# DESIGN AND CONTROL
# OF
# CELLULAR MANUFACTURING SYSTEMS

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DOCTOR OF PHILOSOPHY

By

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# PULLOUTS

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(A Thesis Submitted for the Ph.D. Degree, 1981)

## SUMMARY

The design requirements and control aspects of cellular manufacturing systems are investigated. The problems are tackled with considerations for the needs and capabilities of small firms*, with the expectation that the simple and economic nature of this approach can benefit those manufacturers who are not prepared for large capital investments, but would like to introduce cellular manufacture to their factories.

A simple non-manual coding system has been developed for initial sorting of components. The rough groupings obtained are then analysed by using a new Direct Clustering Algorithm to determine the machine groups and component families. The method has been developed on the basis of material flow analysis and is readily computerised. Also, a new Adjacency Requirements Planning technique has been developed for layout planning to optimise material flows in the system. The method is based on the graph theory concept and can be used with computer aids.

For production control, the ordering method of Material Requirements Planning has been shown to be fully compatible with cellular manufacture. An account of implementing a composite MRP-GT system is given. Also, based on a flowline scheduling method, an algorithm has been designed for operations scheduling in cellular systems.

Finally, the methodology is used for implementing cellular manufacture in a factory of a car manufacturer.

Keywords: Small Firms
Direct Clustering Algorithm
Adjacency Requirements Planning
Composite MRP-GT System
Operations Scheduling

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* "small firms" means small scale productions

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## DECLARATION

No part of the work described in this thesis has been submitted in support of an application for another degree or other qualification of this or any other institution.

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# CHAPTER ONE

## 1. INTRODUCTION

Over the last few decades a new philosophy of manufacturing organisation has emerged under such names as "Group Technology" and "Cellular Manufacture". This is based on the principle that a large organisation can be divided into a number of smaller sections in such a way that each section becomes a specialised area where a number of people can come together to function as a cohesive group, interacting to accomplish a common, whole task. When this philosophy is applied to a production system, the smaller sections formed are called cells, each cell being a management unit in itself, specialising in the manufacture of a family of components. For this reason a production system which is designed according to the Group Technology concept is called a cellular manufacturing system.

Group Technology is a desirable innovation which can, if it is well introduced, result in both major economic gains and improved social structures. Its advantages are already well recognised (1, 26) and have been convincingly demonstrated by several successful industrial applications (2, 3). Cellular manufacture is a strategy of production management which not only can induce a substantial gain in profitability, but also can provide a working environment that is generally preferred by operators. There has been a lot of evidence, both direct and indirect, of the social benefits of GT (4, 5).

In recent years, Group Technology seems to have lost favour in the U.K., and one hears very little about current research into the subject. However, this should not be interpreted that GT has failed and been abandoned. The fact is that the philosophy and technique have flourished in the other industrial nations, notably in the United States (6, 7). These countries see GT not only as a more efficient production method, but also as the essential foundation for an integrated system of batch manufacture. Group Technology may not be a universal panacea for manufacturing industry, but if implementations are carefully planned it can be used with benefits in a wide spectrum of industries.

In this thesis the two most important tasks in the course of implementing a GT system are investigated. These are the design requirements of such a system and the associated controlling aspects. These problems are tackled with considerations for the needs and capabilities of smaller firms. The objective is to provide a way of solving the two major problems in the implementation of GT, with the expectation that the simple and economic nature of this approach can benefit those manufacturers who are not prepared for large capital investments, but would like to introduce cellular manufacture to their factories.

A pre-requisite of implementing GT is the establishment of component families and machine cells. The traditional approach is either by using a classification and coding method, or by employing a material flow analysis technique (11, 12). In this thesis, a compromise of the two methods is shown to be the feasible approach to designing component families and machine cells.

The second important stage in the implementation of GT is to plan the layout of the machine cells and the machines in each cell, so that a well defined and simple pattern of material flow can be achieved. In this thesis, it is shown that layout planning of a cellular manufacturing system is similar to the classical facilities layout problem, and that it can be solved by a heuristic approach.

Aiming at solving these problems, the following are achieved in this research:-

(a) A simple non-manual coding system (13) has been developed. It can be used for initial sorting of components and for improving communications throughout the company.

(b) A new Direct Clustering Algorithm (61) has been developed for finding component families and machine groups from rough groupings obtained by coding and classification. The method is based on a material flow analysis approach and is specifically designed for computer use.

(c) A new Adjacency Requirements Planning algorithm (14) has been developed for solving the layout planning problem. The method is based on the graph theory concept and can be easily implemented by a computer.

Based on these findings, a methodology for designing cellular manufacturing systems is suggested, and is verified with an application in an industrial firm.

After designing the manufacturing cells, the next stage is the planning of production control for the new system. A change in system control methods is essential for the successful application of Group Technology.

A major function of production control is ordering. Previous researchers have shown that the best ordering system for cellular manufacture is one based on a short term flexible ordering method (11, 62). A very popular technique of this kind is the Material Requirements Planning method (17, 18). In the United States, MRP has already been accepted as the standard production control method for batch manufacture (19), and in recent years, the merits of combining it with GT are well publicised (56, 57, 58). However, a successful implementation requires careful study of the technique.

The other main function of production control is operations scheduling. This problem is usually treated by industrial engineers from the standpoint of operational research. Several effective algorithms and theories have been suggested (20, 21, 22), however, few are concerned specifically with Group Technology. Petrov (23) presented a systematic accounting of group production planning, and showed a way to obtain a good schedule. His method is adopted in this thesis, and forms the basis of a scheduling algorithm for cell systems.

The second part of this research aims at providing suitable control methods for cellular manufacturing systems. The following are achieved:-

(a) The method of Material Requirements Planning is studied, and is shown to be fully compatible with a cellular manufacturing system. An account of the strategy of implementing a composite MRP-GT system is also given.

(b) Petrov's method is studied, and is modified to a group scheduling algorithm which can give a near optimal manufacturing sequence of components in a machine cell.

In this thesis, due considerations are given to previous researchers into the topics, and a comprehensive literature survey is included. Also, two computer programmes have been written, one for the Direct Clustering Algorithm and the other for the Adjacency Requirements Planning method.

# CHAPTER TWO

## 2. GROUP TECHNOLOGY AS A MANUFACTURING PHILOSOPHY

### 2.1 Basic Concepts of Group Technology

Finding a universal definition for Group Technology is not an easy task since many have been introduced by a number of people who have written about it. However, the following definition that is given by Solaja (24) helps to clarify its main concepts:-

"Group Technology is the realization that many problems are similar and that, by grouping similar problems, a single solution can be found to a set of problems, thus saving time and effort".

The objectives of Group Technology are best achieved in business concerned with small to medium batch production; these represent a major part of manufacturing industry. The traditional approach to this type of manufacture is to make use of a functional layout in the factory, i.e. similar machines are grouped according to type. Thornley (25) wrote that "as a result of this form of machine layout, where only machining operations of a particular type may be performed in a limited area of the workshop, the workpiece itself must travel a considerable distance around the workshop before all the operations are performed upon it". This usually leads to a long throughput time. The planning of process route becomes an extremely difficult task since a number of similar machine tools may be considered at each point in the sequence of manufacturing operations. Also the scheduling and control in such a system are difficult because numerous alternatives are available.

Faced with this situation, a different concept of manufacturing organisation and layout has been developed to overcome the difficulties. This is the Group Technology concept and the emphasis lies in reducing the dimension of the situation to be controlled, by dividing the factory into sections. Instead of planning the layout by functions, the factory is divided into smaller cells in such a way that each cell is equipped with all the machines and equipment needed to complete a particular family of components. It has been found that by changing to this type of cellular manufacture, many benefits of flowline production can be achieved in a batch production system.

The general achievements of Group Technology have been formulated by Thornley (26) and are illustrated as shown in figure 2.1. The application of GT to a traditional manufacturing system can usually result in a simpler material flow system (see figure 2.2), so that a higher transfer rate and easier production planning and control functions can usually be achieved.

## 2.2 Development of Group Technology

The basic thinking behind Group Technology can be attributed to the Russians, who carried out initial investigations during the 1920's. The progress of GT since then and its gradual adoption in other countries has been traced by Grayson (27). The early work stressed the importance of industrial classification and initial applications were limited to the medium and large batch productions. The work was extended during the war years by Mitrofanov to include workpieces produced in small batches. His major written work on Group Technology was first published in 1959 and was translated into English in 1966 (28). He proposed that it was possible to produce a theoretical composite component which incorporated all the major features of components belonging to a family, and that a machine could be tooled up to produce the composite component, thus providing the set-ups required for each component in the family.

In the early 1960's, Opitz (29) carried out an investigation into workpiece statistics, which showed that although firms manufacture a variety of products, the spectrum of them all was remarkably similar. Based on the findings of this investigation, he established a classification system which enabled components to be codified by means of their geometrical similarity (30).

A number of methods for classification and coding were being investigated at approximately the same time (31).

A significant growth in the interest and application of Group Technology in the U.K. followed the publication of Opitz's work. The most notable were the works conducted by PERA (32) and by MTIRA (33). A government sponsored centre was set up in Blacknest for the dissemination of information about Group

Technology, and there was a specialist division set up by the Institution of Production Engineers which ran seminars and published papers on the subject.

The advances in GT have been greatly influenced by the existence of a classification system devised by Brisch and Partners (34). The Brisch system was originally designed to facilitate variety reduction, component standardisation and product rationalisation. It was later developed to suit GT requirements. There have been many applications of GT using the Brisch system, probably the most sucessful example was that of Serck Audco Valves (35).

During the late 1960's, several well known organisations implemented Group Technology. A notable example of one such companies was Ferodo (36), where reductions in W.I.P. of about 8 to 1 were achieved. Other well known firms such as Ferranti (37), Rolls Royce (38) and Baker Perkins (39) introduced GT at roughly the same time, and these applications provided benefits in many areas. Since then there have been more applications of GT in the U.K. - Herbert Machine Tools (40), Rank Xerox (41), Wildt Mellor Bromley (42) and Simon Container Machinery (43).

Other methods were later developed as alternatives to the classification and coding approach. These were methods based on the analysis of production information. The most representative work was the Production Flow Analysis method proposed by Burbidge (44). Other similar methods were due to EL - Essawy (45), Purcheck (46) and Nagarkar (47). These methods are different with respect to the underlying assumptions and the technique of analysis, but the general approach is to study a company's total system and to determine those families of components which are related by similarities in the production facilities required for their manufacture.

After some initial experience with Group Technology in organisations, it became evident that a change in the workshop was not sufficient on its own. To obtain the full benefits, it was necessary to change other parts of the system, including, for example, production control, planning, payment systems and accounting methods (49). For this reason, Group Technology was changed from being a technique in itself to being part of a new philosophy of production organisation.

Most research efforts of recent years have been directed towards other areas of organisation affected by the introduction of GT (50, 51). This trend was initially reflected at the "Conference on Production Improvement through Group and Cell Formation", held at the University of Aston in Birmingham in February 1973. Most speakers here agreed that Group Technology had to be looked at not only as a machining system but as a complete manufacturing philosophy embracing all functions.

In the late 1970's, Group Technology began to lose favour among British manufacturers. This was partly due to the fact that some companies who had previously introduced GT were discovering not only the advantages but also the problems which sometimes result. This was not altogether unexpected and indeed it was demonstrated by Leonard and Rathmil (10) that Group Technology is not a universal panacea for manufacturing industry. A publication by the EDCME (8) suggested some reasons for the slow rate of adopting GT by the British firms; traditional attitudes and practice, fear of changes and suspicion of extravagant claims for GT were the main factors. Burbidge (9) held a different viewpoint and proposed some other reasons why GT has failed to retain acceptance by British industry.

Although Group Technology is out of favour in the U.K., it has flourished in other industrial nations. Since the 1960's, work has been done, though on smaller scales in the Netherlands, Switzerland, Belgium, Sweden, U.S.A., Japan and West Germany (52). Today many of these countries have more application of GT than in the U.K. and they are continuing to press ahead with its development (53, 54, 55). In the United States, Group Technology has been accepted as a technique of raising manufacturing performance, and the merits of integrating it with the very popular production control technique of Material Requirements Planning are well publicised (56, 57, 58).

British industry appears to have given up GT just when the other industrial nations have become convinced of its value and are taking it up. This suggests that there is still a need for research directed to testing the basic hypotheses and premises of GT. New stimulation is required if Group Technology in Britain is to be revitalized and some benefits gained.

## 2.3 Basic Forms of Cellular Manufacturing (GT) Systems

The principle of Group Technology is to simplify the control of the manufacturing situation by dividing the organisation into smaller sections called cells, each containing the machines needed to accomplish a common task. For this reason an organisation incorporated with this principle is called a cellular manufacturing system. There are three basic forms of cellular manufacture and each has a fairly important effect on the operation of the system.

### a) Flowline Cell

In many families of components there is a high degree of commonality in the manufacturing operations required. If the machines and equipment in the cell are established sequentially as determined by the order of operations, then a flow line can be created within the cell. This differs from a conventional flow line in that, as some components may not require processing on certain machines, some workstations will be under utilised and it will be necessary for some operators to operate more than one machine. This type of cell is highly efficient but its flexibility is poor.

### b) Group Layout Cell

In this type of cell there is a sufficient variety of machines to carry out all the processes required but a flowline is impossible to implement. A component may have to back track to visit a particular workstation more than once, and to allow for this, the workstations within the cell should be placed in such a way that the total material movement cost is minimised. This type of cell can cope with a wide variety of components and can be implemented with less difficulty.

c) <u>Single Machine Cell</u>

This is based on the single machine concept as proposed by Mitrofanov (28). A family of components is loaded consecutively on to a machine in order to make maximum use of a single set up. It is particularly applicable to machines such as lathes where some components are produced completely on one machine. The technique can be used to improve machine utilization under functional layout or group layout.

## 2.4 Characteristics of GT Systems in Small Firms*

The most profitable area for GT is probably the small batch production industry, in particular, small firms where there is little opportunity scope for large capital investment. With careful planning, implementing Group Technology in a factory can be concerned only with the plant, toolings and methods of manufacture currently in use. This does provide an economic approach to improve productivity in small firms, and in many cases where financial situations dominates, it can be the only sensible approach.

Although many outstanding applications of GT have been installed, the main interests have been concentrated on larger firms with sound financial resources. In making the change from a traditional organisation to a cellular manufacturing system in these firms, the cost is often too high and the implementation time is often too long which cannot be met by small firms. To illustrate the justification for the change and to motivate the small firms to initiate the change, a more economical and simpler method is needed.

The extent to which GT can be applied in a manufacturing organisation will depend on the quantity and variety of the individual components being made and the manufacturing processes required by them. Small firms tend to make a wide range of components in small quantities in order to meet the frequently changing demand, and to remain competitive in their own fields. Group layout cells are flexible and can cope with changing specifications of components, and are therefore preferable to small firms.

Theoretically the machines in each cell should be capable of carrying out all the operations required by the components, and this has been reckoned by many writers as the key characteristic of cell systems. However, in practical situations this characteristic cannot always be achieved in all cells, due to lack of resources or other restricting factors. For instance, it is a common practice to install the few expensive special machines in particular cells. In consequence, the few components requiring these facilities, but which are being produced in different cells, will have to be moved to them for these operations. Elimination of these foreign works in every cell is often unjustified economically or geographically, in particular, in small firms which have limited resources. This was demonstrated by the investigation at Lewman Marine Limited in Hampshire (59). The introduction and subsequent running of a cell system at this small engineering firm has shown that foreign works in cells were often unavoidable. The company was forced to operate its cell system with inter-cell material flows, yet positive gains in terms of reduced work in progress, reduced stock and increased production output per employee have resulted.

The overall effect of changing to cellular manufacture is reduction in the length of time a component is in the process of being made. This allows simpler and more effective methods of production control to be employed. At the same time this approach of considering components in related groups can lead to other benefits such as the improved use of standard times and standard tools, or the standardisation of design and production practices. For a small firm, this indeed can form the basis for a beneficial reorganisation of management structure within the company.

