 1 to tnp: HIST(I)=0:next
3450    for I = 2 to tnp
3460       TEMM=B(I)
3470       HIST(TEMM)=HIST(TEMM)+1
3480       print TEMM,HIST(TEMM)
3490    next
3500    ROUT(1)=1: j=1: K=1
3510    for I = 2 to tnp
3520       if HIST(K) = 0 then 3530 else 3550
3530       j=j-1:K=ROUT(j)
3540       goto 3520
3550       HIST(K)=HIST(K)-1
3560       for M=2 to tnp
3570          if K=B(M) then 3580 else 3610
3580          lprint K,M,C(M):j=j+1
3590          K=M:ROUT(j)=K
3600          B(M)=-B(M)
3610       next
3620    next
3622 '
3630 '*------------------------------------------------------------*
3640 '|          Single Linkage Cluster Analysis                   |
3650 '|                                                            |
3660 '|            s: previous point indicator                     |
3670 '|            t: next print indicator                         |
3680 '|          u,v: switches                                     |
3690 '|            k: total number of clusters                     |
3700 '|            h: list which contains end-of-makers            |
3710 '*------------------------------------------------------------*
3711 '
3720 dim G(tnp),H(tnp),X(20*tnp),W1(tnp),W2(tnp)
3721    lprint:lprint
3730    lprint "           Result of Single Linkage Cluster Analysis"
3740    lprint:lprint
3741 '
```

FIGURE 50. (Continued)

```
3750 '*-----------------------------------------------------------*
3760 '|     this loop will find the Dmax (Maximum distance)       |
3770 '*-----------------------------------------------------------*
3771 '
3780    for I=2 to tnp:zz=-B(I):B(I)=zz:print B(I):next
3790    DMAX=C(2)
3800    for I=3 to tnp
3810       if DMAX C(I) then DMAX=C(I)
3820    next
3821 '
3830 '*-----------------------------------------------------------*
3840 '|             Initialization                                |
3850 '*-----------------------------------------------------------*
3851 '
3860    for I= 1 to tnp
3870       G(I)=I :' List G consists initially of all points as single groups
3880       H(I)=1 :' Thus, initially, list H should have all 1's
3890       X(I)=3 :' Initially, t=3 for all points
3900    next
3910    P=0
3920    DELTA=0.05
3930    LEVEL =.DELTA*(1+INT(DMAX/DELTA))
3940    WHILE K  1
3950    P=P+1
3960    for I = 2 to tnp
3961 '
3970 '*-----------------------------------------------------------*
3980 '|      for point whose length is less than level            |
3990 '*-----------------------------------------------------------*
3991 '
4000       if C(I) > LEVEL then 4010 else 4280
4010         j=B(I):C(I)=C(I)-C(I)-0.001  ' Links once used are decreased
4020                                      ' to zero to prevent re-use
4030         K=I
4040         for M=1 to tnp
4050            if G(M)=j then Q=M
4060            if G(M)=K then R=M
4070         next
4080         if Q > R then M=R:R=Q:Q=M
4090         S=Q
4100         if S > tnp goto 4280
4110         if H(S)  0 then 4120 else S=S+1:goto 4100
4120         T=R-1
4130         if T = 0 goto 4280
4140         if H(T)  0 then 4150 else T=T-1:goto 4130
4150         T=T+1:H(S)=0
4160         R=T
```

FIGURE 50. (Continued)

```
4170        if R > tnp goto 4280
4180        W1(R-T)=G(R):W2(R-T)=H(R)
4190        if H(R)  0  then 4200 else R=R+1:goto 4170
4200                       W=S+1:U=R-T+1
4210                       for M=T-1 to W step -1
4220                          G(M+U)=G(M):H(M+U)=H(M)
4230                       next
4240                       U=R-T
4250                       for M=0 to U
4260                          G(M+W)=W1(M):H(M+W)=W2(M)
4270                       next
4280  next
4281 if level > 0.8 or level 0.5 then 4301
4287 '*--------------------------------------------------------*
4288 '|                 prints group                           |
4290 '*--------------------------------------------------------*
4291   lprint "level =";level:lprint
4292   for i=1 to tnp
4293   lprint g(i);
4294   if h(i)=1 then lprint "*"
4295   next:lprint:lprint
4300   print "printing group"
4301 '*
4310   W=N*tnp:U=0:V=0:K=0
4320   for I=2 to tnp:K=K+H(I):next
4330   if P 20 then 4340 else 4480
4340   for I= 1 to tnp
4350      j=G(I):S=X(j+W+N)
4360      if U=0 then 4370 else 4390
4370         if H(I) = 1 then T=3 else if S=3 then T=1:U=1:V=1 else T=0:U=1
4380         goto 4460
4390         if H(I) = 1 then 4400 else 4420
4400         if V = 0 then T=3:U=0 else T=2:U=0:V=0
4410         goto 4460
4420         if S=2 OR S=3 then 4430 else 4450
4430         if V = 0 then T=1:U=1:V=1 else T=5:U=1
4440         goto 4460
4450         if V = 0 then T=0:U=1 else T=4
4460         X(j+W)=T
4470   next
4480   LEVEL=LEVEL-DELTA
4490   print:print:print
4500   print "level=";LEVEL:print
4510   for z = 1 to tnp:print B(z),C(z),G(z),H(z): next
4530   WEND
4540  ' gosub topprint
4550  for I=1 to tnp
```

FIGURE 50. (Continued)

```
4560      j=G(I):' gosub Sideprint
4570      print "printING SIDE"
4580      if P > 19 then P=19
4590      for M=0 to P:' gosub printx
4600         print "printING X"
4610      next
4620   next
4630   return
4640 '
5071 '
5080 '*-------------------------------------------------------------*
5090 '|             printing initial P-M matrix                     |
5100 '*-------------------------------------------------------------*
5101 '
5110     lprint "***** The initial Part-Machine Matrix *****"
5120     lprint:lprint:lprint
5130    lprint USING "                  ";"part/mach";
5140     for j = 1 to id-1:lprint USING "&";mach$(j);:next
5150     lprint USING "&";mach$(id):lprint
5160     for I = 1 to tnp
5170       lprint USING "                    ";pnum$(I);
5180       for j = 1 to id-1
5190          lprint USING "#";pmmat(I,j);
5200       next
5210       lprint USING "#";pmmat(I,id)
5220     next:lprint:lprint:lprint
5230     return
5391 '
5392 '*-------------------------------------------------------------*
5393 '|         Generate P-M Matrix for Opitz coding method         |
5394 '*-------------------------------------------------------------*
5395 '
5400    open "program   code.dat" for input as #4
        j=1
5410    if eof(4) then 5420
          input #4,pnames$(j),pnum$(j),d1,d2,d3,d4,d5,d6,d7,d8,t
          pmmat(j,d1+1)=1
          pmmat(j,d2+11)=1
          pmmat(j,d3+21)=1
          pmmat(j,d4+31)=1
          pmmat(j,d5+41)=1
          j=j+1
          goto 5410
5420   close #2
       tnp=j-1:id=50
       return
```

FIGURE 50. (Continued)

```
100 '*--------------------------------------------------------------------*
110 '|                                                                    |
120 '|        Computer Aided Coding and Classification                    |
130 '|                                                                    |
140 '|        Production Flow Analysis (PFA)                              |
150 '|        Opitz Coding Method                                         |
160 '|        Rank Order Cluster Analysis (ROCA)                          |
170 '|        Cluster Analysis with Similarity Coefficients (CASC)        |
180 '|                                                                    |
190 '|                                                                    |
200 '|        Definitions of Variables                                    |
210 '|                                                                    |
220 '|        tnp: Total Number of Parts in the data file                 |
230 '|        tp:  Total Number of Process of a part                      |
240 '|        id:  Total number of machines                               |
250 '|                                                                    |
260 '*--------------------------------------------------------------------*
261 '
262 '*--------------------------------------------------------------------*
263 '*              production flow analysis                              |
264 '*--------------------------------------------------------------------*
265 '
270    dim pname$(300),pnum$(300),route(10,20),atp(300),mach(50)
271    dim machid$(50)
       input "Read in part data (y/n)";ans$
       if ans$ = "n" then goto 351
280    gosub 470
290    cls:locate 7
300    input "Do you want to add part data (y/n)";ans$
310    if ans$="y" then gosub 1060
320    cls:locate 7:
330    input "Do you want to check the data (y/n) ";ans$
340    if ans$ = "y" then gosub 840
350    gosub 650 :'  find and print machine list
351 '
352 '*--------------------------------------------------------------------*
353 '|              clustering algorithms (ROCA, CASA)                    |
354 '*--------------------------------------------------------------------*
355 '
360    dim pmmat(tnp,40)
370    cls:locate 10,40
380    print "1=";"ROCA"
390    locate 11,40
391    print "2=";"CASC"
392    locate 12,40
393    print "3=";"Exit"
400    locate 14,32:input "Enter the number ";method
```

FIGURE 51. The program listing of the PFA coding method with the CASA and ROCA classification methods

```
410    if method = 1 then 1300  : ' Rank order clustering algorithm
420    if method = 2 then 2750  : ' Cluster analysis with similarity coeff.
430    if method = 3 then end   : ' End of program
440    locate 14,32:input"Enter the number again";method:goto 410
441 '
450 '*-----------------------------------------------------------------------*
460 '|              reading data file                                        |
470 '*-----------------------------------------------------------------------*
471 '
480    key off:cls
481    locate 10,28:print "Part data file is loding"
490    locate 11,31:print "Please  wait ......"
500    tnp=1:id=1
510   open "program    parts.dat" for input as #2
520    if eof(2) then 600
530       input #2,pname$(tnp),pnum$(tnp),atp(tnp)
540       tp=atp(tnp)
550       for j=1 to tp
560          input #2,route(tnp,j)
570       next
580       tnp=tnp+1
590       goto 520
600    tnp=tnp-1:close #2
610    return
611 '
620 '*-----------------------------------------------------------------------*
630 '|               printing machine list                                   |
640 '*-----------------------------------------------------------------------*
641 '
650    read id
660    for i = 1 to id
700        read mach(i)
710        machid$(i)=chr$(i+64)
720    next
801    data 25
802    data 16,10,9,28,18,1,2,17,8,7,24,12,33,21
803    data 14,20,13,11,35,30,23,27,36,31,25
810    print "Press any key to continue"
820    a$=inkey$:if a$="" then 820
830    return
831 '
840 '*-----------------------------------------------------------------------*
850 '|           print a part name, a part number, total # of processes      |
860 '|           and process sequences                                       |
870 '*-----------------------------------------------------------------------*
871 '
880    cls:locate 7
```

FIGURE 51. (Continued)

```
890    print "You finished ";tnp;"part data to type in"
900    print "Press any key to continue"
910    a$=inkey$:if a$="" then 910
920    for i=1 to tnp
930      gosub 4770       :' Correction
940    next
950   open "program    parts.dat" for output as #3
960    for i = 1 to tnp
970    write #3, pname$(I),pnum$(I),atp(I)
980    for j= 1 to atp(I)
990       write #3, route(I,j)
1000    next
1010    next
1020    close #1
1030    print "Press any key to continue"
1040    a$=inkey$:if A$="" then 1040
1050    return
1051 '
1060 '*--------------------------------------------------------------------*
1070 '¦             Interactive input of part data                           ¦
1080 '*--------------------------------------------------------------------*
1081 '
1090    input "How many part data you want to type in";N
1100    for I=tnp+1 to tnp+N
1110       cls:locate 7
1120       input "Enter part name ";pname$(I)
1130       input "Enter part number ";pnum$(I)
1140       input "Enter total number of process for this part";atp(I)
1150       for j= 1 to atp(I)
1160          print "Enter the ";j;"th process sequence"
1170          input route(I,j)
1180       next
1190       gosub 4770
1200      open "program parts.dat" for append as #1
1210       write #1, pname$(I),pnum$(I),atp(I)
1220       for j= 1 to atp(I)
1230          write #1, route(I,j)
1240       next
1250       close #1
1260       cls:locate 7
1270    next
1280    tnp=tnp+n
1290    return
1300 '
1310 '*--------------------------------------------------------------------*
1320 '¦                 Initialization                                     ¦
1330 '*--------------------------------------------------------------------*
1331 '
```

FIGURE 51. (Continued)