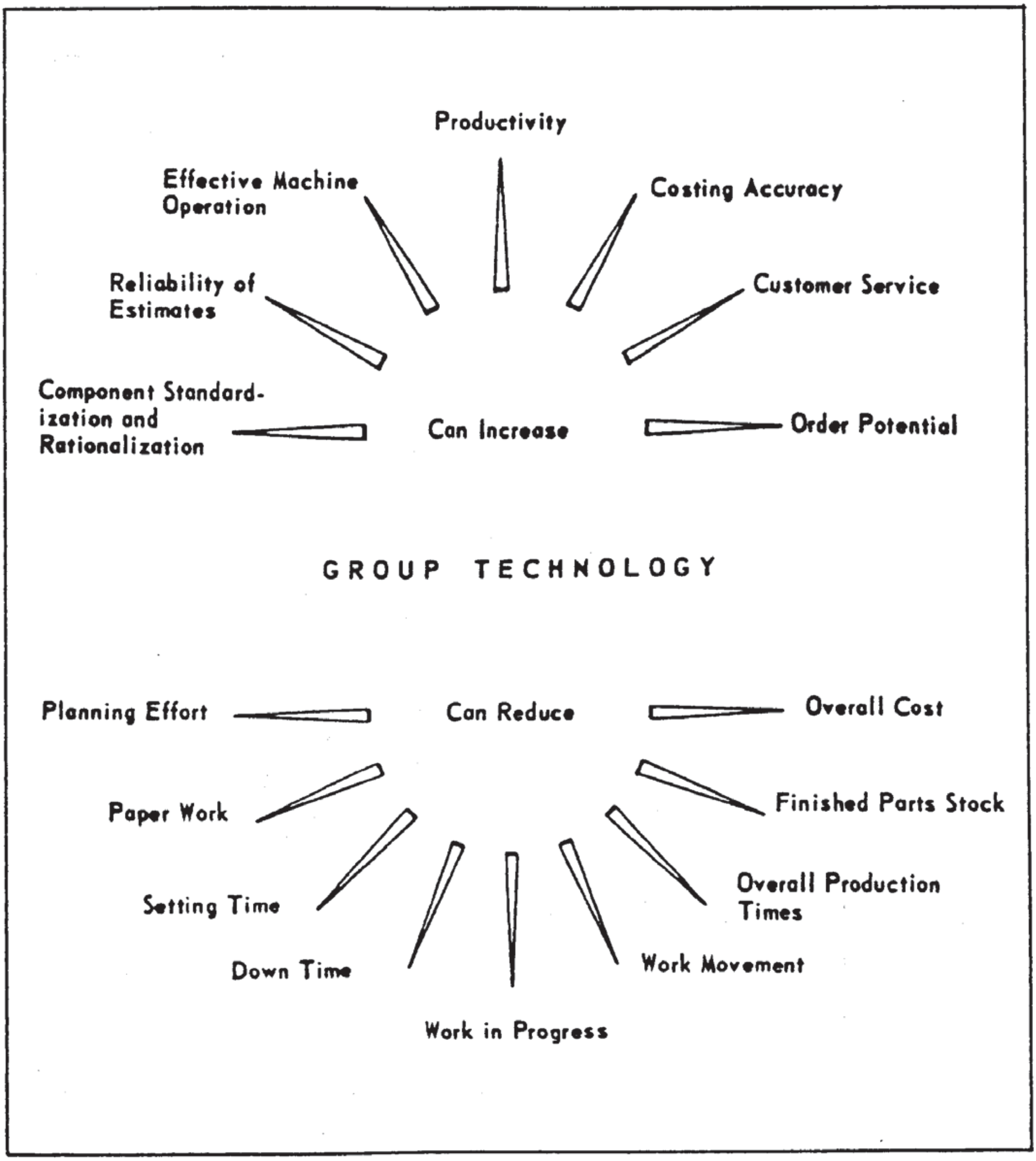
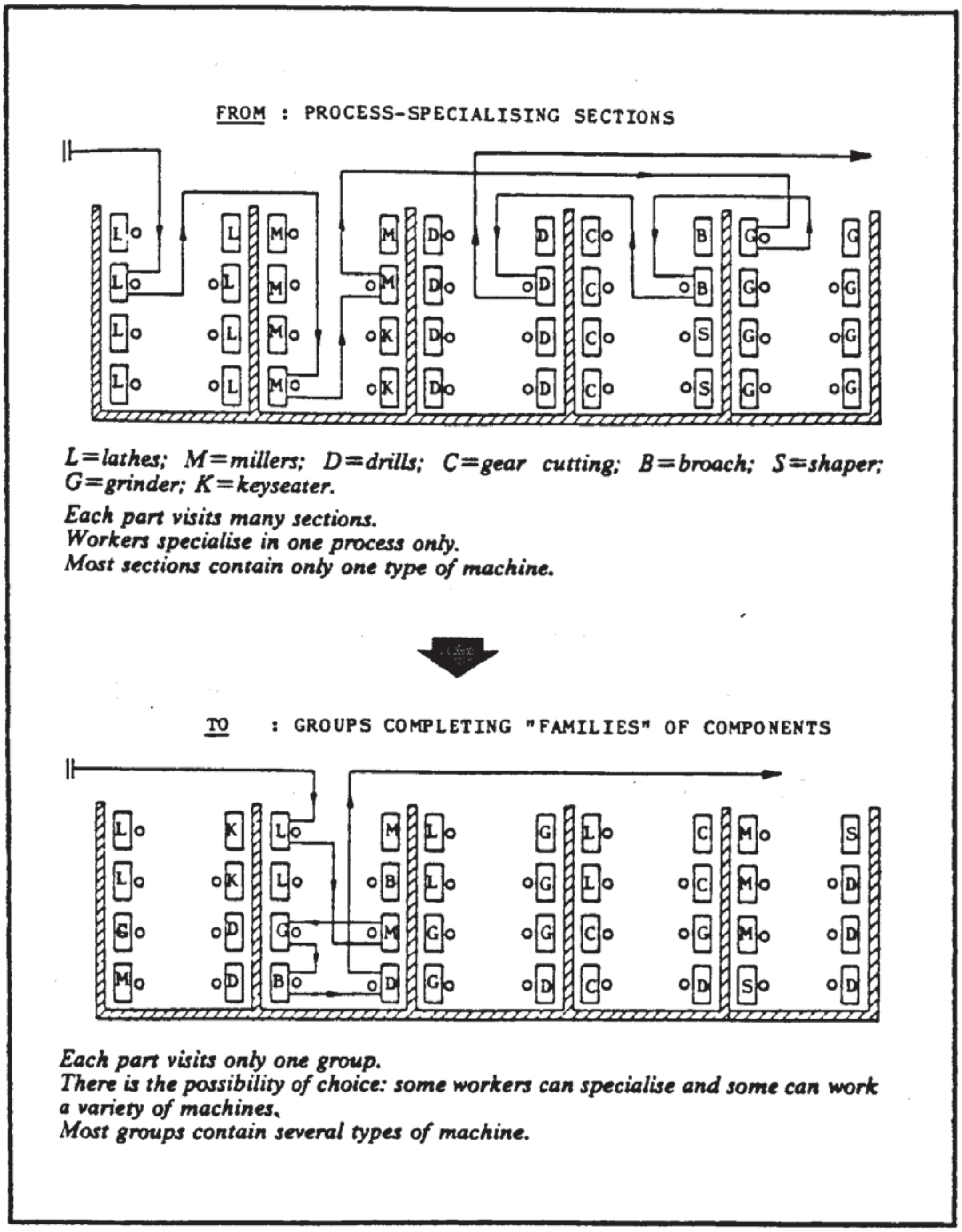


Figure 2.1 General Achievements of Group Technology (after Thornley)



**FROM** : PROCESS-SPECIALISING SECTIONS

*L=lathes; M=millers; D=drills; C=gear cutting; B=broach; S=shaper; G=grinder; K=keyseater.*

*Each part visits many sections.*
*Workers specialise in one process only.*
*Most sections contain only one type of machine.*

**TO** : GROUPS COMPLETING "FAMILIES" OF COMPONENTS

*Each part visits only one group.*
*There is the possibility of choice: some workers can specialise and some can work a variety of machines.*
*Most groups contain several types of machine.*

Figure 2.2 GT Results in Simpler Material Flow (after Burbidge)

## CHAPTER THREE

## 3. GROUP FORMATION IN CELLULAR MANUFACTURING SYSTEMS

### 3.1 Principal Methods of Group Formation

Group formation is the pre-requisite to the effective planning of cellular manufacturing systems. The aim is to find the machine groups and component families such that each group can be specialised in the making of one family of components. There are three main methods of finding these groups and families:-

(a) By visual inspection
(b) By classification and coding
(c) By material flow analysis technique.

The first method is to find the required groups and families by eye, and is usually done by studying the detailed drawings of all components produced in the factory. This process is very tedious, becoming more time consuming as the number of components increases, and is obviously inefficient for those companies having a wide range of products. The visual method is unscientific in that the grouping is arbitrary and is subjectively dependent on the persons carrying out the operation. The families formed are quite possibly inconsistent if more than one person is involved. Unlike the other two methods, this method does not highlight exceptional components and this is essential for the cellular manufacturing system design.

The other two methods are superior in many aspects and more practical, and will be later employed as the basis of a design methodology for cellular manufacture. First the two approaches are examined in more detail.

## 3.2 The Classification and Coding Approach

Of the firms which have turned to cellular manufacture, many have done so by using an analytical classification and coding system. The prime purpose of the technique is to obtain a suitable data base from which similar characteristics can be easily recognised, and from this to group components and form manufacturing cells.

A coding system can have the form of a numerical, alphanumerical or alphabetical string of digits. Numerical systems are most widely used because of their simplicity, both in structure and use. A system that is used to define a range of components can usually include a large amount of data concerning the part, provided that it can be stated in the form of some combination of digits.

The classification and coding systems designed for GT applications can be illustrated by the two major systems used by the companies in Britain, these are the Brisch System (34) and the Opitz System (30). The Brisch System provides a code consisting of four to six digits which, with the secondary polycodes, defines the geometric form and production requirements of a component. Although the code has a common basic structure, each application is tailor made to suit specific customers, and the cost can be very high. The general structure of the Brisch Coding System is shown in figure 3.1.

The Opitz System comprises a five-digit geometric code to which a supplementary four-digit code may be added, as shown in figure 3.2. It describes the geometrical shape, principal dimension, raw material and initial form of the component. Although this code is not as precise as the Brisch System, it is simple to use and readily available at a modest expense.

There are a number of other classification systems that have been developed for GT applications, and a survey sponsored by SRC has found 46 of them (60). These are listed in figure 3.3.

The main advantage of the classification and coding approach is that it enables the group formation to be carried out in a systematic manner, and is particularly advantageous where a large variety of components exists. Moreover, the use of a component classification system throughout an organisation can produce other benefits, such as simplifying design data retrieval, product rationalisation, creating a basis for computer aided process planning, and speeding up estimating and costing.

The major disadvantage of using a classification system for group formation is that it tends to bring together components which are similar in shape, but which due to differences in production requirements should be made in separate cells. This is because most systems are based on design features, and neither the plant nor the processing method is considered. Items of plant which are required to machine a component family are usually allocated to a group after the component family is formed.

Another difficulty with classification is that tailor-made codes are generally costly to obtain and time consuming to install. Universal codes are usually cheaper to implement, but modifications are often required and if these have to be made after implementation, the cost may rise and confidence in the new production system may be lost.

### 3.3 The Material Flow Analysis Approach

Material flow analysis techniques rely on identifying component families and machine groups by analysing the routes followed by all components which are to be manufactured. They are designed to find the natural groups and families which already exist, rather than to create new ones. There are several variants of material flow analysis methods which use different techniques in forming component families and machine groups. However, the basic principle is the same, and is to refine the information contained in the route cards and the plant list currently used in a factory, and from it to form groups and families by a progressive analysis.

The representative method of this kind is the Production Flow Analysis technique devised by Burbidge (44, 62). It consists of four main stages:-

(a) Factory flow analysis, which uses network to analyse process routes in order to find the best division of plant and equipment into major departments to effect simple material flow.

(b) Group analysis, which uses matrices to divide components into families, and plant and equipment into groups within each department.

(c) Line analysis, which uses networks to devise the best approximation to flowline layout within each group.

(d) Tooling analysis, which uses matrices to find the tooling families.

Unlike classification and coding, a material flow analysis technique brings together components which are dissimilar in shape or function, but which are made on the same set of machines, and component families and machine groups are both found at the same time by one process. For manufacturing industries where parameters such as shape and material are of secondary importance, this technique is probably the only approach by which cellular manufacture can be implemented. The information required for the analysis already exists in the factory, and therefore implementation is generally easier and requires a shorter time.

The major disadvantage of material flow analysis methods is that the information produced is sometimes too complex to be analysed directly. For this reason the major applications tend to be found in smaller firms with limited resources and a narrow product range. In particular, these methods have been found ideal for improving an existing system with minimum capital investments.

### 3.4 A Compromise Approach to Group Formation

In this research, a combined classification and flow analysis approach is employed for determining component families and machine groups. First a classification and coding system is used to separate the component range into rough groups, then a material flow analysis technique further divides each rough group into component and machine groupings of practical sizes. Since detailed analysis is not required at the classification stage, a very simple coding system can be used with minimum implementation effort and cost. Once these rough groups are established, the situation is reduced to a stage which can be analysed by a material flow method with maximum efficiency. In this way the two methods compensate for each other's weakness.

A non-manual coding system has been designed for a preliminary sorting of components, and this is described in the next section. Also a Direct Clustering Algorithm has been developed for finding groups and families based on a material flow analysis approach, and will be described in the following chapter.

### 3.5 A Non-Manual Coding System for Rough Grouping

Most classification and coding systems have complicated structures and sophisticated manuals are usually required by the person who has to code a component or to interpret a given code. A considerable amount of time and money often has to be spent on the training of personnel and the implementation of systems.

For the purpose of this exercise, however, the code is not intended as shape codification for design retrieval or product rationalisation. It is to be used for roughly grouping the components, preceding an application of a material flow analysis technique. Therefore the coding system can be a very simple one without any design or operations details included. It is intended that such a coding system will not need a manual and can be quite adequate for the purpose. It must be simple to learn and to use and be easily remembered by heart.

Although the code itself is simple, it has been decided that the code should indicate the complexity of components. Figure 3.4 shows the basic rules for this complexity code.

The code comprises five digits, all numerical, in order to facilitate processing by computer. A combination of hierachical and fixed significance is used. The first digit separates the components into two main classes, rotational and non-rotational. It also gives the general proportions of the component. The other four digits are then specific to each class. Each digit has a fixed significance which represents the number of one kind of variation existing in the component, so that a more complex component will have a larger code number. If any variation exceeds nine in number, the number nine will be used, indicating maximum complexity in that variation.

For the rotational code, it has been found advantageous to consider each component to be made up of a number of cylinders. The complexity of the component increases with the number of cylinders together with the variations between them. The second digit of the code represents the number of non-axial machinings on the component. The third digit represents the number of axial machinings, other than turning and facing. Finally, the fourth and the fifth digits indicate the number of variations in the external and internal diameters, respectively.

For the second digit, any non-axial machining such as plane surfaces, gear teeth, splines and drilled holes not on the rotational axis are included. For the third digit, any machined features which have the same rotational axis as the component axis are counted. These include, for example, internal and external threads and tapers, and cylindrical surfaces which require grinding. The fourth and fifth digits denote only the major diameters of the component; features like chamfers, radii, centres and undercuts are not considered. However, features which are machined from major diameters, such as threaded surfaces, must be included. A typical rotational component and its complexity code is shown in figure 3.5.

The non-rotational code has a similar structure, but in this case, each component is considered to be made up of rectangular blocks. Thus the complexity of the component increases with the number of blocks, together with the machined features. The second digit of the code represents the number of special non-rotational machinings, such as grooves, slots or broached holes. The third digit denotes the number of rotational machinings on the component; these include drilled holes, reamed holes and tapped holes. The fourth digit indicates the number of rectangular blocks which make up the component. Finally, the fifth digit shows the number of main bores and irregular cavities in the component. Figure 3.6 shows an example of a non-rotational component with its complexity code.

The complexity code is simple and easy to learn. After spending only a short time reading the instructions, one can understand and remember the basic rules, and use the code without referring to any manual. This five-digit code can be added to every component drawing and form part of the component specification. It will provide a reasonable data base for comparing similar components. Moreover, it is likely that anyone involved in the company could form an opinion as to any component's features from its code. This could be of additional benefit, in that there may well be better communication between different departments, and between management and engineers.

In the formation of component families, the complexity code of all components are sorted in numerical order by computer, and the components will be grouped according to their classes and complexity, this will be discussed later.

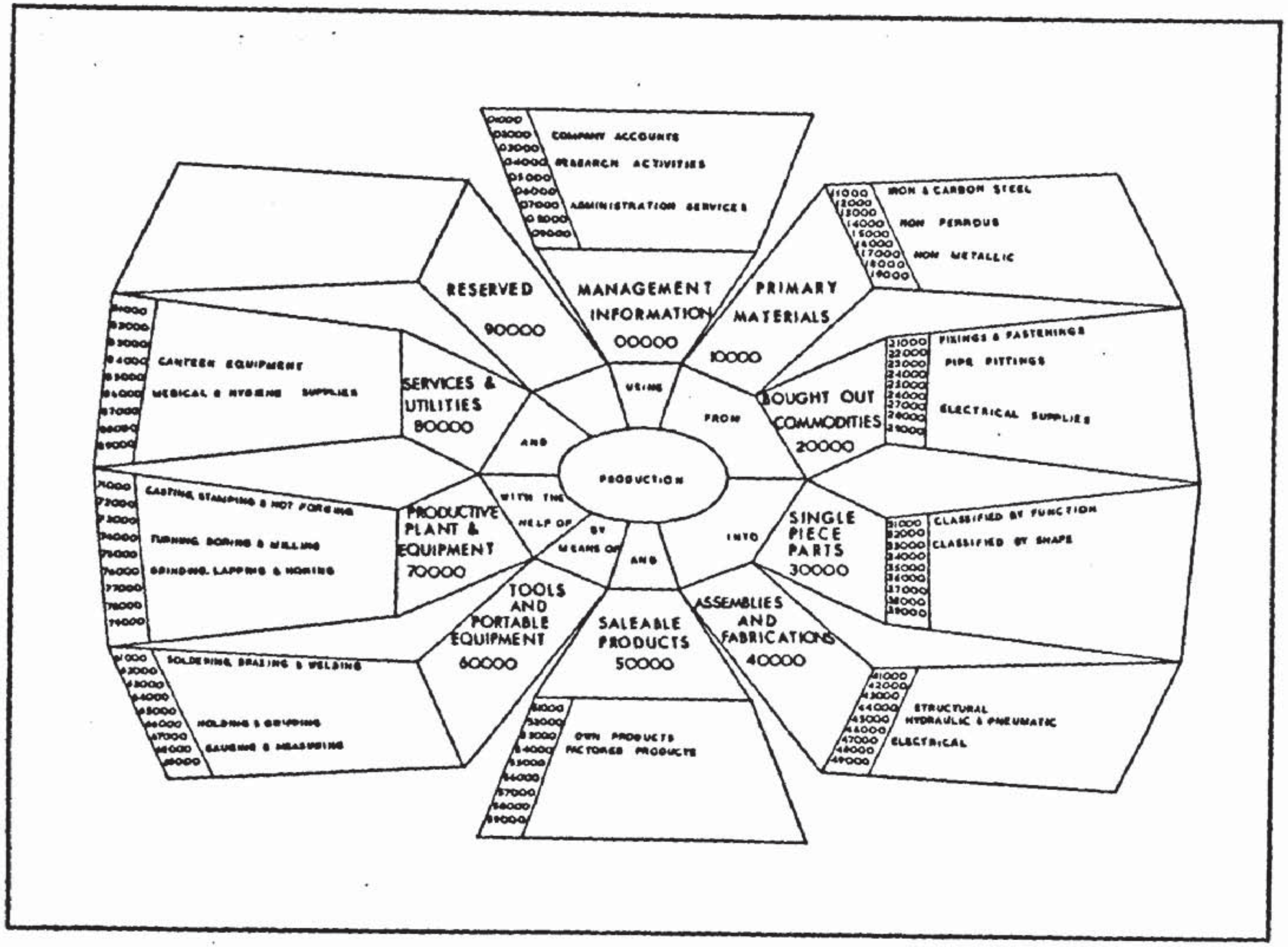


Figure 3.1 Basic Structure of the Brisch Coding System

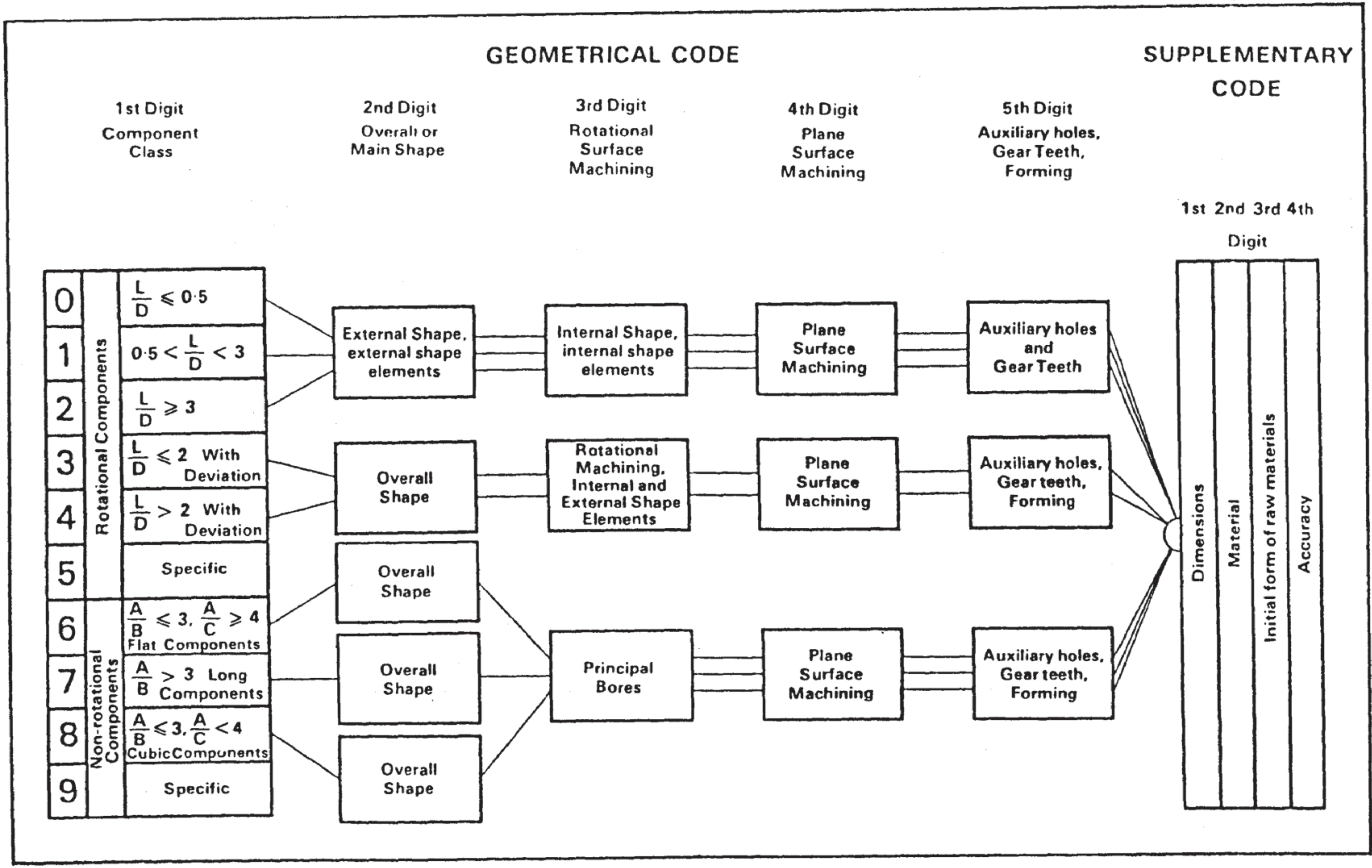


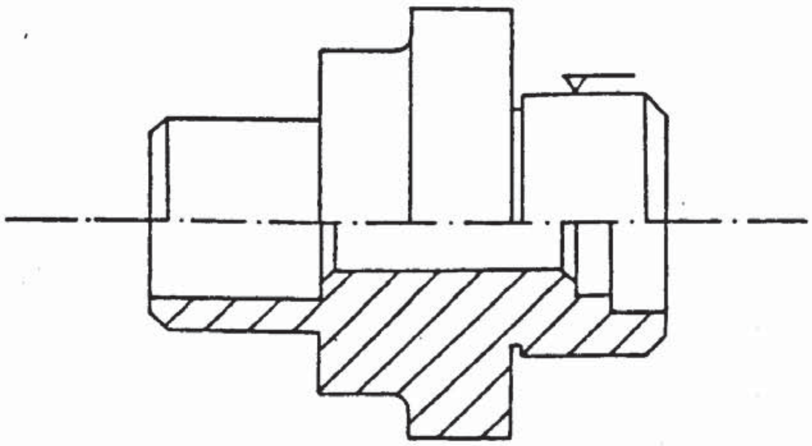
Figure 3.2 Basic Structure of the Opitz Coding System

| *Name of coding system* | *Country of origin* |
|---|---|
| 1. OPITZ | W. Germany |
| 2. BRISCH | UK |
| 3. PERA | UK |
| 4. VUOSO | Czechoslovakia |
| 5. MITROFANOV | Russia |
| 6. WILLIAMSON | UK |
| 7. VUSTE | Czechoslovakia |
| 8. KC—1 | Japan |
| 9. TOYODA | Japan |
| 10. PGM | Sweden |
| 11. NITTMASH | Russia |
| 12. PITTLER | W. Germany |
| 13. GILDEIMEISTER | W. Germany |
| 14. STUTTGART | W. Germany |
| 15. ZAFO | W. Germany |
| 16. COPIC—BRISCH | W. Germany |
| 17. IAMA | Yugoslavia |
| 18. DDR STANDARD | E. Germany |
| 19. HANIMAN GREEN | UK |
| 20. VPTI | Russia |
| 21. KOLAC | Czechoslovakia |
| 22. STOCKMAN | W. Germany |
| 23. CVM—TNO | Holland |
| 24. WERNER and PFLEIDER | Germany |
| 25. PERA SPECIALIST TOOL CODE | UK |
| 26. LITMO | Russia |
| 27. LANGE ROSSBERT | W. Germany |
| 28. FOUNDRY CODE | Russia |
| 29. IVANOV | Russia |
| 30. BRUKHANOV and REBELSKI | W. Germany |
| 31. KUKLEV | Russia |
| 32. ANDREEVA | Russia |
| 33. CZIKEL and ZEBISCH | W. Germany |
| 34. PACYNA | W. Germany |
| 35. GUREVICH | Russia |
| 36. WALTER | E. Germany |
| 37. AUERSWALD | E. Germany |
| 38. PUSCH MAN | W. Germany |
| 39. MALEK | Czechoslovakia |
| 40. SALFORD | UK |
| 41. ROMANOUSKII | Russia |
| 42. KOBLOV | Russia |
| 43. LABUTIN | Russia |
| 44. VOSTRODOUSKII | Russia |
| 45. GRIGOR 'EV | Russia |
| 46. ODINTSOVA | Russia |

Figure 3.3 Classification and Coding Systems (after Burbidge)

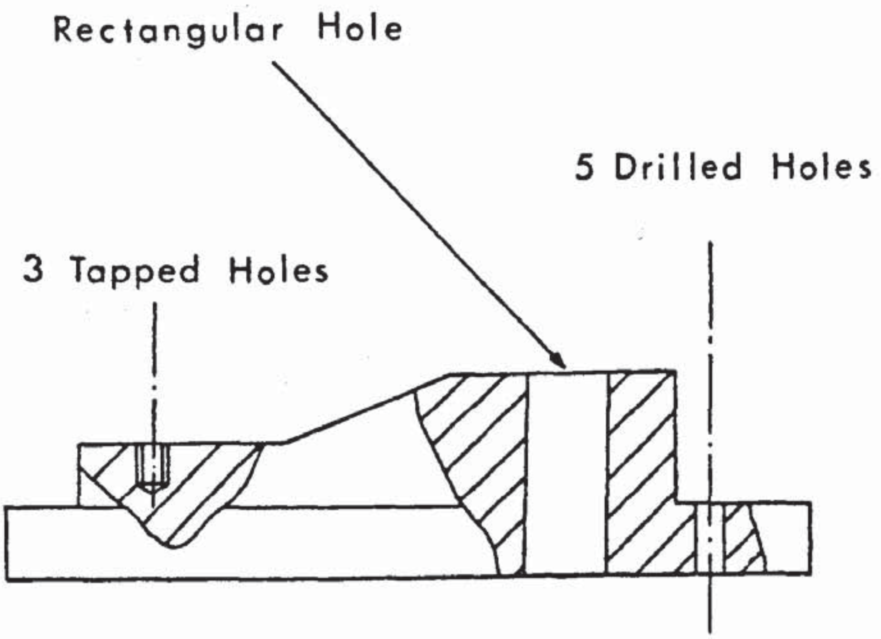
| | | | FIRST DIGIT | | SECOND DIGIT | THIRD DIGIT | FOURTH DIGIT | FIFTH DIGIT |
|---|---|---|---|---|---|---|---|---|
| | | | Overall Sizes and Proportions | | Auxilliary Machining Features | | Principal Machining Features | |
| 1 | Rotational components | $0 < D \leqslant 60$ | $L/D \leqslant 1$ | 0 - 9 | Number of non-axial machinings, e.g. plane surfaces, gear teeth, splines | Number of axial machinings, e.g. threads, tapers, ground cylindrical surfaces | Number of variations in external diameters | Number of variations in internal diameters |
| 2 | | | $1 < L/D \leqslant 6$ | | | | | |
| 3 | | | $L/D > 6$ | | | | | |
| 4 | | $D > 60$ | $L/D \leqslant 1$ | | | | | |
| 5 | | | $1 < L/D \leqslant 4$ | | | | | |
| 6 | | | $L/D > 4$ | | | | | |
| 7 | Non-rotational components | | $A/B \leqslant 3$ $A/C \geqslant 4$<br>Flat components | 0 - 9 | Number of special non-rotational machinings, e.g. grooves, slots, broached holes | Number of rotational machinings, e.g. drilled holes, reamed holes, tapped holes | Number of rectangular blocks | Number of main bores and irregular cavities |
| 8 | | | $A/B > 3$<br>Long components | | | | | |
| 9 | | | $A/B \leqslant 3$ $A/C < 4$<br>Cubic components | | | | | |
| 0 | Specific | | | e.g. cutting tools, bought out parts etc. | | | | |

Figure 3.4 Basic Rules for the Complexity Coding System



| | |
|---|---|
| SMALL SHORT COMPONENT | 2 |
| NO NON-AXIAL MACHINING | 0 |
| ONE GROUND SURFACE | 1 |
| FOUR EXTERNAL DIAMETERS | 4 |
| FOUR INTERNAL DIAMETERS | 4 |

Figure 3.5 Rotational Component with Complexity Code 20144



| | |
|---|---|
| FLAT COMPONENT | 7 |
| NO SPECIAL MACHINING | 0 |
| EIGHT HOLES | 8 |
| THREE RECTANGULAR BLOCKS | 3 |
| ONE RECTANGULAR HOLE | 1 |

Figure 3.6 Non-Rotational Component with Complexity Code 70831

## CHAPTER FOUR

## 4. DIRECT CLUSTERING ALGORITHM FOR GROUP FORMATION

### 4.1 Introduction

Material flow analysis techniques have been recognised as an alternative to the classification and coding approach to implementing Group Technology. All of the variants of material flow analysis are based on the assumptions that the majority of components and machines in a factory already belong to clearly defined families and groups, and that these groups and families can be identified by a progressive analysis of the information contained in the route cards and the plant list. These methods follow generally similar steps, the differences lie in the procedures used for the formation of component and machine groupings. This primary stage of group formation is probably the most difficult and critical in the application of material flow analysis techniques.