```
        erase route:tnp=272
1340    dim rlist(tnp,2),clist(50,2),ylist(tnp),nlist(tnp),tlist(tnp,45)
1350    dim ytlist(tnp),ntlist(tnp),rtemp(tnp),ctemp(50),tmach$(50)
1360    dim tpnum$(tnp),machtemp(50)
1361 '
1370 '*----------------------------------------------------------------------*
1380 '|                   Generate Part-Machine Matrix                       |
1390 '*----------------------------------------------------------------------*
1391 '
        cls:locate 11:input "Reading part-machine matrix (y/n)";ans$
        if ans$ = "n" then 1400
        open "program   incid.dat" for input as #4
        input #4, tnp,id
        erase pmmat:dim pmmat(tnp,45)
        for j = 1 to id
             input #4, machid$(j)
        next
        for j = 1 to id
             input #4, mach(j)
        next
        for i = 1 to tnp
             input #4, pnum$(i)
             for j = 1 to id
                  input #4, pmmat(i,j)
             next
        next
        close #4
        goto 1491
1400    cls:locate 10,25:print "Generating Part-Machine Matrix"
1410    locate 11,31:print "Please  wait ......"
1420    col=1:row=1
1430    if row > tnp then  goto 1491
1440    col=1
1450    for I=1 to id
1460       if route(row,col) = mach(I) then pmmat(row,I)=1
1470    next
1480    if col atp(row) then col=col+1:goto 1450
1490    row=row+1:goto 1430
rem '
rem '  Print the initial p-m matrix
rem '
1491    for i = 1 to tnp:rlist(i,1)=i:next
        for j = 1 to id:rlist(j,1)=j:next
        lprint:lprint:lprint
        lprint "***** The initial Part-Machine *****"
        lprint:lprint:lprint:' gosub 2810
1500    iteration=0:crit=0
```

FIGURE 51. (Continued)

```
     cls:locate 10,25:print "Rank Order Clustering Analysis"
     locate 11,31:print "Please wait ....."
1510 for I = 1 to tnp
1520    rlist(I,1) = I
1530 next
1540 for j = 1 to id
1550    clist(j,1) = j
1560 next
1570 iteration=iteration+1
1580 '  gosub 2610
1581 '
1590 '*---------------------------------------------------------------------*
1600 '|                    Rowwise sorting                                  |
1610 '*---------------------------------------------------------------------*
1611 '
1620 for j = id to 1 step -1
1630    y=0:z=0
1640    for I = tnp to 1 step -1
1650       if pmmat(I,j) = 1 then y=y+1:ylist(y)=I:goto 1670
1660       z=z+1:nlist(z)=I
1670    next
1680    for I = 1 to tnp:rlist(I,2)=0:next:I=1
1690    for l = y to 1 step -1
1700       if I > tnp then goto 1760
1710       if rlist(I,1) = ylist(l) then 1720 else 1740
1720       rlist(I,2)=1
1730       goto 1760
1740       I = I + 1
1750       goto 1700
1760    I=1:next
1770    y=0:z=0
1780    for I = 1 to tnp
1790       if rlist(I,2) = 1 then 1800 else 1830
1800       rlist(I,2)=0:y=y+1
1810       ytlist(y)=rlist(I,1)
1820       goto 1850
1830       z=z+1
1840       ntlist(z)=rlist(I,1)
1850    next
1860    for l= 1 to y: rlist(l,1)=ytlist(l): next
1870    for l=y+1 to tnp: rlist(l,1)=ntlist(l-y): next
1890 next
1900 for i = 1 to tnp: tpnum$(i) = "": next
1910 for i = 1 to tnp
1920     index = rlist(i,1)
1930     tpnum$(i) = pnum$(index)
1940     for j = 1 to id
```

FIGURE 51. (Continued)

```
1950            tlist(i,j) = pmmat(index,j)
1960        next
1970    next
1980    for i = 1 to tnp: pnum$(i) = "": next
1990    for i = 1 to tnp
2000        pnum$(i) = tpnum$(i)
2010        for j = 1 to id
2020            pmmat(i,j) = tlist(i,j)
2030        next
2040    next
2060 '   gosub 2610
2061 '
2070 '*----------------------------------------------------------------------*
2080 '|                 Colummwise sorting                                   |
2090 '*----------------------------------------------------------------------*
2091 '
2100    for I = 1 to tnp:rlist(I,1)=I:next
2110    for j = 1 to id:clist(j,1)=j:next
2120    for I = tnp to 1 step -1
2130       y=0:z=0
2140       for j = id to 1 step -1
2150          if pmmat(I,j) = 1 then y=y+1:ylist(y)=j:goto 2170
2160          z=z+1:nlist(z)=j
2170       next
2180       for j = 1 to id:clist(j,2)=0:next:j=1
2190       for l = y to 1 step -1
2200           if j > id then 2260
2210           if clist(j,1)=ylist(l) then 2220 else 2240
2220           clist(j,2) = 1
2230           goto 2260
2240           j=j+1
2250           goto 2200
2260           j=1
2261       next
2270       y=0:z=0
2280       for j = 1 to id
2290           if clist(j,2) = 1 then 2300 else 2330
2300           clist(j,2)=0:y=y+1
2310           ytlist(y)=clist(j,1)
2320           goto 2350
2330           z=z+1
2340           ntlist(z)=clist(j,1)
2350       next
2360       for l=1 to y:clist(l,1)=ytlist(l):next
2370       for l=y+1 to id:clist(l,1)=ntlist(l-y):next
2390    next
2431    for j = 1 to id: tmach$(j) = "": machtemp(j)=0: next
```

FIGURE 51. (Continued)

```
2440    for j = 1 to id
2450          index = clist(j,1)
2460          tmach$(j) = machid$(index)
              machtemp(j)=mach(index)
2470          for i = 1 to tnp
2480               tlist(i,j) = pmmat(i,index)
2490          next
2500    next
2501    for i=1 to tnp
2502         for j=1 to id
2503            if tlist(i,j) = pmmat(i,j) then goto 2505
2504            crit = crit+1
2505         next
2506   next
2497   if crit = 0 then goto 2554
2510   for j = 1 to id: machid$(j) = "": mach(j)=0: next
2520   for j = 1 to id
2530         machid$(j) = tmach$(j)
             mach(j)=machtemp(j)
2540         for i = 1 to tnp
2550             pmmat(i,j) = tlist(i,j)
2551         next
2552   next
2553   goto 1500
2554 '
2555 ' print final matrix
2556 '
        lprint:lprint:lprint
        lprint "***** Number of machine usage *****"
        lprint:lprint "Number ";"     Machine No.";
        lprint "  Machine id.";"   num. of usage"
        for j = 1 to id
           numuse = 0
           for i = 1 to tnp
              if pmmat(i,j) = 1 then numuse=numuse+1
           next
           lprint j,mach(j),machid$(j),numuse
        next
        lprint:lprint:lprint
        lprint "***** Final Matrix *****":lprint
        lprint:lprint:' gosub 2610
rem
rem    Delete exceptional and bottleneck problem
rem
        cls:locate 11,10
        input "Do you want to investigate the final matrix (y/n)";ans$
        if ans$="n" then goto 2589
```

FIGURE 51. (Continued)

```
        open "program   incid.dat" for output as #4
        write #4, tnp,id
        for j  = 1 to id
            write #4, machid$(j)
        next
        for j  = 1 to id
            write #4, mach(j)
        next
        for i = 1 to tnp
             write #4, pnum$(i)
             for j = 1 to id
                  write #4, pmmat(i,j)
             next
        next
        close #4
        input "Printing final part-machine matrix (y/n)";ans$
        if ans$ = "y" then gosub 2800
rem
rem
rem
        cls:locate 10
        print "1: Bottleneck"
        print "2: Exceptional cases"
        print "3: Delete rows or columns"
        input "Enter the choice";choice
        on choice goto 2580, 2570, 2560
rem
rem
rem
2560    input "Column or row (c/r)";ans$
        if ans$ = "c" then 2561
        input "Enter the number of rows you want to drop";numrow
        tnp=tnp-numrow
        goto 1500
2561    input "Enter the number of columns you want to drop";numcol
        id=id-numcol
        goto 1500
rem
rem
rem
2570   cls:locate 10
       print "1: Machine"
       print "2: Part"
       print "3: Element"
       input "Your choice";choice
       on choice goto 2571, 2572, 2573
```

FIGURE 51. (Continued)

```
rem
rem
rem
2571    input "Enter machine number you want to drop";delmnum
        for i = 1 to tnp
             pmmat(i,delmnum)=0
        next
        input "Do you have more machine to drop";ans$
        if ans$ = "y" then 2571
        goto 1500

rem
rem
rem
2572    input "Enter part number you want to drop";delpnum
        for j = 1 to id
             pmmat(delpnum,j)=0
        next
        input "Do you have more part to drop";ans$
        if ans$ = "y" then 2572
        goto 1500
rem
rem
rem
2573    input "Enter the row and column # of element";r,c
        pmmat(r,c)=2
        input "Do you have further exceptional elements (y/n)";ans$
        if ans$= "y" then goto 2573
        goto 1500
2580    input "Enter the machine # you want to divide";mnum
        input "How many blocks you want to create";blocks
        input "Enter the last machine number";lastmnum
        print blocks;" blocks you requested"
        for ij = 1 to blocks-1
           print "Enter the ";ij;"the block";
           input "limit";blk(ij)
        next
        numofiter=blocks-1
        addition = 1
        if numofiter = 1 then lowlimit=blk(1):upperlimit=tnp:goto 2584
        lowlimit=blk(1)
        upperlimit=blk(2)-1
        gosub 2587
        machid$(id+1)=chr$(id+2+64):mach(id+1)=lastmnum+1
        addition=addition+1
        lowlimit=blk(2)
        upperlimit=tnp
        gosub 2587
```

FIGURE 51. (Continued)

```
       machid$(id+2)=chr$(id+3+64):mach(id+2)=lastmnum+2
       id=id+blocks-1
       gosub 2594
       goto 1500
2584   gosub 2587
       machid$(id+1)=chr$(id+2+64):mach(id+1)=lastmnum+1
       id=id+blocks-1
       gosub 2594
       goto 1500
2585 '
2586 ' Revise the part-machine matrix
2587 '
       for ijk = lowlimit to upperlimit
            if pmmat(ijk,mnum)  1 then 2588
            pmmat(ijk,mnum) = 0
            pmmat(ijk,id+addition) = 1
2588   next
       return
2589 '
2590 '  Saving the final part-machine matrix
2591 '
        goto  370
2594 '
2595 '  Printing the revised information
2596 '
       lprint "After machine";mach(mnum);"is divided";blocks;"machines"
       lprint "Machine 1 =  ";mach(mnum)
       for i = 1 to blocks-1
            lprint "Machine ";i+1;" = ";mach(id-i+1)
       next
       return
2600 '
2610 '  Printing the part-machine matrix
2611 '
2620    lprint "Iteration  ";iteration:lprint:lprint
2630    lprint using "                    ";"  part/  mach ";
2640    for j = 1 to id-1:lprint USING "&"; machid$(j);:next
2650    lprint using "&"; machid$(id):lprint
2660    for I = 1 to tnp
2670       lprint using "###   "; rlist(I,1);
2671       lprint using "                    "; pnum$(i);
2680       for j = 1 to id-1
2690          lprint using "#"; pmmat(I,j);
2700       next
2710       lprint using "#"; pmmat(I,id)
2720    next
2730    lprint:lprint:lprint
2740    return
```

FIGURE 51. (Continued)

```
2741 '
2750 '*--------------------------------------------------------------------*
2760 '¦        Cluster Analysis with Similarity Coefficient                ¦
2770 '*--------------------------------------------------------------------*
2790 dim B(tnp),C(tnp),A(tnp)
2791 '
2800 '*--------------------------------------------------------------------*
2810 '¦           Generate Part-Machine Matrix                             ¦
2820 '*--------------------------------------------------------------------*
2821 '
2830    cls:locate 10,25:print "Generating Part-Machine Matrix"
2840    locate 11,31:print "Please  wait ......";
2850    col=1:row=1
2860    if row > tnp then goto 2930
2870    col=1
2880    for I=1 to id
2890       if route(row,col) = mach(I) then pmmat(row,I)=1
2900    next
2910    if col atp(row) then col=col+1:goto 2880
2920    row=row+1:goto 2860
2921 '
2930 '*--------------------------------------------------------------------*
2940 '¦        Calculation of Similarity Coefficient Matrix                ¦
2950 '*--------------------------------------------------------------------*
2951 '
2960    cls:locate 10,18
2961    print "Cluster Analysis with Similarity Coefficient"
2970    locate 11,20
2971    print "Calculating similarity coefficient matrix"
2980    locate 12,31
2981    print "Please  wait ......"
2982 '*
3131 '
3140 '*--------------------------------------------------------------------*
3150 '¦           Prim Tree Data Structure                                 ¦
3160 '*--------------------------------------------------------------------*
3161 '
3170    DLARGE=0:a=0:b=0:c=0
3180    if tnp  1 then ifAULT=1:end
3190    IFAULT=0
3200    for I=2 to tnp
3210       A(I)=0:B(I)=0:C(I)=DLARGE
3220    next
3230    j=1:
3240    for I=2 to tnp
3250       MIN=DLARGE
3260       for K=2 to tnp
```

FIGURE 51. (Continued)

```
3270         if A(K) = 0 then 3280 else 3320
3280         if j >= K then row1=j:row2=k  else row1=k:row2=j
3281         for col = 1 to id
3282             if pmmat(row1,col)=1 and pmmat(row2,col)=1 then a=a+1
3283             if pmmat(row1,col)=1 and pmmat(row2,col)=0 then b=b+1
3284             if pmmat(row1,col)=0 and pmmat(row2,col)=1 then c=c+1
3285         next
3290         DIST=a/(a+b+c)
3291         a=0:b=0:c=0
3300         if DIST >= C(K) then  C(K)=DIST:B(K)=j
3310         if MIN  C(K)  then  MIN=C(K):NEX=K
3320      next
3330      j=NEX:A(j)=1:print "next = ";nex
3340   next
3360   lprint "                          Results of CASA"
3370   lprint:lprint:lprint
3371   lprint "                       Prim's Tree Structure"
3380   lprint:lprint
3390   for i=2 to tnp:lprint pnums(i),i,b(i),c(i):next:lprint:lprint
3391 '
3400 '*---------------------------------------------------------------------*
3410 '|               printing Minimal Spanning Tree                        |
3420 '*---------------------------------------------------------------------*
3421 '
3430 dim ROUT(tnp),HIST(tnp)
3440   for I= 1 to tnp: HIST(I)=0:next
3450   for I = 2 to tnp
3460      TEMM=B(I)
3470      HIST(TEMM)=HIST(TEMM)+1
3480      print TEMM,HIST(TEMM)
3490   next
3500   ROUT(1)=1: j=1: K=1
3510   for I = 2 to tnp
3520      if HIST(K) = 0 then 3530 else 3550
3530      j=j-1:K=ROUT(j)
3540      goto 3520
3550      HIST(K)=HIST(K)-1
3560      for M=2 to tnp
3570         if K=B(M) then 3580 else 3610
3580         lprint K,M,C(M):j=j+1
3590         K=M:ROUT(j)=K
3600         B(M)=-B(M)
3610      next
3620   next
3622 '
3630 '*---------------------------------------------------------------------*
3640 '|          Single Linkage Cluster Analysis                            |
```

FIGURE 51. (Continued)

```
3650 '|                                                                  |
3660 '|             s: previous point indicator                          |
3670 '|             t: next print indicator                              |
3680 '|           u,v: switches                                          |
3690 '|             k: total number of clusters                          |
3700 '|             h: list which contains end-of-makers                 |
3710 '*------------------------------------------------------------------*
3711 '
3720 dim G(tnp),H(tnp),X(20*tnp),W1(tnp),W2(tnp)
3721    lprint:lprint
3730    lprint "            Result of Single Linkage Cluster Analysis"
3740    lprint:lprint
3741 '
3750 '*------------------------------------------------------------------*
3760 '|             this loop will find the Dmax (Maximum distance)      |
3770 '*------------------------------------------------------------------*
3771 '
3780    for I=2 to tnp:zz=-B(I):B(I)=zz:print B(I):next
3790    DMAX=C(2)
3800    for I=3 to tnp
3810       if DMAX C(I) then DMAX=C(I)
3820    next
3821 '
3830 '*------------------------------------------------------------------*
3840 '|              Initialization                                      |
3850 '*------------------------------------------------------------------*
3851 '
3860    for I= 1 to tnp
3870       G(I)=I :' List G consists initially of all points as single groups
3880       H(I)=1 :' Thus, initially, list H should have all 1's
3890       X(I)=3 :' Initially, t=3 for all points
3900    next
3910    P=0
3920    DELTA=0.05
3930    LEVEL = DELTA*(1+INT(DMAX/DELTA))
3940    WHILE K  1
3950    P=P+1
3960    for I = 2 to tnp
3961 '
3970 '*------------------------------------------------------------------*
3980 '|      for point whose length is less than level                   |
3990 '*------------------------------------------------------------------*
3991 '
4000       if C(I) > LEVEL then 4010 else 4280
4010         j=B(I):C(I)=C(I)-C(I)-0.001  ' Links once used are decreased
4020                                      ' to zero to prevent re-use
4030         K=I
```

FIGURE 51. (Continued)

```
4040         for M=1 to tnp
4050            if G(M)=j then Q=M
4060            if G(M)=K then R=M
4070         next
4080         if Q > R then M=R:R=Q:Q=M
4090         S=Q
4100         if S > tnp goto 4280
4110         if H(S)  0 then 4120 else S=S+1:goto 4100
4120         T=R-1
4130         if T = 0 goto 4280
4140         if H(T)  0 then 4150 else T=T-1:goto 4130
4150         T=T+1:H(S)=0
4160         R=T
4170         if R > tnp goto 4280
4180         W1(R-T)=G(R):W2(R-T)=H(R)
4190         if H(R)  0  then 4200 else R=R+1:goto 4170
4200                        W=S+1:U=R-T+1
4210                        for M=T-1 to W step -1
4220                           G(M+U)=G(M):H(M+U)=H(M)
4230                        next
4240                        U=R-T
4250                        for M=0 to U
4260                           G(M+W)=W1(M):H(M+W)=W2(M)
4270                        next
4280   next
4281  if level > 0.8 or level 0.5 then 4301
4287 '*--------------------------------------------------------------------*
4288 '¦                prints group                                        ¦
4290 '*--------------------------------------------------------------------*
4291    lprint "level =";level:lprint
4292    for i=1 to tnp
4293    lprint g(i);
4294    if h(i)=1 then lprint "*"
4295    next:lprint:lprint
4300    print "printing group"
4301 '*
4310    W=N*tnp:U=0:V=0:K=0
4320    for I=2 to tnp:K=K+H(I):next
4330    if P 20 then 4340 else 4480
4340    for I= 1 to tnp
4350       j=G(I):S=X(j+W+N)
4360       if U=0 then 4370 else 4390
4370          if H(I) = 1 then T=3 else if S=3 then T=1:U=1:V=1 else T=0:U=1
4380          goto 4460
4390          if H(I) = 1 then 4400 else 4420
4400          if V = 0 then T=3:U=0 else T=2:U=0:V=0
4410          goto 4460
4420          if S=2 OR S=3 then 4430 else 4450
4430          if V = 0 then T=1:U=1:V=1 else T=5:U=1
```

FIGURE 51. (Continued)

```
4440          goto 4460
4450          if V = 0 then T=0:U=1 else T=4
4460          X(j+W)=T
4470    next
4480    LEVEL=LEVEL-DELTA
4490    print:print:print
4500    print "level=";LEVEL:print
4510    for z = 1 to tnp:print B(z),C(z),G(z),H(z): next
4530    WEND
4540 ' gosub topprint
4550   for I=1 to tnp
4560      j=G(I):' gosub Sideprint
4570      print "printING SIDE"
4580      if P > 19 then P=19
4590      for M=0 to P:' gosub printx
4600         print "printING X"
4610      next
4620   next
4630   goto 370
4640 '
4650 '
4660 '
4670 '
4680   cls:locate 3
4690   print "The part name is ";pname$(I)
4700   print "The part number is ";pnum$(I)
4710   print "The total numbers of the process sequences are ";atp(I)
4720   for j = 1 to atp(I)
4730   print j,route(I,j)
4740   next
4750   return
4760 '
4770 '
4780 '
4790      gosub 4680
4800      input "Are these correct (y/n)";ans$
4810      if ans$ = "y" then  5070
4820      gosub 4680
4830      print:print:print "Which information you want to change?"
4840      print "1. Part name"
4850      print "2. Part number"
4860      print "3. Total number of process sequence"
4870      print "4. Process sequence"
4880      print "5. None"
4890      input "Enter the corresponding number";ans
4900      if ans = 1 then input "Enter the part name again";pname$(I):goto 4820
4910      if ans = 2 then input "Enter the part number again";pnum$(I):goto 4820
```

FIGURE 51. (Continued)