Burbidge (44) proposed that the group formation problem could be solved by a process called Group Analysis. The basic steps included the construction of a machine/component matrix constituting the data required, and the derivation of machine groups and component families by a quantitative analysis of this data. This approach is feasible, provided it is carefully planned and the data is properly prepared.

Ever since the Group Analysis concept was introduced, there has been one major problem. This is the lack of a general procedure to convert a given machine/component matrix into a clustered form from which independent groups can be identified. The method must be suitable for computer applications since manual methods can be tedious and are not practical for the analysis of the large amount of data obtainable in realistic situations. In his book "The Introduction of Group Technology" (62), Burbidge stated:

"It is comparatively simple to find the groups and families by eye with a small sample. The mental process used combined pattern recognitions, the application of production know how and intuition. It has been proved to be surprisingly difficult to find a method suitable for the computer which will obtain the same results".

A technique called Direct Clustering Algorithm has been developed by the author for solving this problem (61), and will be described in the following sections. First the problem and some earlier approaches to solving it are briefly reviewed.

## 4.2 The Group Formation Problem in Group Analysis

The problem can be summarised as the need to divide the component range of a factory into families, and the machines into groups, in such a way that each group can be specialised in producing one family. The stage preceding group formation involves the formation of a machine/component matrix showing which workstations or machines are needed for the production of each component. The preparation of this matrix and the practical problems that may have to be solved are dealt with in

Chapter six. Here, only the problem of forming groups is discussed and therefore it is assumed that as a starting point a machine/component matrix has already been formed.

A typical machine/component matrix is shown in figure 4.1.a, the rows being labelled with component numbers and the columns with machine numbers (this is contrary to the conventional way of labelling a machine/component matrix. Because the number of components in a factory is usually greater, and more likely to vary than the number of machines, storing this information in rows makes for easier computation). In the matrix, an entry of "X" in cell (I, J) means that component "I" requires processing on machine "J" and a blank entry means that it does not.

In figure 4.1.a, the original form of the machine/component matrix, no particular pattern of grouping can be seen. However, after various exchanges of the relative positions of rows and columns, the same matrix can be converted into a clustered form as shown in figure 4.1.b. In this form the original matrix entries are unaltered but distinct machine component groupings are created along the diagonal of the matrix as a result of the rearrangements. Now it can be seen clearly that components number 2, 3 and 5 are to be processed in the group consisting of machines number 1, 2, 4 and 6, and that components number 1 and 4 are to be processed in the second group consisting of machines number 3, 5 and 7. Hence the problem of group formation is solved.

For a small machine/component matrix, it is comparatively easy to determine the appropriate row and column rearrangements by visual inspection. The difficulty is to find a systematic analytical method which would convert any original matrix into a clustered form to deal with a real size problem.

## 4.3 Some Earlier Contributions to Solving the Problem

Burbidge suggested a punched card sorting approach for solving the problem and this was later adopted by Gallagher et al (63) in an application in the plastic moulding industry. However, it was found that the technique "worked in so far as it created a detailed chart of flow sequences, but it failed to provide a suitable means of establishing groups from this data". This difficulty was recognised by Burbidge who later found a technique of Nuclear Synthesis (48). In this method, the low usage machines are identified as key machines and are made the nuclei of groups to which other machines required for the same components may be added. Larger sized groups can be formed by appropriately combining these nuclear groups. A computer programme was written to use this method (64), unfortunately the programme is not readily obtainable and its feasibility is yet to be examined.

Another approach was described by El-Essawy as Component Flow Analysis (45). This method uses computer assistance in identifying similar manufacturing sequences. The component families and machine groups are formed by a subjective process, which is carried out manually since the use of a computerised procedure has been proved to be "unjustifiably sophisticated". The method has been used successfully in several companies, but is available only on a consultancy basis.

McAulley proposed the use of a similarity coefficient and single linkage cluster analysis for solving the problem (65). This is based on the Numerical Taxonomic Algorithm as published by Ross (66). The similarity coefficient for any machine pair is computed and the result represented pictorially by a dendrogram at an appropriate similarity level. A secondary process of component allocation to machine groups is then required once the groups are formed. This approach has been adopted by several other researchers. Carrie (67) used it as one of several facilities for determining the extent to which the work entailed in the design of a production system may be done by computer.

Other computer simulation methods developed for group formation were due to Crookall and McCromick (68, 69). The former used known data to simulate group manufacture condition by a Monte Carlo method. The latter optimised the bond energy between adjoining row and column elements in a matrix to form groups.

All of the above techniques used the machine/component matrix as a means of recording data only, the matrix was not involved with the actual analysis. Recently, one method has been designed to generate groupings directly from a machine/component matrix. This is the Rank Order Clustering algorithm developed by King (70). It requires the pattern of cell entries in the rows and columns of the matrix to be read as binary words. The corresponding decimal equivalences of these words are then used as the basis for the ranking of the rows and columns.

The algorithm rearranges the rows and columns in an iterative manner and produces a matrix with diagonalised groupings. The main difficulty with this method is that the calculation of decimal equivalences of the binary words becomes very tedious when the matrix is large. This was recognised by King who later suggested a "pairwise" word comparison process in place of the long computation (71). It is claimed that the major advantage of the Rank Order Clustering algorithm is its ability to deal easily with the problems of exceptional elements and bottleneck machines.

## 4.4 The Direct Clustering Algorithm (DCA)

The Direct Clustering Algorithm is a new technique which provides a simple and effective way of clustering data directly from any given machine/component matrix by changing the sequence in which components and machines are listed on the matrix. It does not rely on intuition for its implementation, a systematic procedure is used to determine the required row and column rearrangements.

For the moment, it is sufficient to describe those cells of a machine/component matrix entered with "X" as the positive cells and those with blank entries as the negative cells. The algorithm then goes through the matrix sequentially, moving the rows with the "left-most" positive cells to the top and the columns with the "top-most" positive cells to the left of the matrix. In repeat trips the positive cells will be squashed towards the diagonal of the matrix and a clustered pattern will eventually be formed, extending from the top left corner of the matrix. The basic rule is that each component or machine number must be moved togther with its respective row or column entries during matrix transformation as if the cells are linked together by an imaginary rod. The procedures of the algorithm are described in the following steps.

(1) Count the number of positive cell entries in each column and row and rearrange the matrix with rows in ascending and columns in descending orders of this number.

(2) Starting with the first column, transfer all the rows which have positive cells in this column to the top of the matrix in the order of their appearance. Repeat this process with the other columns until all the rows are reallocated.

(3) Compare this matrix with the one immediately preceding the transformation. Stop the iteration if the two matrices are the same, otherwise continue with the transformation of the columns.

(4) Starting with the first row, transfer all the columns which have positive cells in this row to the left of the matrix in the order of their appearance. Repeat this process with the other rows until all the columns are reallocated.

(5) Compare this matrix with the one immediately preceding the transformation. Stop the iteration if the two matrices are the same, otherwise go back to (2) and continue with the transformation of the rows.

The method is best illustrated with an example problem. Consider a machine component matrix as shown in figure 4.2.a. The number of positive cell entries in each column or row is calculated and listed at the end of the respective column or row. Figure 4.2.b shows the same matrix after the initial changes, the columns and rows are respectively ranked in order of decreasing and increasing values of the number of positive cell entries. This becomes the starting matrix for the iterative algorithm.

The first column to be considered is that consisting of machine number 14. The rows which have positive entries in this column are components number 9, 4, 3 and 6. These are moved to the top of the new matrix in the same order as they appear in the current matrix. Next the second column is considered but nothing happens since all the positive entries in this column have already been allocated. The algorithm applies itself to the third column consisting of machine number 15 and groups together components number 8, 5 and 2. The other rows are rearranged in a similar manner and the resulting matrix after the first row transformation is shown in figure 4.2.c.

Now the algorithm is repeated on the matrix of figure 4.2.c, but this time the columns are rearranged instead of the rows. Figure 4.2.d shows the matrix after the first column transformation. Clustered machine component groupings can be identified along the diagonal of this matrix. Applying the iterative algorithm again will not change the pattern of this matrix, so figure 4.2.d is the finalised form.

## 4.5 Complicated Problems

If mutually independent component and machine groupings exist naturally, the Direct Clustering Algorithm will converge in very few iterations and the necessary groups will be formed quickly. However, in realistic problems, mutually independent groups seldom exist. There may be machines which are required by many components, also there may be overlapping machine component groups due to exceptional components with odd process routes. In such cases, the groupings formed will be very large, more scattered, and not mutually independent.

For example, a machine/component matrix is shown in figure 4.3.a. The Direct Clustering Algorithm will give a finalised pattern as shown in figure 4.3.b, and this cannot be changed any further. Unfortunately, this matrix does not show a desirable solution since the first machine group formed is too large and scattered. In order to let the algorithm continue, the column entries causing obstruction must be temporarily deleted. For this purpose, assumptions are made that one machine type can exist in several groups, and that the columns which are deleted consist of machine types which are readily available to all groups at all times. These machines, allocated to more than one machine group, are termed multiple machines.

Referring to figure 4.3.b, the column which prevents the first family grouping to be further divided is the one containing machine number 6. Thus, to improve the solution, machine 6 has to become a multiple machine. The positive entries in this column are temporarily overwritten by the plus symbol "+" which will be considered as equivalent to a negative entry in the computation. Applying the algorithm to this modified matrix, another finalised pattern, shown in figure 4.3.c, is obtained. This matrix shows that three machine groups have been generated, but of these, the first two are not mutually independent due to the overlap of requirements on machines number 7 and 11. One component from the first family and two components from the second family require processing on machine 7, and in addition one component from the first family and three components from the second family require processing on machine 11. In such cases where obstruction is caused by only a few cell entries, it would be uneconomical to introduce multiple machines. The extra pairings must be considered as exceptional and should be excluded from the grouping process.

An examination of figure 4.3.c shows that the singleton entries which cause obstructions in columns of machine 7 and 11 are cells (9, 7) and (8, 11) respectively. In order to improve the solution further, these exceptional cell entries are overwritten by the asterisk symbol "*", and again this will be considered as equivalent to a negative entry during computation. Figure 4.3.d shows the same machine/component matrix, with the multiple machine entries and the exceptional cell entries marked with appropriate symbols, and with the initial arrangement in decreasing column sums and increasing row sums.

Applying the DCA to figure 4.3.d, the newest version of the matrix, results in the generation of the finalised pattern shown in figure 4.3.e. Now this matrix shows an acceptable solution because mutually independent machine groups and component families are readily observed. The multiple machine entries are shown on the right of the matrix and these can be reinstated into the appropriate groupings to form an ultimate solution as shown in figure 4.3.f.

Problems similar to this example in which some machines are required by many of the components are not uncommon in industry, and this procedure provides the flexibility to resolve the structures and sizes of the groups. The multiple machines are identified from the resulting matrix after the first run of the algorithm, then the exceptional entries are identified. This progressive procedure provides an easy way of detecting the bottleneck machines and odd process routes. Additional machines can be considered for the cases of overlap in component requirements between machine groups, and the exceptional pairings can be eliminated by rerouting or redesigning the components.

## 4.6 DCA and the Computer

The Direct Clustering Algorithm can work with any starting form of machine/component matrix. The procedure is iterative and the ultimate result will be the same. The algorithm can be executed manually for smaller matrices, equally, it is readily computerised to solve all the practical difficulties of data analysis for large matrices. A computer programme has been written for this algorithm (see Appendix IA) and has been successfully used in solving some hypothetical problems as well as in an industrial application. As illustrated by the example in the last section, the DCA method uses an interactive approach which allows the parameters to be altered at intervals during computation, taking into consideration any practical restrictions which may exist. This offers much greater flexibility in deciding between possible options and is therefore preferable to a completely mechanistic process.

A common criticism of the various methods developed for group formation is that they have been applied to matrices only with relatively small number of elements. In realistic situations a large amount of data will be involved and it is these problems which the group forming algorithms will have to resolve. With the aid of a computer, the DCA method can effectively deal with this type of problem.

The practical steps involved in applying the algorithm are as follows. First, form a machine/component matrix with the whole range of machines and only a fraction of the whole component range; the size of this matrix will be dependent on the capacity of the computer. Determine the machine groups and component families from this matrix by applying the Direct Clustering Algorithm. Each component family formed is then renamed and treated as a "new part" which has a production route consisting of the machines included in the respective machine group. Repeat the process with the other components until the whole range is analysed. The result will be a list of "new parts", each represents a number of components, and each requires processing on the range of machines. Using the original list of machines and the "new parts" as data and applying the DCA method again, "new part" families and machine groups will be formed. The original components can then be reinstated into the "new part" families to obtain the final matrix.

With the computer programme, the Direct Clustering Algorithm can be applied repeatedly to a set of data, and the iterative process can be finished in a reasonably short time. Theoretically an unlimited number of components can be analysed, but the number of machines must be limited by the maximum size of the matrix.

## 4.7 Applications of the Direct Clustering Algorithm

The Direct Clustering Algorithm is a technique for grouping data in any two dimensional matrix. Although the method was initially developed for forming machine groups and component families, it is not necessarily confined to such applications. A matrix can be used for recording information between any two classes of objects where one class is related to the other, and the DCA method can be used for finding groups among objects which have similar or common characteristics. This will be shown later to be useful in many parts of a production system.

### 4.7.1 DCA for Component Families and Machine Groups Formation

The first and obvious application of the Direct Clustering

Algorithm is in the formation of component families and machine groups for cellular manufacture. It can be illustrated by solving a problem presented by Burbidge which was also used by King for illustrating the application of his Rank Order Clustering approach (71).

The initial machine/component matrix consisted of 16 machines and 43 components as shown in figure 4.4.a. In this matrix, rows are labelled with machine numbers and columns with component numbers, this will not create any problem since the computer programme can cope with either convention. After the first run, the initial matrix is converted to the pattern shown in figure 4.4.b. This is not a desirable solution since no mutually independent groups are observed. It is apparent that the machines number 6 and 8 are heavily demanded by a large number of components and cause obstructions. To progress further, they are made multiple machines and the positive entries in these two rows are overwritten by the "+" symbols.

The modified matrix is analysed again, by the DCA, and another finalised pattern shown in figure 4.4.c is obtained. Here, it can be seen that clustered groups begin to form, though not all of them are mutually independent; also it is evident that there are overlapping requirements of machines by components number 2, 7 and 9. The exceptional cell entries, identified as (14, 2), (16, 7) and (11, 9) (encircled in the figure 4.4.c) are overwritten by the"*" symbol before the matrix is used for the next iteration. Applying the Direct Clustering Algorithm to this latest edition of the matrix generates a final pattern as shown in figure 4.4.d. Five machine component groupings can be clearly and independently distinguished. The multiple machine entries are shown at the bottom of the matrix and are easily identified with the appropriate groups formed. The ultimate solution matrix with mutually exclusive groups, can be formed simply by reinstating the positive entries of the multiple machines to the clustered groups as shown in figure 4.4.e.

One distinctive facility provided by the Direct Clustering Algorithm is the clear representation of the bottlenecks or exceptional entries which allows extra flexibilities in the final design of the actual groupings. Referring to the solution matrix in figure 4.4.d, there can be three ways of grouping the machines depending on the availability of resources:-

Case 1 - As many additional machines as required are installed (in this example, 4 of each machines 6 and 8 are required). The machine groups formed will be mutually exclusive, as shown in figure 4.4.e. Each component family can be fully processed within one machine group only, provided that all the exceptional machine component pairings can be eliminated by re-routing or re-designing the components. This is the ideal cellular manufacture situation where there is no inter-cell material flow. The flow of components will be between each machine group and between receiving and delivery points only.

Case 2 - Less additional machines than required (say, 2 of each type) are made available, and only some of the exceptional components can be re-routed. This may be necessary because of a lack of resources or other practical restricting factors such as resistance to change from the shopfloor. In this case the solution is to allocate the multiple machines to the most demanding machine groups. This can be determined by considering the number of "+" entries associated with each machine group and the batch quantities of the respective components. For example, in figure 4.4.d, the first and third machine groups have the highest number of "+"s (5 and 6 respectively) associated with machine 6. Also the second and third machine groups have the highest number of "+"s (5 and 8 respectively) associated with machine 8. Therefore one machine 6 should be allocated to each of groups 1 and 3, and one machine 8 should be allocated to each of group 2 and group 3 accordingly.