```
4920      if ans = 3 then 4950
4930      if ans = 4 then 5010
4940      if ans = 5 then 4790
4950      input "Enter total number of process sequence ";atp(I)
4960      for j=1 to atp(I)
4970         print "Enter the ";j;"th process sequence"
4980         input route(I,j)
4990      next
5000      goto 4820
5010      input "Enter the number of process sequence ";SEQ
5020      input "Enter the correct process number ";route(I,SEQ)
5030      input "Is there any other correction on sequence ";ans$
5040      if ans$ = "y" then 5010
5050      goto 4820
5060      print "Enter the number again":goto 4820
5070      return
```

FIGURE 51. (Continued)

APPENDIX B: GEOMETRICAL CODES OF PARTS

TABLE 30. Codes of parts with the Opitz system

Part name	Part number	Codes	Accuracy
BODYVALVE	7J1025	4 2 4 5 3 1 0 0	.04
HOUSING	5J0766	8 9 2 0 2 2 0 0	.04
COVER	6J0433	6 9 2 2 0 3 0 0	.06
COVER	6J0434	6 9 7 2 2 4 0 0	.06
COVER	3J0601	4 2 3 0 1 1 0 0	.047
BLOCK	4J1091	4 1 4 5 2 1 0 0	.12
ADAPTER	5J1340	4 7 3 5 1 1 0 0	.08
BLOCK	3J2973	8 3 1 5 0 2 0 0	.002
CAP-FILTER	6F4350	3 2 4 0 0 2 0 0	.41
COVER	2J8069	6 0 1 2 2 2 0 0	.12
RETAINER	5J8773	6 0 2 2 1 2 0 0	.04
COVER	8J0130	6 0 2 5 2 3 0 0	.08
COVER	8J0444	3 2 4 2 1 2 0 0	.12
COVER	1U0488	8 3 2 3 1 3 0 0	.04
COVER	4T1014	3 2 4 3 1 1 0 0	.02
COVER	4J1137	8 3 5 5 1 3 0 0	.008
BODY-VALVE	9J1234	8 9 6 2 1 2 0 0	.02
HOUSING	5J1553	4 2 4 1 1 1 0 0	.04
BLOCK	3J1970	8 2 5 3 1 2 0 0	.12
COVER	8J2045	8 3 5 5 1 2 0 0	.06
BODY-PILOT	5J2438	4 2 4 2 1 2 0 0	.08
BODY-PILOT	4J2696	3 2 3 3 1 1 0 0	.08
ACTUATOR	1U2764	7 1 6 0 2 2 0 0	.04
COVER	3G2840	8 3 4 3 0 2 0 0	.002
COVER	3G2841	8 3 4 3 0 2 0 0	.02
COVER	3G2842	3 1 4 3 1 2 0 0	.002
BODY-VALVE	3J2975	4 3 4 0 2 1 0 0	.005
ADAPTER	4J3291	4 1 3 3 1 1 0 0	.06
HOUSING	9J3441	3 1 4 2 1 1 0 0	.06
RETAINER	7J3897	3 3 4 3 1 1 0 0	.04
HEAD	1U4010	3 5 4 2 1 1 0 0	.002
COVER	9J4077	3 5 4 2 1 1 0 0	.06
RETAINER	9J4097	3 1 4 2 1 1 0 0	.12
HOUSING-VALVE	4J4571	4 3 4 2 1 1 0 0	.04
HOUSING	4T4632	4 1 4 2 1 1 0 0	.02
COVER	4T4636	3 3 4 2 1 1 0 0	.02
BODY	9J4847	3 1 4 2 1 1 0 0	.12
ADAPTER	9J4941	6 1 2 5 1 2 0 0	.12
HOUSING-VALVE	2J5143	8 3 2 3 1 2 0 0	.05
MANIFOLD	6P5391	3 1 0 0 2 1 0 0	.12
BODY-VALVE	9M5550	3 1 4 0 1 1 0 0	.04
COVER	8J5618	6 0 7 2 1 2 0 0	.06
BODY	8J5875	4 2 4 2 2 3 1 0	.06
BODY	7J5928	4 3 4 5 4 2 0 0	.06

TABLE 30 (Continued)

Part name	Part number	Codes	Accuracy
HOUSING-SPRING	4J6485	4 5 3 2 1 3 0 0	.04
BODY-PILOT	7J7674	4 3 4 2 2 1 0 0	.06
HOUSING	9J7749	4 1 3 5 2 1 0 0	.06
HOUSING-SPRING	3J7807	3 5 4 4 2 2 0 0	.12
COVER	6J7908	3 5 4 2 4 1 0 0	.04
COVER	7J8056	6 5 2 5 1 3 0 0	.06
BODY-VALVE	7J8308	3 5 4 2 2 1 0 0	.06
COVER	8J8573	3 3 4 2 2 1 0 0	.12
HOUSING-EJECTOR	8J8660	2 0 0 2 2 1 0 0	.12
BODY	8J8661	4 2 4 0 1 1 0 0	.12
HEAD	5J8774	3 1 4 5 1 1 0 0	.04
HEAD	5J8793	8 3 1 3 1 2 0 0	.04
BODY	8J8829	8 9 6 2 2 2 0 0	.06
BODY	4T9151	4 1 4 5 2 2 0 0	.01
ADAPTER	4T9156	3 1 4 5 1 2 0 0	.002
BODY	8J9257	4 3 4 5 1 1 0 0	.08
RETAINER-SPRING	6J9992	3 8 4 3 1 2 0 0	.04
BODY-VALVE	5J9110	3 3 4 2 0 2 0 0	.04
BODY-BRAKE VALVE	3S7445	2 6 0 1 0 0 2 0	.01
HOUSING-VALVE	8J2308	8 3 1 5 1 3 0 0	.06
BODY	8J2302	6 9 6 3 2 3 0 0	.12
BODY	8J0084	8 3 2 3 3 3 7 0	.128
BODY-VALVE	8J0510	8 5 6 6 4 3 0 0	.06
BODY-VALVE	3G0650	4 5 4 3 4 1 0 0	.12
BODY	9J0752	4 1 4 0 2 0 0 0	.02
BODY-VALVE	5J0899	8 3 5 3 1 3 1 0	.04
BODY-VALVE	4T0958	4 5 4 3 2 1 0 0	.02
COVER	9T1495	6 5 2 3 1 4 0 0	.005
COVER	8J1701	8 9 2 5 1 3 0 0	.06
BODY	4T1889	8 0 6 5 1 3 0 0	.005
BODY-VALVE	8J1917	8 1 6 3 2 4 0 0	.06
HOUSING	1U2083	8 1 6 5 1 2 0 0	.005
BODY	1U2177	8 3 2 5 1 2 0 0	.005
BODY-VALVE	7J2266	8 3 6 5 1 2 1 0	.05
BODY	8J2305	8 1 6 3 1 3 0 0	.12
COVER	3T2321	4 5 4 1 1 1 0 0	.005
TUBE	9T2382	2 0 0 0 1 2 2 0	.01
MANIFOLD	9T2887	6 0 6 3 1 4 0 0	.005
BODY	9J3382	8 3 6 3 2 3 0 0	.24
HOUSING-ELEV	9J3453	4 1 3 2 1 2 0 0	.24
HOUSING-VALVE	8J3554	4 5 4 3 1 0 0 0	.06
COVER	8J3665	8 3 4 5 3 4 0 0	.24
DIAP-ADAPTER	0W019819012	4 5 3 3 1 1 0 0	.016
PLUG-M-FORM	10A7182X012	2 1 0 0 1 0 2 0	.0156
PLUG-VALVE	11A5214X022	1 4 0 2 1 1 0 0	.0156
PLUG-VALVE	11A5216X012	1 4 0 2 1 1 0 0	.0156

TABLE 30 (Continued)

Part name	Part number	Codes	Accuracy
PLUG-VALVE	11A5324X012	1 7 1 1 1 2 0 0	.0156
PLUG-VALVE	11A5326X012	1 7 1 1 1 2 0 0	.0156
BUSHING	15A1288X012	1 1 0 0 1 0 8 0	.0156
PLUG-LINER	15A6470X012	1 4 2 2 0 1 3 0	.0156
PLUG-EQ-%	15A6480X012	1 5 2 2 0 1 2 0	.0156
PLUG-QUICK-OPENING	15A6490X012	1 1 2 2 0 1 2 0	.0156
MICRO-FORM	15A6503X012	2 1 2 2 0 1 2 0	.0156
SEAT-RING	1A510735072	0 2 1 3 0 1 0 0	.0313
BUSHING	1B169135012	1 0 0 0 0 1 2 0	.0156
SPRING-CASE	1B883119012	1 1 0 2 0 3 0 0	.0156
VALVE-BODY	1C477219012	3 8 4 0 6 3 0 0	.0625
CONT-VVE-HOUSING	1C794935032	0 4 1 0 6 0 2 0	.0313
PROP-ADJ-BLOCK	1C899514022	3 0 4 2 8 1 2 0	.0313
BOTTOM-RING	1D228235072	0 2 1 3 8 2 0 0	.0313
REGULATOR-BODY	1E3943000A2	3 2 4 2 7 3 0 0	.0313
SPRING-CASE	1E501208012	4 2 6 0 4 2 0 0	.0625
ORING-HOLDER	1E824609092	1 4 2 0 4 1 2 0	.0156
FLANGE-PACKING	1E944223072	8 3 5 5 0 2 0 0	.0156
POPPET	1H830814012	1 1 2 3 0 1 2 0	.0156
REGULATOR-BODY	1J1277000B2	1 1 2 3 0 2 0 0	.0625
STEM-PLUG	1K586935162	2 0 0 0 0 0 2 0	.0625
RETAINER-SPRING	1L432314012	1 1 1 0 0 0 7 0	.0313
CAGE	1R124835072	3 2 4 3 4 1 0 0	.0313
FLANGE-BOTTOM	1R125624092	0 0 0 1 4 2 2 0	.0313
SEAT-RING	1R126335072	0 1 1 0 4 1 2 0	.0625
STEM-PLUG	1R250935162	2 0 0 0 4 0 2 0	.0625
SEAT-RING	1U222646172	0 4 1 0 4 2 2 0	.0156
CAGE-LOWER	20A3382X022	3 2 4 2 0 2 0 0	.0156
DIAPHRAGM-RETAINER	25A1289X012	1 6 1 0 0 0 2 0	.0156
CAGE	25A6687X012	1 1 1 0 0 2 0 0	.0156
SEAL-CARRIER	28A2514X012	0 1 1 1 0 3 0 0	.0156
FOLLOWER-SHAFT	28A2519X012	2 3 2 1 0 1 2 0	.0156
REGULATOR-BODY	2E4085000A2	1 1 1 1 0 3 0 0	.0156
SPRING-CASE	2E542919042	3 2 5 4 1 3 0 0	.0156
PLUG-MICRO-FORM	2F1428000A2	2 5 0 0 1 1 2 0	.02
BONNET	2F143224092	1 5 1 1 1 2 2 0	.0156
SPRING-CASE	2J496219012	1 1 2 2 1 2 0 0	.0156
BONNET	2K562523022	1 4 2 1 1 2 0 0	.0156
VALVE-BODY	2L342619012	1 1 2 0 0 3 0 0	.001
VALVE-BODY	2L339519012	1 0 2 0 0 2 0 0	.001
VALVE-BODY	2L373522012	1 1 2 0 0 3 0 0	.001
SPRING-CASE	2L416322012	1 1 2 1 0 2 0 0	.001
PLUG-MICRO-FORM	2N5532000A2	2 5 0 0 0 0 2 0	.001
BONNET	2R124724092	3 2 4 3 4 2 2 0	.001
PLUG-EQ-%	2R2454000A2	2 5 0 0 4 1 2 0	.001
BONNET	2R2617X0012	3 2 4 3 0 2 2 0	.0313

TABLE 30 (Continued)

Part name	Part number	Codes	Accuracy
BONNET	2R331019022	3 2 4 3 4 3 0 0	.0313
QUICK-OPEN-CAGE	2U223433272	3 2 4 3 0 2 0 0	.0156
EQUAL-%-CAGE	2U223733272	3 2 4 3 2 2 0 0	.0156
QUICK-OPEN-CAGE	2U740448932	3 2 4 3 0 2 7 0	.0156
EQUAL-%-CAGE	2U741048932	3 2 4 3 0 2 7 0	.0156
UPPER-CAGE	36A2065X012	3 2 4 3 0 2 7 0	.0156
SEAL-PROTECTOR-RING	38A2508X012	0 6 1 2 0 4 0 0	.0156
BODY-OUTLET	38A2511X012	0 6 3 2 0 4 0 0	.0156
VALVE-BODY	3B186522012	4 8 4 0 7 2 3 0	.0156
SPRING-CASE	3C780819042	1 1 1 1 0 3 0 0	.0156
SPRING-CASE	3N698122012	1 1 2 2 0 4 3 0	.0156
SPRING-CASE	3N698322012	1 1 2 2 0 3 3 0	.0156
VALVE-BODY-RELIEF	3P786933092	3 8 4 0 0 4 0 0	.0156
VALVE-BODY	3R124624092	3 8 4 5 1 2 3 0	.0156
SPRING-CASE	3V708322012	3 5 4 3 1 4 3 0	.0156
SPRING-CASE	4E397919012	1 1 2 2 1 5 0 0	.0156
INSERT	T1095224102	1 0 1 0 1 1 2 0	.01
PLUG	T1173614012	0 1 2 0 1 1 7 0	.015
CONTACT	6870004001	2 4 0 0 0 0 7 0	.005
SLEEVE	6870005001	2 0 0 0 0 0 9 0	.003
ROD	6870006001	2 4 0 0 0 0 7 0	.0004
CONNECTOR	6870007003	1 0 1 0 0 0 7 0	.001
PLATE	6870007001	6 3 1 0 1 3 7 0	.008
SKIN	6870008002	6 1 0 0 0 4 7 0	.008
TUBE	6870008004	2 0 1 2 0 0 7 0	.002
CONTACT	6870008005	8 1 1 0 0 0 7 0	.002
CAP	6870008006	7 2 1 1 1 3 7 0	.008
P/P-B.KN	6870020002	6 2 4 3 6 4 7 0	.002
COVER-FRONT	6870021002	6 1 5 5 6 4 7 0	.008
COVER-REAR	6870036002	6 1 1 5 5 2 7 0	.008
COVER-REAR	6870027002	6 1 4 5 5 4 7 0	.008
SHIELD	6870043001	7 0 0 5 0 6 8 0	.008
SHIELD	6870060001	6 0 5 0 0 3 7 0	.008
SHIELD	6870060001	6 3 0 5 5 1 9 0	.008
SHIELD	6870093001	6 3 0 5 5 1 9 0	.008
WASHER	6870110001	0 0 0 1 5 0 8 0	.002
SHIELD	6870112001	6 1 0 0 5 1 8 0	.008
SHIELD	6870127001	6 1 0 0 5 3 8 0	.008
COVER	6870148001	8 9 0 5 1 4 7 0	.008
COVER	6870148002	6 1 0 5 0 4 7 0	.008
PARTITIO	6870167002	7 1 0 5 0 1 7 0	.002
PARTITIO	6870167003	7 1 0 5 5 1 7 0	.002
PARTITIO	6870167004	7 1 0 0 0 1 7 0	.005
PARTITIO	6870167005	7 1 0 0 0 1 7 0	.005
PLATE	6870173002	0 0 0 2 0 0 7 0	.008
PLATE	6870174001	0 0 0 2 0 3 7 0	.008

TABLE 30 (Continued)

Part name	Part number	Codes	Accuracy
P/P-B.K	6870181001	0 0 0 2 0 3 7 0	.008
INSULATO	6870327001	6 0 0 0 5 0 9 0	.02
INSULATO	6870327001	0 0 0 0 5 1 9 0	.02
CAP	6870341001	0 0 0 0 5 0 8 0	.005
BAR	6870364001	7 1 0 0 1 3 7 0	.008
BUS	6870444001	6 0 0 0 0 0 8 0	.015
SPACER	6870444001	0 0 0 0 0 0 8 0	.002
HOUSING	6874008002	6 0 0 0 1 4 7 0	.008
HEATSINK	6874098001	6 3 0 5 0 0 8 0	.001
CONNECTO	6874138001	4 2 4 0 0 0 8 0	.003
SUB-SHIELD	6874139002	6 2 0 5 5 3 8 0	.008
FRAME	6874140002	6 2 0 5 6 4 7 0	.008
P/P-PER	6874216002	6 2 0 0 1 1 7 0	.008
SPRING	7574570001	7 0 4 0 0 0 8 0	.005
ANT-SECT	7575872001	2 0 0 0 0 2 7 0	.008
TUBE	7575872002	2 0 0 2 0 2 7 0	.008
SLEEVE	7575872003	0 1 0 2 0 2 7 0	.008
END	7575872004	0 0 0 0 0 2 7 0	.008
BASE	7575875001	3 1 4 2 0 2 7 0	.008
CROSS	5755955002	8 3 1 0 1 0 0 0	.008
SKIRT	7576591001	0 0 1 0 1 1 7 0	.005
COVER	7575896001	6 0 0 0 1 3 7 0	.005
LOAD	7578424001	8 8 0 4 1 4 0 0	.008
OVERLAY	7578431001	6 0 0 3 1 6 8 0	.008
SPRING	7578612001	6 1 0 0 6 1 8 0	.008
ARM-LOCK	7578614001	6 4 1 0 0 1 9 0	.008
FRAME	7578677001	6 0 0 5 5 3 7 0	.008
CHASSIS	7578887001	6 0 0 0 6 2 8 0	.008
CHASSIS	7578887002	7 0 0 5 0 2 8 0	.008
BAR-No.1	7578887003	8 0 0 0 0 0 8 0	.008
BAR-No.2	7578887994	8 0 0 0 0 0 8 0	.008
SHIELD1	7578887005	7 1 0 0 0 1 8 0	.008
SHIELD2	7578887006	7 1 0 0 0 1 8 0	.008
SHIELD3	7578887007	7 1 0 0 0 1 8 0	.008
BAR-No.3	7578887009	8 0 0 0 0 0 8 0	.008
PLATE	7578887010	6 0 0 0 0 0 8 0	.008
CHASSIS	7578889001	6 0 0 0 6 2 8 0	.008
CHASSIS	7578889002	6 0 0 0 6 2 8 0	.008
BLOCK1	7578889004	8 0 0 0 0 0 8 0	.008
DIVIDER	7578889006	7 0 0 0 0 1 8 0	.008
HOLDER	7610504001	4 2 2 3 2 0 8 0	.008
HOLDER	7610504002	4 2 2 3 2 0 8 0	.008
WASHER	7610014003	2 0 1 0 2 0 8 0	.008
PLATE	7610167002	6 4 0 5 6 1 7 0	.008
COVER	7610463001	7 2 0 7 6 7 9 0	.008
GROMMET	7610493001	2 0 1 0 6 0 9 0	.008

TABLE 30 (Continued)

Part name	Part number	Codes	Accuracy
BASE	7610464001	6 4 0 7 6 6 7 0	.005
INSULATO	6870003001	2 3 1 0 6 0 9 0	.002
TUBE	7575863002	1 0 0 0 0 2 7 0	.004
END	7575863004	0 0 1 2 0 2 7 0	.003
SPACER	7575863005	2 0 1 0 0 0 7 0	.008
CONDUIT	7575863006	2 0 0 0 0 0 7 0	.008

APPENDIX C: GEOMETRICAL AND DIMENSIONAL CHARACTERISTICS OF PART FAMILY

TABLE 31. Geometrical and dimensional characteristics of part family 1 of PFA/CASC (16 members)

Part	Geometrical	Dimensions					
number	Code	L	D	A	B	C	Weight
0W019819012	45331	5.462	1.372				1.0
1J1277000B2	11230	2.4375	2.25				5.0
1R124835072	32434	1.4375	1.184				5.0
1R125624092	00014	0.5	3.25				3.0
2E542919042	32541	3.9688	4.125				5.0
2F143224092	15111	7.4375	3.125				10.0
2J496219012	11221	3.375	2.215				5.0
2L342619012	11200	3.3125	4.885				5.0
2L339519012	10200	2.8125	3.26				5.0
2L373522012	11200	3.3125	4.885				5.0
2L416322012	11210	3.375	2.8125				4.0
2R124724092	32434	4.375	2.75				6.0
3C780819042	11110	7.5	4.625				7.0
3N698122012	11220	7.0	7.125				7.0
3N698322012	11220	7.5	4.625				7.0
4E397919012	11221	5.5	10.1875				7.0

TABLE 32. Geometrical and dimensional characteristics of part family 2 of PFA/CASC (10 members)

Part	Geometrical	Dimensions					
number	Code	L	D	A	B	C	Weight
6870008005	81100			0.78	0.5	0.428	2.0
6870008006	72111			5.0	0.75	0.124	3.0
6870092001	63055			2.0	0.675	0.031	0.0179
6870093001	63055			2.0	0.675	0.03	1.0
6870239001	60005			6.0	0.38	0.125	0.0057
7578887003	80000			0.422	0.375	0.25	1.0
7578887004	80000			0.4	0.4	0.2	0.0166
7578887009	80000			0.437	0.422	0.2	1.0
7578887010	60000			0.375	0.375	0.064	1.0
7578889004	80000			0.421	0.203	0.203	1.0

TABLE 33. Geometrical and dimensional characteristics of part family 3 of PFA/CASC (10 members)

Part	Geometrical	Dimensions					
number	Code	L	D	A	B	C	Weight
6870112001	61005			2	0.675	0.005	2.0
6874139001	62055			4.65	3.29	0.006	1.0426
7574570001	70400			0.796	0.155	0.005	1.0
7576591001	00101	0.032	1.0				1.0
7576896001	60001			4.406	3.128	0.032	0.054
7578887005	71000			1.484	0.4219	0.03	1.0
7578887006	71000			1.484	0.4219	0.03	1.0
7578887007	71000			1.89	0.4219	0.03	1.5
7610014003	20102	0.312	0.031				1.0
7610167002	64056			0.891	0.415	0.04	1.0

TABLE 34. Geometrical and dimensional characteristics of part family 4 of PFA/CASC (46 members)

Part	Geometrical			Dimensions			
number	Code	L	D	A	B	C	Weight
7J1025	42453	4.125	0.812				3.5
5J0766	89202			3.06	2.062	1.935	3.0
6J0433	69220			5.63	2.38	1.344	9.0
6J0434	69722			8.01	4.76	1.94	12.0
4J1091	41452	2.46	1.125				3.0
2J8069	60122			2.884	1.62	0.562	1.0
5J8773	60221			2.51	2.36	0.56	1.0
8J0130	60252			5.13	4.0	0.94	5.0
8J0444	32421	2.85	2.372				3.0
4T1014	32431	1.062	1.56				2.0
9J1234	89621			3.25	2.742	2.375	3.5
5J1553	42411	3.73	1.375				5.0
4J2696	32331	1.81	1.12				3.0
3G2842	31431	2.99	2.28				5.0
4J3291	41331	2.812	1.0				7.0
9J3441	31421	2.5	1.62				3.0
7J3897	33431	3.382	1.94				5.0
1U4010	35421	2.28	1.38				5.0
9J4077	35421	2.21	1.406				2.5
9J4079	31421	2.0	1.375				7.0
4J4571	43421	4.188	1.0				9.0
9J4847	31421	1.87	1.0				2.0
9J4941	61251			3.8	3.5	0.932	3.0
9M5550	31401	1.75	1.0				3.0
8J5875	42422	5.562	1.375				7.5
7J5928	43454	2.5	1.12				1.5
4J6485	45321	4.69	1.375				4.0
3J7807	35442	4.12	2.22				4.0
7J8308	35422	1.75	1.0				3.0
8J8660	20022	4.687	1.25				4.0
8J8661	42401	3.25	1.3				2.0
5J8774	31451	1.312	1.375				2.0
5J8793	83131			2.562	2.24	1.0	3.0
4T9151	41452	3.622	1.064				11.51
4T9165	31451	1.693	2.48				5.0
8J9257	43451	2.5	0.875				3.0
6J9992	38431	3.58	2.0				3.0
5J9110	33420	2.156	1.625				5.0
3S7445	26010	6.25	0.48				3.25
8J0084	83233			4.56	2.03	1.688	4.0
3G0650	45434	4.31	1.38				16.5
4T0958	45432	5.512	1.969				15.0

TABLE 34. (Continued)

Part number	Geometrical Code	L	D	Dimensions A	B	C	Weight
8J1701	89251			5.358	4.813	2.86	11
8J1917	81632			8.062	4.75	2.5	20
3T2321	45411	5.91	1.875				6.0
9J3453	41321	5.062	2.16				5.0

TABLE 35. Geometrical and dimensional characteristics of part family 5 of PFA/CASC (20 members)

Part number	Geometrical Code	L	D	Dimensions A	B	C	Weight
3J0601	42301	2.63	1.125				2.0
5J1340	47351	2.25	1				5.5
1U0488	83231			5.49	4	2.12	4.79
3G2840	83430			3.25	2.63	1.1	3.0
3G2841	83430			3.25	2.63	1.57	4.0
4T4632	41421	4.37	1.57				3.0
6P5391	31002	2.75	1.562				2.0
7J8056	65251			5.13	4.0	0.94	5.0
8J8573	33422	1.38	1.25				2.0
8J2308	83151			4.375	3.75	2.12	6.0
9J0752	41402	6.63	0.7505				13.5
5J0899	83531			4.5	2.125	1.38	5.0
9T1495	65231			6.85	4.646	1.339	11.0
1U2083	81651			3.74	2.244	1.378	7.0
7J2266	83651			3.5	2.88	1.38	5.5
9J2382	20001	23.72	3.69				8.5
9T2887	60631			7.87	3.436	1.375	4.68
9J3382	83632			6.495	3.75	2.5	14.0
8J3554	45431	2.58	0.75				4.0
8J3665	83453			6.875	3.25	3.09	14.0

TABLE 36. Geometrical and dimensional characteristics of part family 1 of PFA/ROCA (27 members)

Part number	Geometrical Code	Dimensions					Weight
		L	D	A	B	C	
4J3291	41331	2.812	1.0				7.0