Case 3 - No additional machine is available and no exceptional component route can be changed. This is not uncommon in industry for there is usually resistance to substantial changes, especially when new investments are involved. The solution is to allocate the available machines to the most demanding machine groups as in case 2, i.e. the only machines 6 and 8 should be allocated to machine group 3. Alternatively, the bottleneck machines can form an independent group which will be visited by components from the other groups, i.e. machine 6 and machine 8 together become the sixth machine group.

In both cases 2 and 3, there would be some components flowing between cells but the greater part of the material flow would be restricted to within one group. The inter-cell flow can be determined by considering the solution matrix. For example, it can be seen in figure 4.4.d that component 2 will require processing in machine groups 1, 4 and 3, if machine 6 and 8 are available in group 3 only. Thus the flow of material among these three groups can be determined from the batch quantity of component 2. The inter-cell flow value will be the essential data required for the layout planning of the machine groups, as will be discussed in the next chapter.

Figure 4.5 shows Burbidge's trial and error solution and figure 4.6 shows King's ROC solution to the same problem. A comparison of figure 4.4.e with these two alternative solutions shows that the number and structure of the machine component groups, and also the exceptional elements, are in fact identical in Burbidge's manual solution and in the solution derived from the Direct Clustering Algorithm. However, King's solution shows some differences in the number of machine component groups (4 compared with 5) and in the exceptional elements (2 instead of 3 and different elements). In all three cases, 4 machine 8, and 4 machine 6 are required in order to achieve a solution with mutually exclusive groups.

When the DCA solution is compared with the ROC solution, it is observed that the groups in the former case are more dense, and they will mean a higher machine utilization within the groups. The Direct Clustering Algorithm effectively deals with the problems of exceptional elements and bottleneck machines with a progressive procedure. It also regulates the initial matrix by pre-arranging the rows and columns before iteration, and can work with any starting format of machine/component matrix to obtain the same result. In these aspects, the DCA is superior to the ROC algorithm as the basis of designing groups for cellular manufacture.

### 4.7.2 DCA for Tooling Families Formation

The production families allocated to each machine group can usually be broken down into a number of smaller families requiring similar toolings and set-ups. By establishing these tooling families and planning new jobs so that they can be produced by the existing tooling, it is possible to reduce both setting up costs and the investment in tooling. These tooling families can again be found by analysing the data in the route cards using the Direct Clustering Algorithm approach.

All components in a tooling family are likely to utilize the same material since a change in material generally involves changes in cutting lubricants, tooling and set-ups. Therefore the first step is to divide the component family allocated to a machine group into sub-families by material. The number of parts processed in one group is relatively small, and so these sub-families can be found without difficulty by listing the material of each component and sorting manually.

For most processes the second factor likely to earmark a component for its tooling family is the method of holding the work on machine. On lathes, for example, figure 4.7 shows the possible workholding methods. It is an easy matter to number the workholding methods, including the jigs and fixtures used in a machine group and use this as a basis to establish the tooling families. After this, a matrix is prepared showing which workholding methods or fixtures are required for the processing of each component in the group. Then this matrix is analysed by a similar procedure to that in the component families formation using the DCA, and smaller families of components requiring similar workholding methods are formed.

In many cases the first two stages of analysis coupled with a final sorting by eye will be all that is needed for tooling family formation. However, when the families formed are still too large, it will be necessary to further break them down by considering their tooling. This can be done by applying the DCA technique to a matrix listing the tools used for the processing of each component belonging to a sub-family found in the first two stages.

### 4.7.3 Other Applications of the DCA Technique

Another application of the group formation method using DCA is for determining similarity characteristics among a group of components when no classification is suitable for coding the attributes relevant to the objective of analysis. In this case the DCA technique can serve the purpose of a universal classification and coding system.

First a data field in matrix form is used for displaying the variables and features of the components. The positive entries in the matrix will indicate which attributes are found in which components. By applying the clustering algorithm, the components with similar attributes will be grouped together and any exceptions will be determined. This approach to classification is highly flexible and easy to operate.

This concept of universal classification can be applied, for example, to the identification of product groups which comprise similar components. Products are usually made of assemblies and sub-assemblies. Therefore a product/component matrix can be created, with the positive entries indicating which components are used in which products. Then the product and component families can be found by the DCA approach. Thus one product, no matter how complicated, can be considered as consisting of several component sub-groups rather than hundreds of single components. Production planning and control can be carried out in terms of component groups and the problem can be simplified.

In general, the combination of a data field matrix and the Direct Clustering Algorithm may provide an effective solution to many management requirements for information relevant to production functions.

| | M/C NO. | | | | | | |
|---|---|---|---|---|---|---|---|
| COMP NO. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1 | | | X | | X | | X |
| 2 | X | X | | X | | X | |
| 3 | | X | | X | | X | |
| 4 | | | X | | X | | X |
| 5 | X | | | X | | X | |

Figure 4.1.a Typical Machine/Component Matrix

| | M/C NO. | | | | | | |
|---|---|---|---|---|---|---|---|
| COMP NO. | 1 | 2 | 4 | 6 | 3 | 5 | 7 |
| 2 | X | X | X | X | | | |
| 5 | X | | X | X | | | |
| 3 | | X | X | X | | | |
| 1 | | | | | X | X | X |
| 4 | | | | | X | X | X |

Figure 4.1.b Same Matrix in Clustered Form

M/C NO.

| COMP NO. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | X | | | | | | | | X | X | X | | | | 4 |
| 2 | | | X | | X | | | X | | | | | X | | X | 5 |
| 3 | X | | | | | X | | | X | | | | | X | | 4 |
| 4 | X | | | X | | | | | X | | | | | X | | 4 |
| 5 | | | X | | X | | | X | | | | | X | | X | 5 |
| 6 | X | | | X | | X | | | X | | | | | X | | 5 |
| 7 | | X | | | | | X | | | X | X | X | | | | 5 |
| 8 | | | X | | X | | | X | | | | | X | | X | 5 |
| 9 | | | | X | | X | | | X | | | | | X | | 4 |
| 10 | | X | | | | | X | | | X | X | X | | | | 5 |
| | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 4 | 3 | 3 | 3 | 3 | 4 | 4 | |

Figure 4.2.a Example Machine/Component Matrix

M/C NO.

| COMP NO. | 14 | 9 | 15 | 13 | 12 | 11 | 10 | 8 | 6 | 5 | 4 | 3 | 2 | 1 | 7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | X | X | | | | | | | X | | X | | | | | 4 |
| 4 | X | X | | | | | | | | | X | | | X | | 4 |
| 3 | X | X | | | | | | | X | | | | | X | | 4 |
| 1 | | | | | X | X | X | | | | | | X | | | 4 |
| 10 | | | | | X | X | X | | | | | | X | | X | 5 |
| 8 | | | X | X | | | | X | | X | | X | | | | 5 |
| 7 | | | | | X | X | X | | | | | | X | | X | 5 |
| 6 | X | X | | | | | | | X | | X | | | X | | 5 |
| 5 | | | X | X | | | | X | | X | | X | | | | 5 |
| 2 | | | X | X | | | | X | | X | | X | | | | 5 |
| | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | |

Figure 4.2.b Matrix After Initial Arrangements

| | M/C NO. | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COMP NO. | 14 | 9 | 15 | 13 | 12 | 11 | 10 | 8 | 6 | 5 | 4 | 3 | 2 | 1 | 7 |
| 9 | X | X | | | | | | | X | | X | | | | |
| 4 | X | X | | | | | | | | | X | | | X | |
| 3 | X | X | | | | | | | X | | | | | X | |
| 6 | X | X | | | | | | | X | | X | | | X | |
| 8 | | | X | X | | | | X | | X | | X | | | |
| 5 | | | X | X | | | | X | | X | | X | | | |
| 2 | | | X | X | | | | X | | X | | X | | | |
| 1 | | | | | X | X | X | | | | | | X | | |
| 10 | | | | | X | X | X | | | | | | X | | X |
| 7 | | | | | X | X | X | | | | | | X | | X |

Figure 4.2.c Matrix After Row Transformation

| | M/C NO. | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COMP NO. | 14 | 9 | 6 | 4 | 1 | 15 | 13 | 8 | 5 | 3 | 12 | 11 | 10 | 2 | 7 |
| 9 | X | X | X | X | | | | | | | | | | | |
| 4 | X | X | | X | X | | | | | | | | | | |
| 3 | X | X | X | | X | | | | | | | | | | |
| 6 | X | X | X | X | X | | | | | | | | | | |
| 8 | | | | | | X | X | X | X | X | | | | | |
| 5 | | | | | | X | X | X | X | X | | | | | |
| 2 | | | | | | X | X | X | X | X | | | | | |
| 1 | | | | | | | | | | | X | X | X | X | |
| 10 | | | | | | | | | | | X | X | X | X | X |
| 7 | | | | | | | | | | | X | X | X | X | X |

Figure 4.2.d Matrix After Column Transformation

| | M/C NO. | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COMP NO. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 | | X | | | | X | X | | | | X | X | | | |
| 2 | | | | | X | | | | X | X | | | X | | X |
| 3 | X | | X | | | X | | | | | | | | X | |
| 4 | X | | X | X | | X | | | | | | | | X | |
| 5 | | | | | | | | X | X | X | | | X | | X |
| 6 | | X | | | | X | X | | | | X | X | | | |
| 7 | | X | | | | X | | | | | X | X | | | |
| 8 | X | | X | X | | X | | | | | X | | | X | |
| 9 | | | X | X | | X | X | | | | | | | X | |
| 10 | | | | | | | | X | X | X | | | X | | X |

Figure 4.3.a Complex Example Matrix

| | M/C NO. | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COMP NO. | 6 | 12 | 11 | 2 | 14 | 3 | 1 | 7 | 4 | 15 | 13 | 10 | 9 | 8 | 5 |
| 7 | X | X | X | X | | | | | | | | | | | |
| 3 | X | | | | X | X | X | | | | | | | | |
| 9 | X | | | | X | X | | X | X | | | | | | |
| 8 | X | | X | | X | X | X | | X | | | | | | |
| 6 | X | X | X | X | | | | X | | | | | | | |
| 4 | X | | | | X | X | X | | X | | | | | | |
| 1 | X | X | X | X | | | | X | | | | | | | |
| 10 | | | | | | | | | | X | X | X | X | X | |
| 5 | | | | | | | | | | X | X | X | X | X | |
| 2 | | | | | | | | | | X | X | X | X | | X |

Figure 4.3.b Result After First Iteration

| | M/C NO. | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COMP NO. | 14 | 3 | 1 | 7 | 4 | 11 | 12 | 2 | 15 | 13 | 10 | 9 | 8 | 5 | 6 |
| 3 | X | X | X | | | | | | | | | | | | + |
| 9 | X | X | | X | X | | | | | | | | | | + |
| 4 | X | X | X | | X | | | | | | | | | | + |
| 8 | X | X | X | | X | X | | | | | | | | | + |
| 6 | | | | X | | X | X | X | | | | | | | + |
| 1 | | | | X | | X | X | X | | | | | | | + |
| 7 | | | | | | X | X | X | | | | | | | + |
| 10 | | | | | | | | | X | X | X | X | X | | |
| 5 | | | | | | | | | X | X | X | X | X | | |
| 2 | | | | | | | | | X | X | X | X | | X | |

Figure 4.3.c Result After Second Iteration with
Obstruction Removed

| | M/C NO. | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COMP NO. | 14 | 3 | 15 | 13 | 12 | 11 | 10 | 9 | 4 | 2 | 1 | 8 | 7 | 5 | 6 | |
| 9 | X | X | | | | | | | X | | | | * | | + | 3 |
| 7 | | | | | X | X | | | | X | | | | | + | 3 |
| 3 | X | X | | | | | | | | | X | | | | + | 3 |
| 8 | X | X | | | | * | | | X | | X | | | | + | 4 |
| 6 | | | | | X | X | | | | X | | | X | | + | 4 |
| 4 | X | X | | | | | | | X | | X | | | | + | 4 |
| 1 | | | | | X | X | | | | X | | | X | | + | 4 |
| 10 | | | X | X | | | X | X | | | | X | | | | 5 |
| 5 | | | X | X | | | X | X | | | | X | | | | 5 |
| 2 | | | X | X | | | X | X | | | | | | X | | 5 |
| | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 1 | 0 | |

Figure 4.3.d Matrix with Obstructions and Exceptions Marked

| | M/C NO. | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COMP NO. | 14 | 3 | 4 | 1 | 15 | 13 | 10 | 9 | 8 | 5 | 12 | 11 | 2 | 7 | 6 |
| 9 | X | X | X | | | | | | | | | | | * | + |
| 3 | X | X | | X | | | | | | | | | | | + |
| 8 | X | X | X | X | | | | | | | | * | | | + |
| 4 | X | X | X | X | | | | | | | | | | | + |
| 10 | | | | | X | X | X | X | X | | | | | | |
| 5 | | | | | X | X | X | X | X | | | | | | |
| 2 | | | | | X | X | X | X | | X | | | | | |
| 7 | | | | | | | | | | | X | X | X | | + |
| 6 | | | | | | | | | | | X | X | X | X | + |
| 1 | | | | | | | | | | | X | X | X | X | + |

Figure 4.3.e Result After Last Iteration

| | M/C NO. | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COMP NO. | 14 | 3 | 4 | 1 | 6 | 15 | 13 | 10 | 9 | 8 | 5 | 12 | 11 | 2 | 7 | 6 |
| 9 | X | X | X | | + | | | | | | | | | | * | |
| 3 | X | X | | X | + | | | | | | | | | | | |
| 8 | X | X | X | X | + | | | | | | | | * | | | |
| 4 | X | X | X | X | + | | | | | | | | | | | |
| 10 | | | | | | X | X | X | X | X | | | | | | |
| 5 | | | | | | X | X | X | X | X | | | | | | |
| 2 | | | | | | X | X | X | X | | X | | | | | |
| 7 | | | | | | | | | | | | X | X | X | | + |
| 6 | | | | | | | | | | | | X | X | X | X | + |
| 1 | | | | | | | | | | | | X | X | X | X | + |

Figure 4.3.f The Final Matrix

Figure 4.4.a The Machine/Component Matrix Presented by Burbidge

| | COMP. NO. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M/C NO | 37 | 42 | 2 | 38 | 32 | 10 | 7 | 18 | 40 | 28 | 4 | 19 | 43 | 23 | 14 | 1 | 33 | 17 | 13 | 12 | 8 | 39 | 34 | 6 | 24 | 21 | 9 | 41 | 27 | 3 | 31 | 20 | 15 | 11 | 35 | 36 | 5 | 29 | 16 | 25 | 26 | 30 | 22 |
| 1 | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 16 | X | X | X | X | X | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | X | X | X | X | X | X | | | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 9 | X | X | X | X | X | X | | X | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6 | X | X | X | | X | | X | | X | | | X | X | X | X | X | X | X | X | X | X | X | X | X | | | | | | | | | | | | | | | | | | | |
| 8 | X | | X | X | | | | | | X | | X | X | X | | X | | | | X | X | | | | X | X | X | X | X | X | X | X | X | X | | | | | | | | | |
| 14 | | | X | | | | | | | | | | | | | | | X | | | | | | X | | | | | | | | | | | X | | | | | | | | |
| 3 | | | | | | | X | | | | | | | | | | | X | | | | | X | | | | | | | | | | | | X | X | | | | | | | |
| 15 | | | | | | | | | | | | X | X | | X | | X | | | | | | | | | X | | X | | | | | | | | | X | | | | | | |
| 4 | | | | | | | | | | | | X | | X | X | | | | | | | | | | | X | X | | | | | | | | | | X | X | | | | | |
| 5 | | | | | | | | | | | | X | X | X | X | | X | | | | X | | | | | X | X | X | | | | | X | | | | X | X | X | | | | |
| 7 | | | | | | | | | | | | | | | | X | | | X | | | | | | | | | | | | | | | | | | | | | X | | | |
| 10 | | | | | | | | | | | | | | | | X | | | X | X | | X | | | | | | | | | X | | | | | | | | | X | X | | |
| 13 | | | | | | | | | | | | | | | | | | | | | | | | | X | | | | | X | | | | | | | | | | | | | |
| 12 | | | | | | | | | | | | | | | | | | | | | | | | | X | | | | X | | | | | X | | | | | | | | X | X |
| 11 | | | | | | | | | | | | | | | | | | | | | | | | | X | | X | | X | X | | X | | | | | | | | | | X | |