0W019819012	45331	5.462	1.372				1.0
10A7182X012	21001	9.1	0.501				1.0
11A5214X022	14021	2.125	1.406				1.0
11A5216X012	14021	2.125	1.406				1.0
1E3943000A2	32427	2.6875	4.25				5.0
1J1277000B2	11230	2.4375	2.25				5.0
1K586935162	20000	12.25	0.4375				3.0
1R124835072	32434	1.4375	1.184				5.0
1R250935162	20004	7.6875	0.3125				3.0
2E542919042	32541	3.9688	4.125				5.0
2F1428000A2	25001	14.9	1.119				5.0
2J496219012	11221	3.375	2.215				5.0
2L342619012	11200	3.3125	4.885				5.0
2L339519012	10200	2.8125	3.26				5.0
2L373522012	11200	3.3125	4.885				5.0
2L416322012	11210	3.375	2.8125				4.0
3C780819042	11110	7.5	4.625				7.0
3N698122012	11220	7.0	7.125				7.0
3N698322012	11220	7.5	4.625				7.0
3P786933092	38400	4.875	8.375				7.0
3V708322012	35431	4.125	1.7969				4.5
4E397919012	11221	5.5	10.1875				7.0
6874216002	62001			1.97	0.7	0.04	2.0
7575872002	20020	11.78	2.5				3.0
7575875001	31420	5.156	3.5				4.0
7610504001	42232	1.683	0.146				2.0

TABLE 37. Geometrical and dimensional characteristics of part family 2 of PFA/ROCA (45 members)

Part	Geometrical	Dimensions					
number	Code	L	D	A	B	C	Weight
7J1025	42453	4.125	0.812				3.5
5J0766	89202			3.06	2.062	1.935	3.0
6J0433	69220			5.63	2.38	1.344	9.0
6J0434	69722			8.01	4.76	1.94	12.0
4J1091	41452	2.46	1.125				3.0
3J2973	83150			3.01	2.18	0.875	1.0
2J8069	60122			2.884	1.62	0.562	1.0
5J8773	60221			2.51	2.36	0.56	1.0
8J0130	60252			5.13	4.0	0.94	5.0
8J0444	32421	2.85	2.372				3.0
5J1553	42411	3.73	1.375				5.0
3J1970	82531			2.124	1.5	0.75	1.0
8J2045	83551			3.88	2.63	1.0	4.0
5J2438	42421	3.59	1				3.0
4J2696	32331	1.81	1.12				3.0
1U2764	71602			2.28	0.74	0.55	0.5
3G2842	31431	2.99	2.28				5.0
7J3897	33431	3.382	1.94				5.0
4J4571	43421	4.188	1.0				9.0
2J5143	83231			3.75	2.84	2.12	6.0
8J5875	42422	5.562	1.375				7.5
7J5928	43454	2.5	1.12				1.5
4J6485	45321	4.69	1.375				4.0
7J7674	43422	3.69	1				3.0
3J7807	35442	4.12	2.22				4.0
8J8660	20022	4.687	1.25				4.0
8J8661	42401	3.25	1.3				2.0
5J8793	83131			2.562	2.24	1.0	3.0
8J8829	89622			2.36	2.215	1.5	1.5
8J9257	43451	2.5	0.875				3.0
6J9992	38431	3.58	2				3.0
5J9110	33420	2.156	1.625				5.0
8J1701	89251			5.358	4.813	2.86	11.0
8J1917	81632			8.062	4.75	2.5	20.0
3T2321	45411	5.91	1.875				6.0
9J3453	41321	5.062	2.16				5.0
11A5324X012	17111	2.125	2.401				1.0
11A5326X012	17111	2.125	2.813				1.0
1E501208012	42604	6.8125	2.625				5.0
28A2514X012	01110	1.2031	4.25				3.0
2F143224092	15111	7.4375	3.125				10.0
2R124724092	32434	4.375	2.75				6.0

TABLE 37. (Continued)

Part number	Geometrical Code	L	D	Dimensions A	B	C	Weight
38A2508X012	06120	1.8438	6.37				4.0
38A2511X012	06320	2.6875	6.37				6.0
3R124624092	38451	3.375	2.0				5.0

TABLE 38. Geometrical and dimensional characteristics of part family 3 of PFA/ROCA (22 members)

Part number	Geometrical Code	L	D	Dimensions A	B	C	Weight
4T1889	80651			4.409	3.248	2.776	13.25
15A6470X012	14220	2.593	0.869				1.0
15A6503X012	21220	2.625	0.869				1.0
1U222646172	04104	0.5625	3.2813				2.0
28A2519X012	23210	5.625	1.25				4.0
2R2617X0012	32430	3.6563	3.0				4.0
6870005001	20000	3.5	0.5773				0.2238
6870008004	20120	6.32	0.685				0.1255
6870008005	81100			0.78	0.5	0.428	2.0
6870008006	72111			5	0.75	0.124	3.0
6870092001	63055			2.0	0.675	0.031	.0179
6870093001	63055			2.0	0.675	0.03	1.0
6870174001	00020	0.125	5.06				1.0
6870239001	60005			6	0.38	0.125	0.0057
7578887003	80000			0.422	0.375	0.25	1.0
7578887004	80000			0.4	0.4	0.2	0.0166
7578887009	80000			0.437	0.422	0.2	1.0
7578887010	60000			0.375	0.375	0.064	1.0
7578889004	80000			0.421	0.203	0.203	1.0
7610493001	20106	0.04	0.315				0.0001
6870003001	23106	2.48	0.568				0.2222
7575863006	20000	27.0	0.375				0.1056

TABLE 39. Geometrical and dimensional characteristics of part family 4 of PFA/ROCA (32 members)

Part	Geometrical			Dimensions			
number	Code	L	D	A	B	C	Weight
6870007001	63101			5.749	2.25	0.09	0.3
6870020002	62436			8.756	5.739	0.125	4.0
6870021002	61556			8.866	5.795	0.125	4.0
6870026002	61155			5.843	4.108	0.38	1.5
6870027002	61455			6.57	5.57	0.38	3.0
6870043001	70050			7.705	0.304	0.021	2.0
6870060001	60500			4.396	4.314	0.025	1.0
6870110001	00015	0.01	0.38				1.0
6870112001	61005			2.0	0.675	0.005	2.0
6870127001	61005			5.2	3.35	0.005	0.0386
6870148002	61050			7.488	3.272	0.032	1.0
6870167003	71055			1.643	0.325	0.032	1.0
6870181001	00020	0.062	5.1				1.0
6870341001	00005	0.0002	0.39				1.0
6870364001	71001			6.225	0.25	0.09	1.5
6870407001	60000			0.25	0.25	0.005	0.0002
6870444001	00000	0.052	0.125				0.0006
6874008002	60001			7.12	3.0	1.75	1.3345
6874098001	63050			0.19	0.09	0.0159	1.0
6874139001	62055			4.65	3.29	0.006	1.0426
7574570001	70400			0.796	0.155	0.005	1.0
7575872001	20000	14.125	2.5				3.0
7575955002	83101			0.7188	0.6875	0.375	2.0
7576591001	00101	0.032	1.0				1.0
7576896001	60001			4.406	3.128	0.032	0.054
7578614001	64100			0.125	1.5	2.0	0.5
7578677001	60055			6.204	2.585	0.9063	4.0
7578887001	60006			3.562	1.562	0.484	4.0
7578887002	70050			3.562	0.4219	0.484	1.0
7578889001	60006			3.562	1.562	0.484	4.0
7578889002	60006			3.562	1.562	0.406	0.2778
7610167002	64056			0.891	0.415	0.04	1.0

TABLE 40. Geometrical and dimensional characteristics of part family 5 of PFA/ROCA (30 members)

Part number	Geometrical Code	Dimensions L	D	A	B	C	Weight
3J0601	42301	2.63	1.125				2
5J1340	47351	2.25	1				5.5
1U0488	83231			5.49	4	2.12	4.79
4T1014	32431	1.062	1.56				2
9J1234	89621			3.25	2.742	2.375	3.5
3G2840	83430			3.25	2.63	1.1	3.0
3G2841	83430			3.25	2.63	1.57	4.0
1U4010	35421	2.28	1.38				5.0
9J4077	35421	2.21	1.406				2.5
4T4632	41421	4.37	1.57				3.0
9J4847	31421	1.87	1.0				2.0
9J4941	61251			3.8	3.5	0.932	3.0
6P5391	31002	2.75	1.562				2.0
9M5550	31401	1.75	1.0				3.0
7J8056	65251			5.13	4.0	0.94	5.0
8J8573	33422	1.38	1.25				2.0
5J8774	31451	1.312	1.375				2.0
4T9165	31451	1.693	2.48				5.0
8J2308	83151			4.375	3.75	2.12	6.0
9J0752	41402	6.63	0.7505				13.5
5J0899	83531			4.5	2.125	1.38	5.0
9T1495	65231			6.85	4.646	1.339	11.0
1U2083	81651			3.74	2.244	1.378	7.0
7J2266	83651			3.5	2.88	1.38	5.5
9J2382	20001	23.72	3.69				8.5
9T2887	60631			7.87	3.436	1.375	4.68
9J3382	83632			6.495	3.75	2.5	14.0
8J3554	45431	2.58	0.75				4.0
8J3665	83453			6.875	3.25	3.09	14.0
2R331019022	32434	5.0625	5.875				5.0

TABLE 41. Geometrical and dimensional characteristics of part family 1 of Opitz/CASC (60 members)

Part	Geometrical	Dimensions					
number	Code	L	D	A	B	C	Weight
7J1025	42453	4.125	0.812				3.5
3J0601	42301	2.63	1.125				2.0
5J1340	47351	2.25	1.0				5.5
6F4350	32400	1.75	3.0				1.0
8J0444	32421	2.85	2.372				3.0
4T1014	32431	1.062	1.56				2.0
4T1014	32431	1.062	1.56				2.0
5J1553	42411	3.73	1.375				5.0
5J2438	42421	3.59	1.0				3.0
4J2696	32331	1.81	1.12				3.0
3G2842	31431	2.99	2.28				5.0
4J3291	41331	2.812	1.0				7.0
9J3441	31421	2.5	1.62				3.0
7J3897	33431	3.382	1.94				5.0
1U4010	35421	2.28	1.38				5.0
9J4077	35421	2.21	1.406				2.5
4J4571	43421	4.188	1.0				9.0
4T4632	41421	4.37	1.57				3.0
4T4636	33421	1.26	1.1				1.0
9J4847	31421	1.87	1.0				2.0
9M5550	31401	1.75	1.0				3.0
8J5875	42422	5.562	1.375				7.5
7J5928	43454	2.5	1.12				1.5
4J6485	45321	4.69	1.375				4.0
7J7674	43422	3.69	1.0				3.0
3J7807	35442	4.12	2.22				4.0
6J7908	35424	1.96	1.406				2.5
7J8308	35422	1.75	1.0				3.0
8J8573	33422	1.38	1.25				2.0
8J8661	42401	3.25	1.3				2.0
5J8774	31451	1.312	1.375				2.0
6J9992	38431	3.58	2.0				3.0
5J9110	33420	2.156	1.625				5.0
3G0650	45434	4.31	1.38				16.5
4T0958	45432	5.512	1.969				15.0
3T2321	45411	5.91	1.875				6.0
9J3453	41321	5.062	2.16				5.0
8J3554	45431	2.58	0.75				4.0
0W019819012	45331	5.462	1.372				1.0
1C477219012	38406	7.25	5				7.0
1C899514022	30428	1.5625	.4688				1.5
1E3943000A2	32427	2.6875	4.25				5.0

TABLE 41. (Continued)

Part number	Geometrical Code	Dimensions					Weight
		L	D	A	B	C	
1E501208012	42604	6.8125	2.625				5.0
1R124835072	32434	1.4375	1.184				5.0
1R124835072	32434	1.4375	1.184				5.0
20A3382X022	32420	1.985	3.125				4.0
2E542919042	32541	3.9688	4.125				5.0
2R124724092	32434	4.375	2.75				6.0
2R2617X0012	32430	3.6563	3.0				4.0
2R331019022	32434	5.0625	5.875				5.0
2U223433272	32430	3.5	3.5				5.5
2U223733272	32432	3.5	3.5				5.5
2U740448932	32430	3.5	3.5				5.5
2U741048932	32430	3.5	3.5				5.5
36A2065X012	32430	4.0625	3.5				1.0
3P786933092	38400	4.875	8.375				7.0
3R124624092	38451	3.375	2.0				5.0
3V708322012	35431	4.125	1.7969				4.5
6874138001	42400	1.03	0.3				2.0
7575875001	31420	5.156	3.5				4.0

TABLE 42. Geometrical and dimensional characteristics of part family 2 of Opitz/CASC (25 members)

Part number	Geometrical Code	Dimensions					
		L	D	A	B	C	Weight
1U0488	83231			5.49	4	2.12	4.79
4J1137	83551			5.94	2.88	2.5	6.0
9J1234	89621			3.25	2.742	2.375	3.5
3J1970	82531			2.124	1.5	0.75	1.0
8J2045	83551			3.88	2.63	1.0	4.0
3G2840	83430			3.25	2.63	1.1	3.0
2J5143	83231			3.75	2.84	2.12	6.0
5J8793	83131			2.562	2.24	1.0	3.0
8J8829	89622			2.36	2.215	1.5	1.5
8J2308	83151			4.375	3.75	2.12	6.0
8J0084	83233			4.56	2.03	1.688	4.0
8J0510	85664			5.61	3.33	2.4	10.0
5J0899	83531			4.5	2.125	1.38	5.0
8J1701	89251			5.358	4.813	2.86	11.0
4T1889	80651			4.409	3.248	2.776	13.25
8J1917	81632			8.062	4.75	2.5	20.0
1U2083	81651			3.74	2.244	1.378	7.0
1U2177	83251			3.54	3.07	1.97	5.0
7J2266	83651			3.5	2.88	1.38	5.5
8J2305	81631			4.51	4.19	2.041	9.0
9J3382	83632			6.495	3.75	2.5	14.0
8J3665	83453			6.875	3.25	3.09	14.0
1E944223072	83550			2.5625	15.0	.7188	3.0
6870007001	63101			5.749	2.25	0.09	0.3
7575955002	83101			0.7188	0.6875	0.375	2.0

TABLE 43. Geometrical and dimensional characteristics of part family 3 of Opitz/CASC (37 members)

Part	Geometrical	Dimensions					
number	Code	L	D	A	B	C	Weight
8J5618	60721			4.0	2.755	0.875	3.0
9T2887	60631			7.87	3.436	1.375	4.68
6870008002	61000			7.294	4.5	0.314	4.0
6870043001	70050			7.705	0.304	0.021	2.0
6870060001	60500			4.396	4.314	0.025	1.0
6870092001	63055			2.0	0.675	0.031	0.0179
6870093001	63055			2.0	0.675	0.03	1.0
6870112001	61005			2.0	0.675	0.005	2.0
6870127001	61005			5.2	3.35	0.005	0.0386
6870148002	61050			7.488	3.272	0.032	1.0
6870167002	71050			1.643	0.325	0.032	0.0095
6870167004	71000			1.148	0.335	0.032	0.0093
6870167005	71000			1.068	0.325	0.032	1.0
6870239001	60005			6.0	0.38	0.125	0.0057
6870364001	71001			6.225	0.25	0.09	1.5
6870407001	60000			0.25	0.25	0.005	0.0002
6874008002	60001			7.12	3.0	1.75	1.3345
6874139001	62055			4.65	3.29	0.006	1.0426
6874216002	62001			1.97	0.7	0.04	2.0
7574570001	70400			0.796	0.155	0.005	1.0
7576896001	60001			4.406	3.128	0.032	0.054
7578431001	60031			19.245	6.463	0.156	8.0
7578612001	61006			0.8438	0.5	0.05	1.0
7578677001	60055			6.204	2.585	0.9063	4.0
7578887001	60006			3.562	1.562	0.484	4.0
7578887002	70050			3.562	0.4219	0.484	1.0
7578887003	80000			0.422	0.375	0.25	1.0
7578887004	80000			0.4	0.4	0.2	0.0166
7578887005	71000			1.484	0.4219	0.03	1.0
7578887006	71000			1.484	0.4219	0.03	1.0
7578887007	71000			1.89	0.4219	0.03	1.5
7578887009	80000			0.437	0.422	0.2	1.0
7578887010	60000			0.375	0.375	0.064	1.0
7578889001	60006			3.562	1.562	0.484	4.0
7578889002	60006			3.562	1.562	0.406	0.2778
7578889004	80000			0.421	0.203	0.203	1.0
7578889006	70000			1.981	0.421	0.03	1.0

TABLE 44. Geometrical and dimensional characteristics of part family 4 of Opitz/CASC (57 members)

Part	Geometrical			Dimensions			
number	Code	L	D	A	B	C	Weight
8J8660	20022	4.687	1.25				4.0
10A7182X012	21001	9.1	0.501				1.0
15A1288X012	11001	0.718	0.2813				0.5
15A6470X012	14220	2.593	0.869				1.0
15A6480X012	15220	2.532	0.869				1.0
15A6490X012	11220	2.0	1.125				1.0
15A6503X012	21220	2.625	0.869				1.0
1A510735072	02130	0.875	1.75				1.5
1B169135012	10000	1.75	1.125				2.0
1B883119012	11020	6.1875	4.875				5.0
1D228235072	02138	1.0625	2.5983				2.0
1H830814012	11230	0.625	1.062				3.0
1J1277000B2	11230	2.4375	2.25				5.0
1K586935162	20000	12.25	0.4375				3.0
1L432314012	11100	0.4688	0.6863				0.75
1R250935162	20004	7.6875	0.3125				3.0
25A1289X012	16100	1.0	1.149				1.5
25A6687X012	11100	3.5	3.4844				5.5
28A2514X012	01110	1.2031	4.25				3.0
2E4085000A2	11110	3.5	6.0625				4.0
2F1428000A2	25001	14.9	1.119				5.0
2J496219012	11221	3.375	2.215				5.0
2L342619012	11200	3.3125	4.885				5.0
2L373522012	11200	3.3125	4.885				5.0
2L416322012	11210	3.375	2.8125				4.0
2N5532000A2	25000	9.94	0.62				5.0
2R2454000A2	25004	7.41	1.62				4.0
38A2508X012	06120	1.8438	6.37				4.0
38A2511X012	06320	2.6875	6.37				6.0
3C780819042	11110	7.5	4.625				7.0
3N698122012	11220	7.0	7.125				7.0
3N698322012	11220	7.5	4.625				7.0
4E397919012	11221	5.5	10.1875				7.0
T1095224102	10101	0.84	0.876				1.0
6870004001	24000	4.8	0.371				2.0
6870005001	20000	3.5	0.5773				0.2238
6870006001	24000	8.55	0.506				2.0
6870007003	10100	2.21	0.75				2.0
6870008004	20120	6.32	0.685				0.1255
6870173002	00020	0.08	2.3				1.0
6870174001	00020	0.125	5.06				1.0
6870181001	00020	0.062	5.1				1.0

TABLE 44. (Continued)

Part	Geometrical	Dimensions					
number	Code	L	D	A	B	C	Weight
6870327001	00005			0.8	0.35	0.05	1.0
6870341001	00005	0.0002	0.39				1.0
6870444001	00000	0.052	0.125				0.0006
7575872001	20000	14.125	2.5				3.0
7575872002	20020	11.78	2.5				3.0
7575872003	01020	2.5	1.125				0.7174
7575872004	00000	2.5	0.125				0.7174
7576591001	00101	0.032	1.0				1.0
7610014003	20102	0.312	0.031				1.0
7610493001	20106	0.04	0.315				0.0001
6870003001	23106	2.48	0.568				0.2222
7575863002	10000	3.7188	2.5				2.0
7575863004	00120	0.125	2.412				0.18
7575863005	20100	0.04	0.315				0.0001
7575863006	20000	27.0	0.375				0.1056

TABLE 45. Geometrical and dimensional characteristics of part family 1 of Opitz/ROCA (21 members)

Part	Geometrical			Dimensions			
number	Code	L	D	A	B	C	Weight
1A510735072	02130	0.875	1.75				1.5
1C794935032	04106	0.4688	0.25				0.5
1D228235072	02138	1.0625	2.5983				2.0
1R125624092	00014	0.5	3.25				3.0
1R126335072	01104	0.4375	1.154				1.5
1U222646172	04104	0.5625	3.2813				2.0
28A2514X012	01110	1.2031	4.25				3.0
38A2508X012	06120	1.8438	6.37				4.0
38A2511X012	06320	2.6875	6.37				6.0
T1173614012	01201	0.37	0.945				1.0
6870110001	00015	0.01	0.38				1.0
6870173002	00020	0.08	2.3				1.0
6870174001	00020	0.125	5.06				1.0
6870181001	00020	0.062	5.1				1.0
6870327001	00005			0.8	0.35	0.05	1.0
6870341001	00005	0.0002	0.39				1.0
6870444001	00000	0.052	0.125				0.0006
7575872003	01020	2.5	1.125				0.7174
7575872004	00000	2.5	0.125				0.7174
7576591001	00101	0.032	1.0				1.0
7575863004	00120	0.125	2.412				0.18

TABLE 46. Geometrical and dimensional characteristics of part family 2 of Opitz/ROCA (16 members)

Part	Geometrical	Dimensions					
number	Code	L	D	A	B	C	Weight
8J8660	20022	4.687	1.25				4.0
1B169135012	10000	1.75	1.125				2.0
1K586935162	20000	12.25	0.4375				3.0
1R250935162	20004	7.6875	0.3125				3.0
2L339519012	10200	2.8125	3.26				5.0
T1095224102	10101	0.84	0.876				1.0
6870005001	20000	3.5	0.5773				0.2238
6870007003	10100	2.21	0.75				2.0
6870008004	20120	6.32	0.685				0.1255
7575872001	20000	14.125	2.5				3.0
7575872002	20020	11.78	2.5				3.0
7610014003	20102	0.312	0.031				1.0
7610493001	20106	0.04	0.315				0.0001