Figure 4.4.b Result After Applying Direct Clustering Algorithm

|  | COMP. NO. |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M/C NO | 42 | 37 | 2 | 38 | 32 | 10 | 18 | 7 | 40 | 28 | 4 | 35 | 17 | 6 | 36 | 34 | 24 | 3 | 30 | 27 | 22 | 11 | 9 | 20 | 21 | 19 | 14 | 5 | 29 | 23 | 43 | 41 | 33 | 16 | 15 | 8 | 25 | 13 | 1 | 39 | 31 | 26 | 12 |
| 1 | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 16 | x | x | x | x | x | x | x | ⓧ |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 2 | x | x | x | x | x | x |  |  | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 9 | x | x | x | x | x | x | x |  | x | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 14 |  |  | ⓧ |  |  |  |  |  |  |  |  | x | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 3 |  |  |  |  |  |  |  | x |  |  |  | x | x |  | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 13 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 12 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | x |  | x | x | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 11 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | x | x | x | x |  |  | ⓧ | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | x |  | x | x | x | x | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 5 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | x |  | x | x | x | x | x | x | x | x | x | x | x | x |  |  |  |  |  |  |  |
| 15 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | x | x | x | x |  |  | x | x | x |  |  |  |  |  |  |  |  |  |  |
| 7 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | x | x | x |  |  |  |  |
| 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | x | x | x | x | x | x | x |
| 8 |  | + | + | + |  |  |  |  |  | + |  |  |  |  |  |  | + | + |  | + |  | + | + | + | + | + |  |  |  | + | + | + |  |  | + | + |  |  | + |  | + |  | + |
| 6 | + | + | + |  | + |  |  | + | + |  |  |  | + | + |  | + |  |  |  |  |  |  |  |  |  | + | + |  |  | + | + |  | + |  |  | + |  | + | + | + |  |  | + |

Figure 4.4.c Result After Second Iteration with Obstructing Rows Deleted

|  | COMP. NO. |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M/C NO | 42 | 37 | 38 | 32 | 10 | 2 | 18 | 40 | 28 | 4 | 24 | 3 | 30 | 27 | 22 | 11 | 20 | 21 | 19 | 14 | 5 | 43 | 41 | 33 | 29 | 23 | 9 | 16 | 15 | 8 | 35 | 17 | 6 | 36 | 34 | 7 | 25 | 13 | 1 | 39 | 31 | 26 | 12 |
| 1 | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 16 | x | x | x | x | x | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | * |  |  |  |  |  |  |  |
| 2 | x | x | x | x | x | x |  | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 9 | x | x | x | x | x | x | x | x | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 13 |  |  |  |  |  |  |  |  |  |  | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 12 |  |  |  |  |  |  |  |  |  |  | x |  | x | x | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 11 |  |  |  |  |  |  |  |  |  |  | x | x | x | x |  |  | x |  |  |  |  |  |  |  |  |  | * |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 15 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | x | x | x | x | x | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | x | x | x | x |  |  |  | x | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 5 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | x | x | x | x | x | x | x | x | x | x | x | x | x |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 14 |  |  |  |  |  | * |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | x | x | x |  |  |  |  |  |  |  |  |  |  |
| 3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | x | x |  | x | x | x |  |  |  |  |  |  |  |
| 7 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | x | x | x |  |  |  |  |
| 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | x | x | x | x | x | x | x |
| 8 |  | + | + |  |  | + |  |  | + |  | + | + |  | + |  | + | + | + | + |  |  | + | + |  |  | + | + |  | + | + |  |  |  |  |  |  |  |  | + |  | + |  | + |
| 6 | + | + |  | + |  | + |  | + |  |  |  |  |  |  |  |  |  |  | + | + |  | + |  | + |  | + |  |  |  | + |  | + | + |  | + | + |  | + | + | + |  |  | + |

Figure 4.4.d Result After Final Iteration Showing Five Groups with Multiple and Exceptional Entries

| | COMP NO. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M/C NO | 42 | 37 | 38 | 32 | 10 | 2 | 18 | 40 | 28 | 4 | 24 | 3 | 30 | 27 | 22 | 11 | 20 | 21 | 19 | 14 | 5 | 43 | 41 | 33 | 29 | 23 | 9 | 16 | 15 | 8 | 35 | 17 | 6 | 36 | 34 | 7 | 25 | 13 | 1 | 39 | 31 | 26 | 12 |
| 1 | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 16 | X | X | X | X | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | * | | | | | | | |
| 2 | X | X | X | X | X | X | | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 9 | X | X | X | X | X | X | X | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 8 | | + | + | | | + | | | + | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6 | + | + | | + | | + | | + | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 13 | | | | | | | | | | | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 12 | | | | | | | | | | | X | | X | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 11 | | | | | | | | | | | X | X | X | X | | | X | | | | | | | | | | * | | | | | | | | | | | | | | | | |
| 8 | | | | | | | | | | | + | + | | + | | + | + | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 15 | | | | | | | | | | | | | | | | | | X | X | X | X | X | X | X | | | | | | | | | | | | | | | | | | | |
| 4 | | | | | | | | | | | | | | | | | | X | X | X | X | | | | X | X | X | | | | | | | | | | | | | | | | |
| 5 | | | | | | | | | | | | | | | | | | X | X | X | X | X | X | X | X | X | X | X | X | X | | | | | | | | | | | | | |
| 8 | | | | | | | | | | | | | | | | | | + | + | | | + | + | | | + | + | | + | + | | | | | | | | | | | | | |
| 6 | | | | | | | | | | | | | | | | | | | + | + | | + | | + | | + | | | | + | | | | | | | | | | | | | |
| 14 | | | | | | * | | | | | | | | | | | | | | | | | | | | | | | | | X | X | X | | | | | | | | | | |
| 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | X | | X | X | X | | | | | | | |
| 6 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | + | | + | + | | | | | | | |
| 7 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | X | X | | | | |
| 10 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | X | X | X | X | X | X |
| 8 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | | + | | + |
| 6 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | + | + | | | + |

Figure 4.4.e The Solution Matrix by Using DCA Method, Compare this with Burbidge's and King's Solutions

Figure 4.5 The Solution Matrix by Burbidge

Figure 4.6 The Solution Matrix by King

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | Others | 09 | 19 | 29 | 39 | 49 | 59 | 69 | 79 | 89 | 99 |
| 8 | Barfeed+Centre | 08 | - | - | - | - | 58 | 68 | - | - | 98 |
| 7 | Bar Feed | 07 | - | - | - | - | 57 | 67 | - | - | 97 |
| 6 | Chuck+Steady | 06 | 16 | - | - | - | 56 | 66 | - | - | 96 |
| 5 | T.Stock Chuck | 05 | 15 | - | - | - | 55 | 65 | - | - | 95 |
| 4 | Centre+T.Steady | 04 | 14 | 24 | 34 | - | 54 | 64 | - | - | 94 |
| 3 | Centre+F.Steady | 03 | 13 | 23 | 33 | - | 53 | 63 | - | - | 93 |
| 2 | Fixed Steady | 02 | 12 | 22 | - | 42 | 52 | 62 | - | - | 92 |
| 1 | T.Stock Centre | 01 | 11 | 21 | 31 | - | 51 | 61 | 71 | 81 | 91 |
| 0 | Free End | 00 | 10 | 20 | - | 40 | 50 | 60 | 70 | 80 | 90 |
| | Tail Stock<br>Head Stock | 3 Jaws Chuck | 4 Jaws Chuck | Face Plate | Centre | Mandrel | Collets | Special Jaws | Fixture/Jigs | Chuck+Fixture | Others |
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |

Figure 4.7 Workholding Methods for Lathes

## CHAPTER FIVE

## 5. FACILITIES LAYOUT IN CELLULAR MANUFACTURING SYSTEMS

### 5.1 Significance of Facilities Layout in Cellular Manufacture

In the last chapter a method of finding component families and machine groups was described. Now for each machine group formed there is a list of machines and workstations which have to be installed, so there is a problem of planning the layout of these facilities.

In a cellular manufacturing environment, it is desirable to have as much work as possible completed within a cell without the work having to leave, and to try and achieve a smooth flow of work. However, in practice this idealised situation is often impossible to achieve due to various restrictions. The cost of establishing mutually exclusive machine groups is usually unjustified from both economic and geographic viewpoints. Moreover, machine cells cannot be entirely self-contained because there are restrictions imposed by some specialist technologies, for example, heat treatment and plating. Therefore, it is common for some components to leave a cell and return later for subsequent processes, creating inter-cell material flow. It is thought that for economy and flexibility, it could well be advantageous to allow a controlled flow of materials in between cells. When this is the case the relative positions of all the cells must be carefully planned since the material movement cost will be dependent on these.

After the machine cells are formed, the facilities in each cell would be ideally arranged in a flowline with the fully integrated use of conveyors for internal work-flow. However, this situation is often difficult to establish since not all components assigned to a cell follow the same production sequence. Also components which have to leave the cell for special work and return for subsequent operations would cause back tracking along the flow line. Therefore, it is more common to adopt a group layout in which the machines are placed together without any handling aids. In such cases, it is important to plan the relative positions of machines inside the same cell so that a minimum total cost of material movement is assured.

The planning of facility layout is significant to the effectiveness of a cellular manufacturing system. This is similar to the classical facilities layout problems that are found in traditional organisations. Unfortunately it has not attracted much attention of many writers on Group Technology, who tend to assume that ideal cellular manufacturing situations can always be achieved. In this chapter, this particular area of the group layout problem will be studied in detail and a method of determining an optimal plan using a new algorithm will be described.

## 5.2 The Classical Facilities Layout Problem

Facilities layout is an ill-defined complex problem, the large number of variations in possible analyses has led to many diverse concepts and methods of solution. There are a number of literature surveys and technique reviews on the subject, for example, those of Moore (73) and Foulds (74).

The earliest approach to layout problem involved a detailed examination of all the qualitative factors, it lacked both a systematic method and quantitative analysis. Muther (75) reorganised the early method into a systematic procedure based on a combination of flow considerations and qualitative factors. Improvements were made by the use of a variety of empirical charts for evaluating layout decisions. Here again the method was concerned with the total problem and lacked a quantitative basis.

Later, it was realized that by considering material movement, defined as the product of distance and quantity, to be the sole criterion, and by reducing physical representation of facilities to a set of points, it was possible to formulate a mathematical or semi-mathematical solution to the layout problem. However, these methods have proved to be limited to small problems because of the need to manipulate a huge amount of information and the extensive calculations required. This has been discussed by El-Rayah and Hollier (76), and leads to only one conclusion, the use of the computer.

Computer solutions have been applied to the planning of facilities layout for about a decade. The development has come from a variety of disciplines, each examining the problem from different viewpoints, as shown by Moore (73). Due to the complexity of the problem, the methods developed for layout design are all heuristic in nature. In the computerised methods, for example, CRAFT (77) and CORELAP (78), either the material movement or the closeness desirability is employed as the evaluation criterion, and the facilities are represented either by points, unit areas or blocks.

These computerised layout methods suffer from two drawbacks. Firstly the lack of control over the resulting shape of the facility area limits their usefulness in dealing with fixed shaped machine tools. Secondly all these methods require much computer space and time for applications. In recent years a new approach to preparing block diagrams which avoids using the unit area principle has been developed, and it is highly suitable for computer treatment. Its basis is on graph theory as described in the following sections.

## 5.3 Graph Theory and Facilities Layout

Graph theory is a branch of mathematics which was first developed in the eighteenth century by the great mathematician Euler, and it has become of practical value only in recent years (for a full treatment of graph theory see Harary (79) or Wilson (80)).

The basic concept of graph theory can be illustrated by a simple graph as shown in figure 5.1. A *graph* consists of a set of *vertices*, for example, A, B, C and a set of *edges*, for example, a, b, c (figure 5.1). Edges may be associated with some values such as length, and may be directed or undirected. Here, only undirected edges are considered. A graph is said to be connected if any one vertex can reach any other vertex by travelling along the edges. Figure 5.1 is a *connected graph*. A *tree* is a connected graph which contains no closed loop or circuit, for example, edges a, b, c and f. A *spanning tree* is a tree connecting all vertices of the graph, for example, edges a, b, c, f, e and h. A *minimal spanning tree* is the spanning tree for which the sum of edge lengths is minimum.

A graph which can be drawn in such a way that the edges have no intersections or common points except at the vertices is called a *planar graph*, otherwise it is a *non-planar graph*. The graph of figure 5.1 is actually planar because although edges e and g apparently intersect, one of them could have been drawn outside area abfhid. A *maximal planar graph* is a planar graph to which no edge can be added without losing planarity. The spaces contained by the edges are called *faces* and the infinite or *exterior face* is the one outside the graph. Therefore in figure 5.1 there are four faces, namely abgid, fgh, eih and the exterior face.

Every graph has a *dual graph*, if a point is placed on each face of the graph, including the exterior face, then the dual graph has these points as vertices and edges connecting those vertices whose faces in the original graph are bounded by a common edge. If the original graph is planar, so is its dual, this is illustrated in figure 5.2.

Some important characteristics concerning planar graphs have been discovered which are of particular relevance to facilities layout. It has been found that if V, E and F are the number of vertices, edges and faces respectively, then

$$V - E + F = 2$$

$$F = 2V - 4$$

$$E = 3V - 6$$

Probably the first hint that the mathematics of graphs might be useful in layout planning was given by Levin (81). Later, Seppanen and Moore (82) observed that a two dimensional plant layout block diagram could be considered as a planar graph. Since then, much effort has been devoted to the development of various approaches to apply graph theory to layout problems. Some important findings are due to Foulds and Robinson (83), Carrie (84) and Moore (85).

It has been shown that in a layout block diagram such as figure 5.2, each block can represent an area assigned to a department, a machine cell or a single machine tool. The dual graph of the block diagram is the relationship graph which shows the lines of material flow between adjacent areas. If this relationship graph is planar, then all the relationships can be satisfied by a layout plan in which all material flows are between adjacent areas. If the relationship diagram is non-planar, then no layout plan can satisfy them all.

The objective of layout planning is to minimize the total material flow by placing adjacent to each other, those facilities between which a large amount of material is moved, and to preserve the planarity of the relationship diagram at the same time. If a maximal planar graph can be constructed having the maximum possible total edge length (i.e. the maximum possible total material flow between adjacent facilities), then the associated plant layout block diagram should be optimal or very nearly so.

The crucial property of layout planning methods based on graph theory is planarity and most methods involve testing for it in the final graph. Planarity testing is difficult and has always been the major problem in applying this technique to layout planning. Seppanen and Moore (82) have introduced a method which utilizes string processing techniques, and it provides a convenient way of testing the planarity of a graph. Foulds and Robinson (83) examined the problem and proposed two new procedures which dealt solely with maximal planar graphs. Their methods are superior to the others because the difficult, tedious and unreliable process of planarity testing is avoided.

Foulds and Robinson's techniques are based on the principle that in a complete planar graph all faces must be triangular, and they formulate a procedure of constructing triangles in a planar graph, starting with the preparation of a cross chart showing the cost of moving materials between facilities. Four facilities are chosen from the chart as the initial vertices and they are all linked together to form four triangles in a tetrahedron. The remaining vertices (i.e. facilities) are then added one at a time, choosing each time a triangle in which the new vertex is inserted. Three new triangles will be created as one vertex is joined to the vertices of a triangle, and triangular faces are gradually built up until all the vertices are inserted. The graph remains maximal plannar throughout the operation. Both techniques give near optimal solutions, they differ only in the way in which the initial vertices and the order for inserting vertices are chosen.

A new Adjacency Requirements Planning algorithm based on the same principle as Foulds and Robinson's method has now been developed by the author. The algorithm is simpler and more efficient, and is particularly suitable for planning the layout in a cellular manufacturing environment where the size of the problem has been reduced by the initial formation of the cells. The new algorithm uses a different approach for choosing the vertices and gives a near optimal solution. It follows a clearly defined procedure which is easily computerised.

### 5.4 The Adjacency Requirements Planning Algorithm

The evaluation criterion used in this ARP algorithm is the total cost of material movement between facilities. This can be defined as:-

$$\text{Total Cost} = \sum_{i=1}^{n} \sum_{j=1}^{n} Dij\ Wij$$

where n = number of facilities

Dij = distance from facilities i to j

Wij = weighted factor for movement from i to j

The weighted factor is defined as: (cost/unit distance of moving unit batch from facilities i to j) X (number of batches to be moved in unit time).

The Adjacency Requirements Planning algorithm will determine the relative positions of the facilities for this total cost to be minimum, i.e. which facilities should be placed adjacent to each other to effect a minimum total cost. The method is best described with an illustrative example.

A cross chart showing the cost of moving materials between ten facilities is shown in the top part of the table in figure 5.3. Each entry in the table, which is the cost of moving materials between two facilities, represents an edge of a triangle, the length of the edge being proportional to the value of the entry; the two respective facilities represent two vertices of a triangle connected by the edge.

First, for each column determine the optimal triangle. This is formed by the vertex of that column and two other vertices which when combined will have the largest total sum of edge lengths. All possible combinations must be tried to find this optimal triangle. For example, in the third column of the table in figure 5.3, triangle CAE has a total edge length of (CA + CE + AE = 30 + 51 + 90 =) 171 and is the optimal triangle in that column.

After the optimal triangle in each column has been determined and entered into the table, the optimum triangle is chosen from these as the one with the greatest total edge length. In this example, ADE is the optimum triangle and therefore its vertices are entered on the right of the table as shown.

(If there are two or more optimal triangles with equal edge length, any one can be used). The numbers in the brackets represent the sequence in which the vertices should be added to the graph.

Next enter the optimum triangle on the left of the table and calculate the total edge length of each triangle formed by inserting another vertex into it. For example, by inserting vertex B into triangle ADE, a total edge length of (BA + BD + BE = 53 + 25 + 59 =) 137 will result. For triangle ADE the largest total edge length is obtained by inserting vertex J into it, so that J is chosen as the next vertex to be inserted.

Now there are four triangles into which the next vertex can be inserted, these include the three triangles formed by vertex J and the vertices of triangle ADE and the exterior face of ADE. The total edge lengths resulting from the insertion of each of the remaining vertices into these triangles are now calculated, and the selected vertex which forms the largest total edge length is the next one to be inserted. In this example, vertex H is the one to be added after J and it should be inserted into triangle JAE. This is followed by B into triangle ADE, I into triangle BAE and so on. The process continues in this way until all the vertices have been inserted.

At any time, only one vertex is to be inserted inside any triangle, except for the first or optimum triangle which can have two vertices inserted, one to the inside and the other to the exterior face of the triangle.

The complete solution for the example problem is shown in the table of figure 5.3. The corresponding maximal planar graph can then be constructed by inserting the vertices into the graph following the sequence shown. The triangles formed are the ones on the left of the table, and they will appear in the planar graph in exactly the same order as they are listed. Figure 5.4 shows the complete maximal planar graph which defines the adjacency requirements of each machine cell relative to the others. A block diagram can then be constructed from this graph following a procedure as described in the next section.

A maximal planar graph may have up to (3V - 6) edges, where V is the number of vertices. Therefore the sum of the (3V - 6) largest entries in the cross chart should give an upper bound value to the solution. In the present example this upper bound value is 1270, which is the sum of the (3 x 10 - 6 =) 24 highest values in the cross chart in figure 5.3. The sum of the edges of the solution graph in figure 5.4, obtained by adding together the encircled sums in figure 5.3, amounts to 1267. Therefore it can be seen that the solution value obtained by employing the ARP technique is extremely close to the optimum.

Like all other graph theoretical methods for layout planning, the ARP approach does not initially take shapes or areas of facilities into account. The algorithm terminates before the construction of block diagram. This is advantageous in that it allows greater flexibility for the designer who can study the state of layout at the block diagram stage.

## 5.5 Construction of Block Diagrams for Layout Planning

The Adjacency Requirements Planning algorithm defines the best relative positions of the machine cells. A block diagram for layout planning is still to be constructed from the resultant maximal planar graph. First the graph must be redrawn, and a dual graph for the new maximal planar graph has to be constructed. Then a block diagram is drawn with reference to the dual graph. The method is illustrated with the same example as in the last section.

In graph theory terms, a maximal planar graph may have up to (2V - 4) triangular faces including the exterior face, where V is the number of vertices. Now the maximal planar graph in figure 5.4 can be drawn in (2 X 10 - 4 =) 16 possible ways so that any face may become the exterior face. This is particularly significant in layout planning because the exterior face does not form part of the layout. In practice it is desirable to place those machine cells with heavy inter-cell material flows near to the centre of the workshop so that there is less chance for the flows to be disrupted. This can be achieved by making the triangular face with the smallest total edge length the exterior face, and putting the other faces inside it. The result will be that the exterior face in the new maximal planar graph is the most diffused face in the graph.

In figure 5.4, triangle FGI has the smallest edge length of

121. Therefore it is made the exterior face in the new maximal planar graph in figure 5.5. Vertex B is the next one to be inserted in the graph since it has connections to all the three vertices of triangle FGI. This is followed by inserting vertex A which is connected to the three vertices of triangle GBI. As a general rule, a vertex which is connected to the outside of a triangular face in figure 5.4 must be inserted inside the same face in figure 5.5. In this way the maximal planar graph in figure 5.4 is redrawn and the new graph shown in figure 5.5 satisfies the same adjacency requirements, but has the light inter-cell material flows restricted to the outer zone of the final layout.

Now it is necessary to construct the dual graph of the maximal planar graph. Each face of the dual graph will become a cell area in the block diagram and the vertices of the dual graph will become points of intersection of the cell boundaries. Since the block diagram, as a graph, also contains an exterior face, a dummy vertex must be introduced into the maximal planar graph in order to maintain the one to one correspondence between vertices and faces.

The dummy vertex is located on the outside of the redrawn maximal planar graph and is connected to the vertices on the periphery of the graph, i.e. F, G and I. This modified graph will then be used to construct the dual graph shown in figure 5.6. As explained in section 5.3, the dual graph is plotted in the following manner:-

Place a labelled dual vertex in each face of the modified graph including the exterior face. Then for two faces which have an edge e in common, join the corresponding dual vertices by an edge e' crossing only e.

Finally, using the maximal planar graph and its dual graph, a block diagram for plant layout can be constructed, satisfying the adjacency requirements and taking into consideration the shapes and areas of the machine cells. A block diagram for the example problem is shown in figure 5.7.

## 5.6 The ARP Algorithm and the Computer

Many computer programmes for layout planning such as CRAFT and CORELAP, deal mainly with overall layout of a factory, and are of little benefit to the reorganisation of small sections. These programmes require detailed structured data, and its preparation for use is a problem in itself. Consequently, there has to be computer assistance in extracting and processing the data before the actual analysis is carried out. These computer packages are very sophisticated and very expensive to use.

The ARP algorithm is specifically developed for minor projects, in particular, for the detailed layout planning within a department or a workshop. It is designed to use the data obtained from an analysis by the DCA technique, therefore a prior division on the basis of machine cells within the workshop is assumed. This largely reduces the complexity in preparing the data since the only evaluation criterion, namely the material flow, has already been simplified following the clustering analysis and cell formation.

A computer programme has been written for data management and for compiling the cross chart needed for ARP analysis (see Appendix IB). The data required has a similar format to that for the DCA programme, but with some additional information. Once the cross chart has been created it should be as quick to carry out the ARP analysis manually as to have it done by a computer. The computation involved is so simple that a computer programme specifically developed for this job might not be justified. However, the nature of the ARP algorithm does permit easy computerisation if later it is necessary, say, to analyse an extra large cross chart.

### 5.7 Applications of the ARP Algorithm

The Adjacency Requirements Planning algorithm is initially developed for solving the facilities layout problem in cellular manufacturing systems. It is used for determining the optimal relative positions of the machine cells in a plant and of the machine tools in a cell.

The ARP analysis requires the preliminary preparation of a cross chart. Each vertex in the cross chart represents a facility, which can be a machine cell or a single machine tool; and each entry represents the cost of material movement between any two facilities. A zero entry indicates that there is no material flowing between the two facilities concerned and their relative position is unimportant. In some cases it may be necessary to place two facilities adjacent to each other at all times due to technological requirements. This can be ensured by overwriting the corresponding entry in the cross chart by an infinitely large number, say $10^{10}$, to give that edge a very high priority. Conversely if two facilities must not be placed adjacent to each other, then the corresponding entry must be overwritten by an infinitely large negative number, say $-10^{10}$, to give the edge a very low priority.

When determining the adjacency requirements for machine cells within a workshop, the cross chart should be composed of the costs of material movement between cells. This data can be obtained by considering the components which require processing in more than one cell. These components, which are far fewer in number than the total component range, should become apparent after the group formation process. A data management facility provided by the computer programme will convert the material movement costs between machine tools in different cells into material flow costs between machine cells. In the case of planning the layout of machine tools within a cell, the preparation of the cross chart will be straight forward.

Foulds and Robinson presented an example with ten facilities for illustrating their construction algorithms (83). The same problem is now used for illustrating the application of the ARP algorithm. Figure 5.8 shows the cross chart to the example problem and the manually worked solution. The corresponding maximal planar graph is shown in figure 5.9. A comparison of this planar graph with the one obtained by applying Fould and Robinson's S construction method (figure 5.10) shows some differences. The total edge value in the former graph is 1063 and that in the latter is 1055. Thus the solution obtained by the ARP approach is closer to the optimum value of 1094. Foulds and Robinson suggested another method called the R construction which gave a solution to the same problem with a total edge value of 1081. However, this more ambitious construction involved much tedious and complicated computations, and yet it did not consistently give a better solution than the S construction. This is evidenced by their results of using the S and R constructions on several problems. In any case, no constructive method of this kind can guarantee to produce the optimum solution, however complex the decision rules are designed. Therefore it would be desirable to stick to a simple one such as the ARP algorithm.

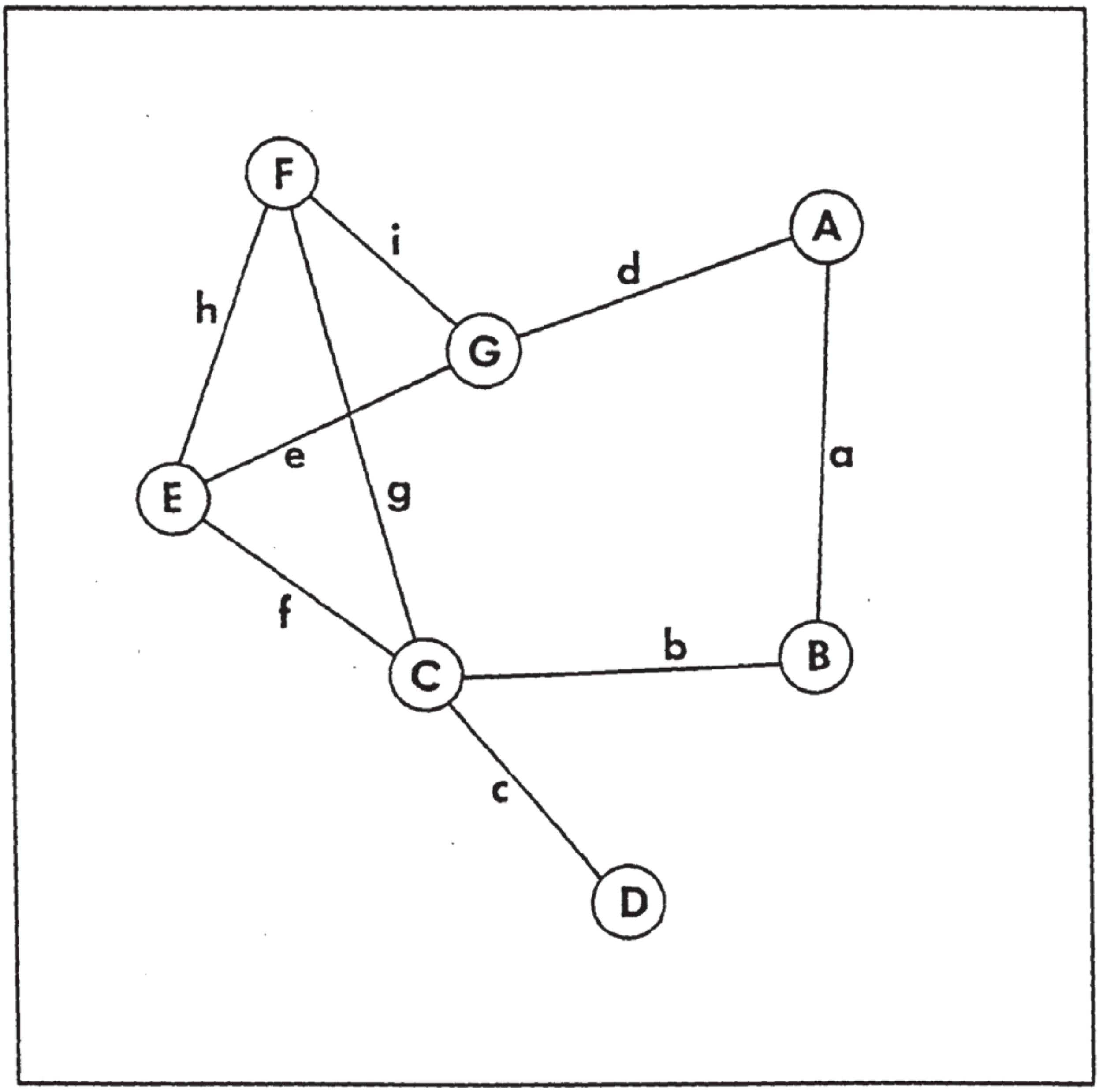


Figure 5.1 A Typical Graph

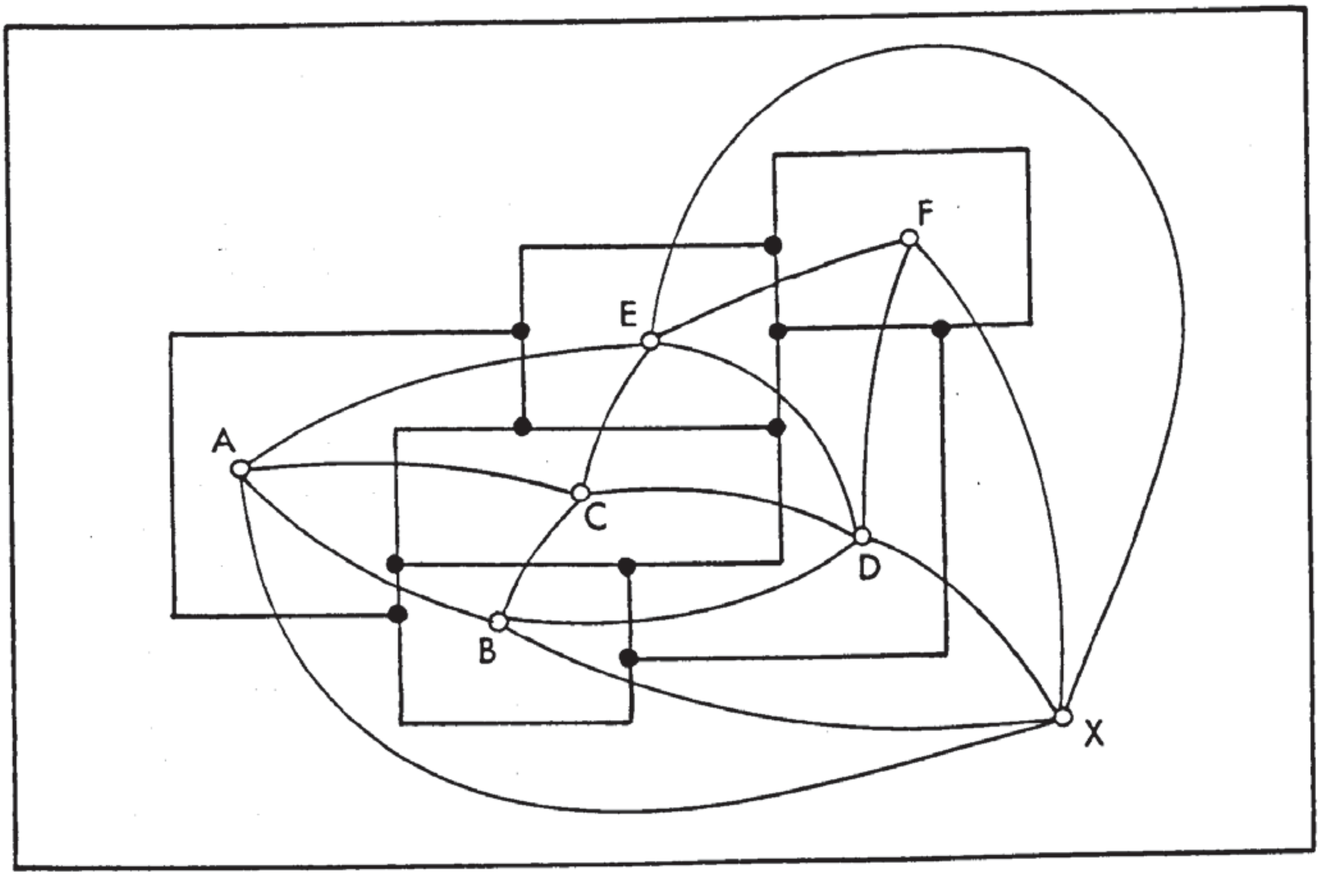


Figure 5.2 A Block Diagram and Its Dual Graph (after Seppanen and Moore)