7575863002	10000	3.7188	2.5				2.0
7575863005	20100	0.04	0.315				0.0001
7575863006	20000	27	0.375				0.1056

TABLE 47. Geometrical and dimensional characteristics of part family 3 of Opitz/ROCA (11 members)

Part	Geometrical	Dimensions					
number	Code	L	D	A	B	C	Weight
3S7445	26010	6.25	0.48				3.25
10A7182X012	21001	9.1	0.501				1.0
11A5214X022	14021	2.125	1.406				1.0
11A5216X012	14021	2.125	1.406				1.0
15A1288X012	11001	0.718	0.2813				0.5
1B883119012	11020	6.1875	4.875				5.0
2F1428000A2	25001	14.9	1.119				5.0
2N5532000A2	25000	9.94	0.62				5.0
2R2454000A2	25004	7.41	1.62				4.0
6870004001	24000	4.8	0.371				2.0
6870006001	24000	8.55	0.506				2.0

TABLE 48. Geometrical and dimensional characteristics of part family 4 of Opitz/ROCA (11 members)

Part	Geometrical	Dimensions					
number	Code	L	D	A	B	C	Weight
15A6470X012	14220	2.593	0.869				1.0
15A6480X012	15220	2.532	0.869				1.0
15A6490X012	11220	2.0	1.125				1.0
15A6503X012	21220	2.625	0.869				1.0
1H830814012	11230	0.625	1.062				3.0
1J1277000B2	11230	2.4375	2.25				5.0
28A2519X012	23210	5.625	1.25				4.0
2L416322012	11210	3.375	2.8125				4.0
3C780819042	11110	7.5	4.625				7.0
3N698122012	11220	7.0	7.125				7.0
3N698322012	11220	7.5	4.625				7.0

TABLE 49. Geometrical and dimensional characteristics of part family 5 of Opitz/ROCA (38 members)

Part	Geometrical			Dimensions			
number	Code	L	D	A	B	C	Weight
6F4350	32400	1.75	3.0				1.0
8J0444	32421	2.85	2.372				3.0
4T1014	32431	1.062	1.56				2.0
4J2696	32331	1.81	1.12				3.0
3G2842	31431	2.99	2.28				5.0
9J3441	31421	2.5	1.62				3.0
7J3897	33431	3.382	1.94				5.0
1U4010	35421	2.28	1.38				5.0
9J4077	35421	2.21	1.406				2.5
4T4636	33421	1.26	1.1				1.0
9J4847	31421	1.87	1.0				2.0
6P5391	31002	2.75	1.562				2.0
9M5550	31401	1.75	1.0				3.0
3J7807	35442	4.12	2.22				4.0
6J7908	35424	1.96	1.406				2.5
7J8308	35422	1.75	1.0				3.0
8J8573	33422	1.38	1.25				2.0
5J8774	31451	1.312	1.375				2.0
6J9992	38431	3.58	2.0				3.0
5J9110	33420	2.156	1.625				5.0
1C477219012	38406	7.25	5.0				7.0
1C899514022	30428	1.5625	0.4688				1.5
1E3943000A2	32427	2.6875	4.25				5.0
1R124835072	32434	1.4375	1.184				5.0
20A3382X022	32420	1.985	3.125				4.0
2E542919042	32541	3.9688	4.125				5.0
2R124724092	32434	4.375	2.75				6.0
2R2617X0012	32430	3.6563	3.0				4.0
2R331019022	32434	5.0625	5.875				5.0
2U223433272	32430	3.5	3.5				5.5
2U223733272	32432	3.5	3.5				5.5
2U740448932	32430	3.5	3.5				5.5
2U741048932	32430	3.5	3.5				5.5
36A2065X012	32430	4.0625	3.5				1.0
3P786933092	38400	4.875	8.375				7.0
3R124624092	38451	3.375	2.0				5.0
3V708322012	35431	4.125	1.7969				4.5
7575875001	31420	5.156	3.5				4.0

TABLE 50. Geometrical and dimensional characteristics of part family 6 of Opitz/ROCA (16 members)

Part number	Geometrical Code	Dimensions L	D	A	B	C	Weight
7J1025	42453	4.125	0.812				3.5
5J1553	42411	3.73	1.375				5.0
5J2438	42421	3.59	1.0				3.0
3J2975	43402	4.78	1.44				9.0
4J4571	43421	4.188	1.0				9.0
8J5875	42422	5.562	1.375				7.5
7J5928	43454	2.5	1.12				1.5
7J7674	43422	3.69	1.0				3.0
8J8661	42401	3.25	1.3				2.0
8J9257	43451	2.5	0.875				3.0
3G0650	45434	4.31	1.38				16.5
4T0958	45432	5.512	1.969				15.0
3T2321	45411	5.91	1.875				6.0
8J3554	45431	2.58	0.75				4.0
3B186522012	48407	8.25	3.011				12.0
6874138001	42400	1.03	0.3				2.0

TABLE 51. Geometrical and dimensional characteristics of part family 7 of Opitz/ROCA (41 members)

Part number	Geometrical Code	Dimensions					
		L	D	A	B	C	Weight
6J0433	69220			5.63	2.38	1.344	9.0
6J0434	69722			8.01	4.76	1.94	12.0
2J8069	60122			2.884	1.62	0.562	1.0
5J8773	60221			2.51	2.36	0.56	1.0
8J0130	60252			5.13	4.0	0.94	5.0
9J4941	61251			3.8	3.5	0.932	3.0
8J5618	60721			4	2.755	0.875	3.0
7J8056	65251			5.13	4.0	0.94	5.0
8J2302	69632			5.19	4.38	1.281	11.0
9T1495	65231			6.85	4.646	1.339	11.0
9T2887	60631			7.87	3.436	1.375	4.68
6870007001	63101			5.749	2.25	0.09	0.3
6870008002	61000			7.294	4.5	0.314	4.0
6870020002	62436			8.756	5.739	0.125	4.0
6870021002	61556			8.866	5.795	0.125	4.0
6870026002	61155			5.843	4.108	0.38	1.5
6870027002	61455			6.57	5.57	0.38	3.0
6870060001	60500			4.396	4.314	0.025	1.0
6870092001	63055			2	0.675	0.031	0.0179
6870093001	63055			2	0.675	0.03	1.0
6870112001	61005			2	0.675	0.005	2.0
6870127001	61005			5.2	3.35	0.005	0.0386
6870148002	61050			7.488	3.272	0.032	1.0
6870239001	60005			6	0.38	0.125	0.0057
6870407001	60000			0.25	0.25	0.005	0.0002
6874008002	60001			7.12	3	1.75	1.3345
6874098001	63050			0.19	0.09	0.0159	1.0
6874139001	62055			4.65	3.29	0.006	1.0426
6874140002	62056			9.781	6.06	0.595	2.0
6874216002	62001			1.97	0.7	0.04	2.0
7576896001	60001			4.406	3.128	0.032	0.054
7578431001	60031			19.245	6.463	0.156	8.0
7578612001	61006			0.8438	0.5	0.05	1.0
7578614001	64100			0.125	1.5	2	0.5
7578677001	60055			6.204	2.585	0.9063	4.0
7578887001	60006			3.562	1.562	0.484	4.0
7578887010	60000			0.375	0.375	0.064	1.0
7578889001	60006			3.562	1.562	0.484	4.0
7578889002	60006			3.562	1.562	0.406	0.2778
7610167002	64056			0.891	0.415	0.04	1.0
7610464001	64076			24.0	10.875	0.064	1.9728

TABLE 52. Geometrical and dimensional characteristics of part family 8 of Opitz/ROCA (11 members)

Part number	Geometrical Code	Dimensions L	D	A	B	C	Weight
6870148001	89051			7.56	7.488	3.272	2.0
6870167002	71050			1.643	0.325	0.032	0.0095
6870167003	71055			1.643	0.325	0.032	1.0
6870167004	71000			1.148	0.335	0.032	0.0093
6870167005	71000			1.068	0.325	0.032	1.0
6870364001	71001			6.225	0.25	0.09	1.5
7578424001	88041			8.75	6.375	3.75	5.0
7578887005	71000			1.484	0.4219	0.03	1.0
7578887006	71000			1.484	0.4219	0.03	1.0
7578887007	71000			1.89	0.4219	0.03	1.5
7610463001	72076			25.593	5.25	0.815	7.0

TABLE 53. Geometrical and dimensional characteristics of part family 9 of Opitz/ROCA (15 members)

Part number	Geometrical Code	Dimensions L	D	A	B	C	Weight
1U0488	83231			5.49	4.0	2.12	4.79
4J1137	83551			5.94	2.88	2.5	6.0
9J1234	89621			3.25	2.742	2.375	3.5
3J1970	82531			2.124	1.5	0.75	1.0
8J2045	83551			3.88	2.63	1.0	4.0
2J5143	83231			3.75	2.84	2.12	6.0
5J8793	83131			2.562	2.24	1.0	3.0
8J2308	83151			4.375	3.75	2.12	6.0
5J0899	83531			4.5	2.125	1.38	5.0
8J1701	89251			5.358	4.813	2.86	11.0
1U2083	81651			3.74	2.244	1.378	7.0
1U2177	83251			3.54	3.07	1.97	5.0
7J2266	83651			3.5	2.88	1.38	5.5
8J2305	81631			4.51	4.19	2.041	9.0
6870008006	72111			5.0	0.75	0.124	3.0

APPENDIX D: RESULTS FOR THE PART FAMILIES WHICH HAD FIVE OR MORE PART MEMBERS

The families which had five or more part members were selected for each method. Grippers were configured for those families. The configured grippers were evaluated. The results are presented in Table 54.

TABLE 54. Result of gripper evaluation for the part families which had five or more parts

Method	Total number of grouped parts	Number of parts grasped successfully
PFA/CASC	123 [20]	76(0.582) (+ 3.5%)
PFA/ROCA	216 [59]	125(0.541) (+ 3.8%)
Opitz/CASC	197 [18]	148(0.743) (+ 0.8%)
Opitz/ROCA	233 [49]	184(0.750) (+ 4.0%)

The percentage of number of parts grasped successfully were increased. The amount of the increase is indicated within parenthesis under the fraction of parts successfully grasped in Table 54. The increase shown is for the comparison of the same analysis for families with ten or more parts. The Opitz/ROCA method showed highest percentage. The PFA/CASC method showed the lowest percentage. The same result was obtained when the analysis was performed for the families which had ten or more part members.

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