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| A | - | 53 | 30 | 75 | 90 | 00 | 46 | 62 | 51 | 79 |
| B | 53 | - | 00 | 25 | 59 | 48 | 62 | 00 | 56 | 00 |
| C | 30 | 00 | - | 20 | 51 | 57 | 00 | 41 | 00 | 39 |
| D | 75 | 25 | 20 | - | 56 | 37 | 30 | 00 | 27 | 46 |
| E | 90 | 59 | 51 | 56 | - | 00 | 39 | 59 | 48 | 51 |
| F | 00 | 48 | 57 | 37 | 00 | - | 30 | 41 | 32 | 00 |
| G | 46 | 62 | 00 | 30 | 39 | 30 | - | 00 | 59 | 42 |
| H | 62 | 00 | 41 | 00 | 59 | 41 | 00 | - | 16 | 50 |
| I | 51 | 56 | 00 | 27 | 48 | 32 | 59 | 16 | - | 25 |
| J | 79 | 00 | 39 | 46 | 51 | 00 | 42 | 50 | 25 | - |

| | ADE 221 | BAE 202 | CAE 171 | DAE 221 | EDA 221 | FEH 139 | GBI 177 | HAE 211 | IAE 189 | JAE 220 | A(1), D(2), E(3) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ADE | - | 137 | 101 | - | - | 37 | 115 | 121 | 134 | 176 | J(4), B(6) |
| JAD | - | 116 | 89 | - | - | 37 | 118 | 112 | 111 | - | H(5) |
| JAE | - | 150 | 120 | - | - | 00 | 127 | 171 | 124 | - | |
| JDE | - | 122 | 110 | - | - | 37 | 111 | 109 | 108 | - | |
| HJA | - | 91 | 110 | - | - | 41 | 121 | - | 92 | - | C(9) |
| HJE | - | 97 | 131 | - | - | 41 | 114 | - | 89 | - | |
| HAE | - | 112 | 122 | - | - | 41 | 127 | - | 115 | - | |
| BAD | - | - | 97 | - | - | 85 | 138 | - | 142 | - | I(7) |
| BAE | - | - | 128 | - | - | 48 | 147 | - | 155 | - | |
| BDE | - | - | 118 | - | - | 85 | 131 | - | 139 | - | |
| IBA | - | - | 103 | - | - | 80 | 167 | - | - | - | G(8) |
| IBE | - | - | 124 | - | - | 80 | 160 | - | - | - | |
| IAE | - | - | 107 | - | - | 32 | 144 | - | - | - | |
| GIB | - | - | 101 | - | - | 110 | - | - | - | - | F(10) |
| GIA | - | - | 84 | - | - | 62 | - | - | - | - | |
| GBA | - | - | 105 | - | - | 78 | - | - | - | - | |
| CHI | - | - | - | - | - | 98 | - | - | - | - | |
| CHE | - | - | - | - | - | 98 | - | - | - | - | |
| CJE | - | - | - | - | - | 57 | - | - | - | - | |
| FGI | - | - | - | - | - | - | - | - | - | - | |
| FGB | - | - | - | - | - | - | - | - | - | - | |
| FIB | - | - | - | - | - | - | - | - | - | - | |

Figure 5.3 An Example to Illustrate the Adjacency Requirements Planning Algorithm

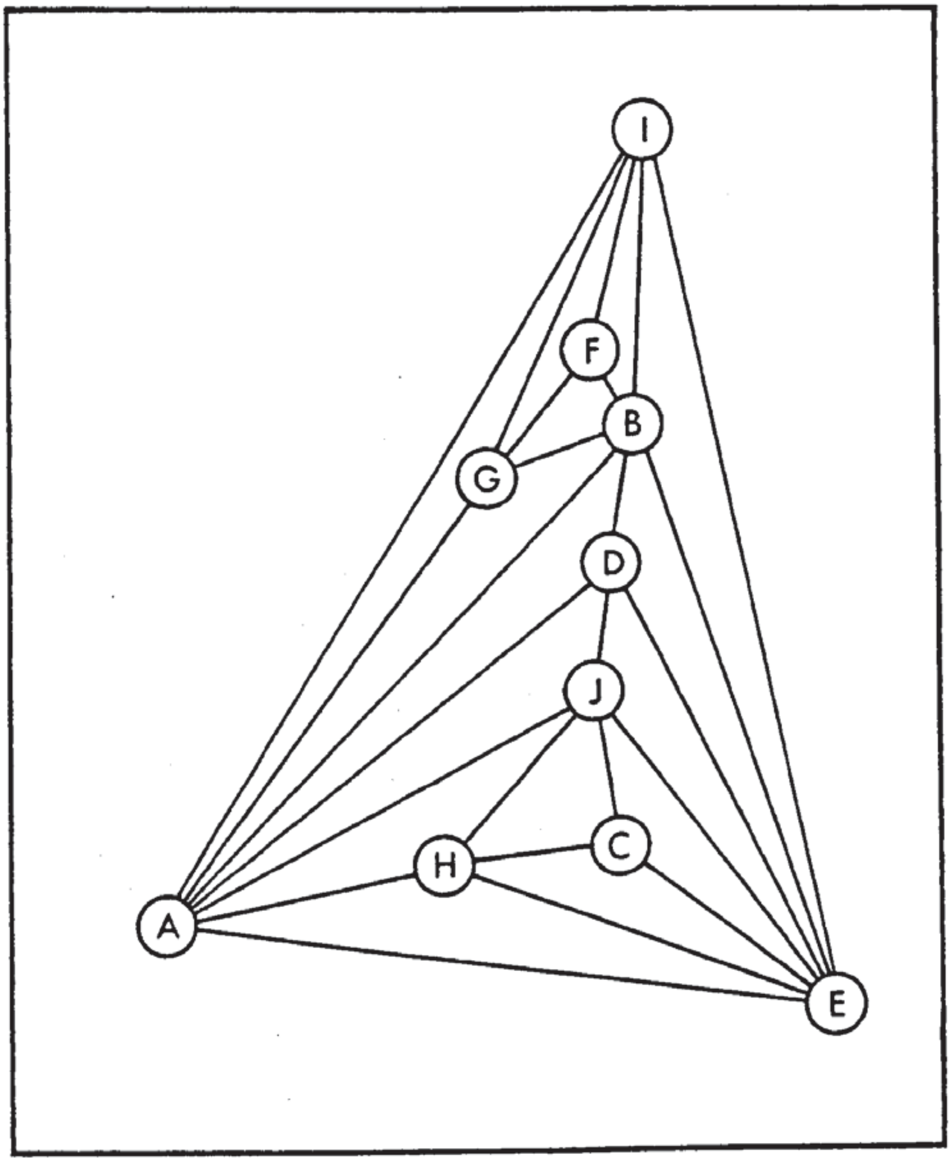


Figure 5.4 Maximal Planar Graph Drawn from Results in Figure 5.3

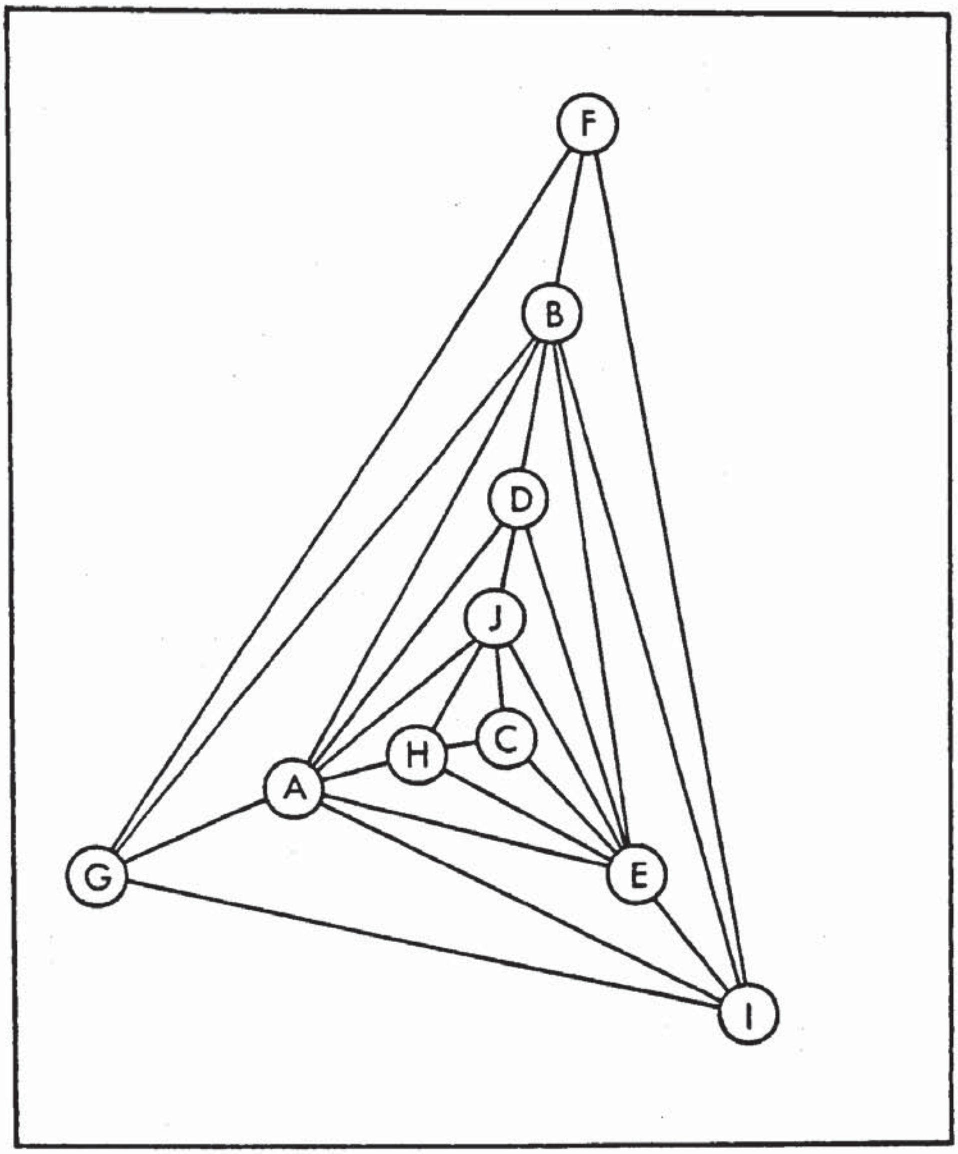


Figure 5.5 The Redrawn Maximal Planar Graph of Figure 5.4

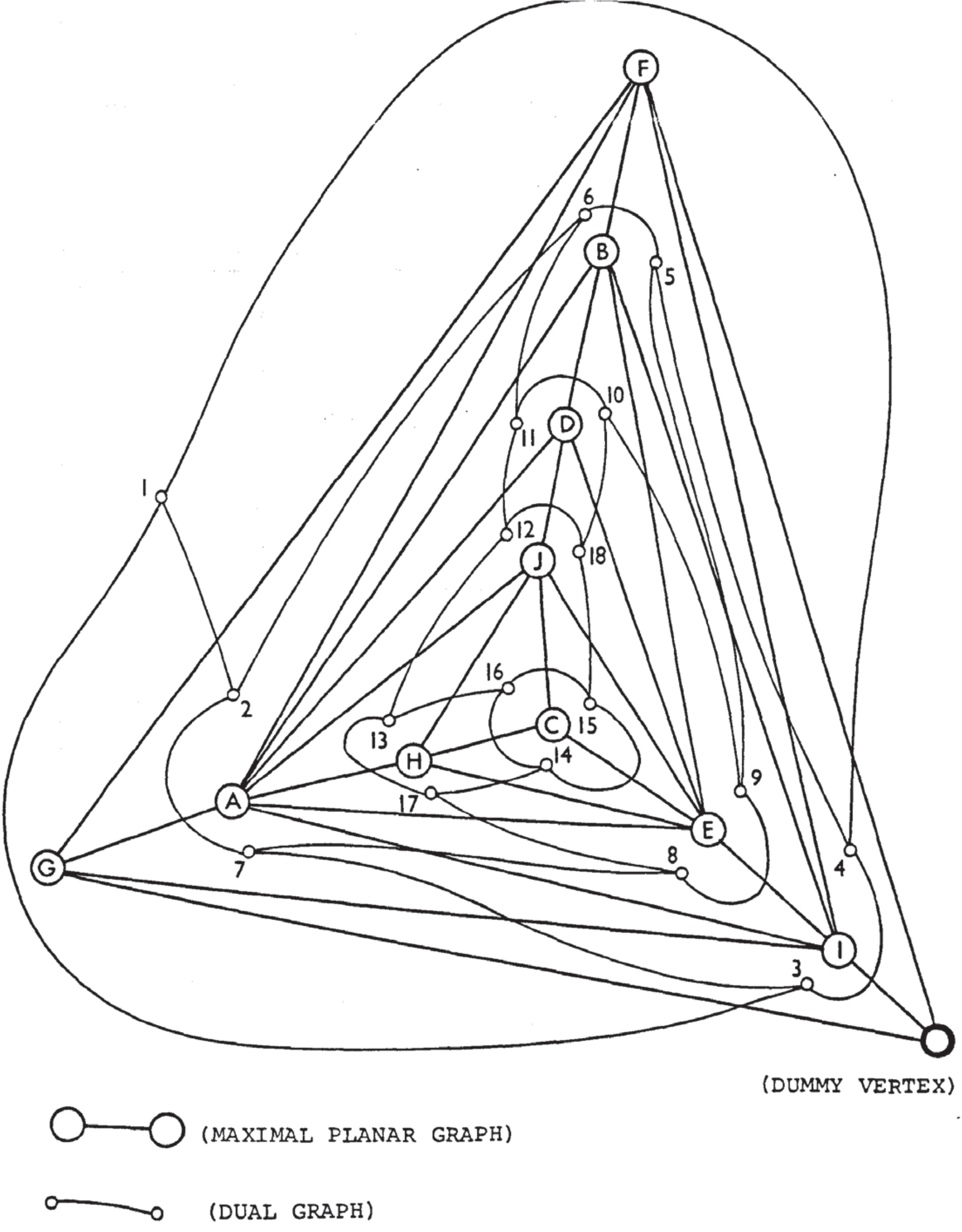


Figure 5.6 The Dual Graph of Figure 5.5

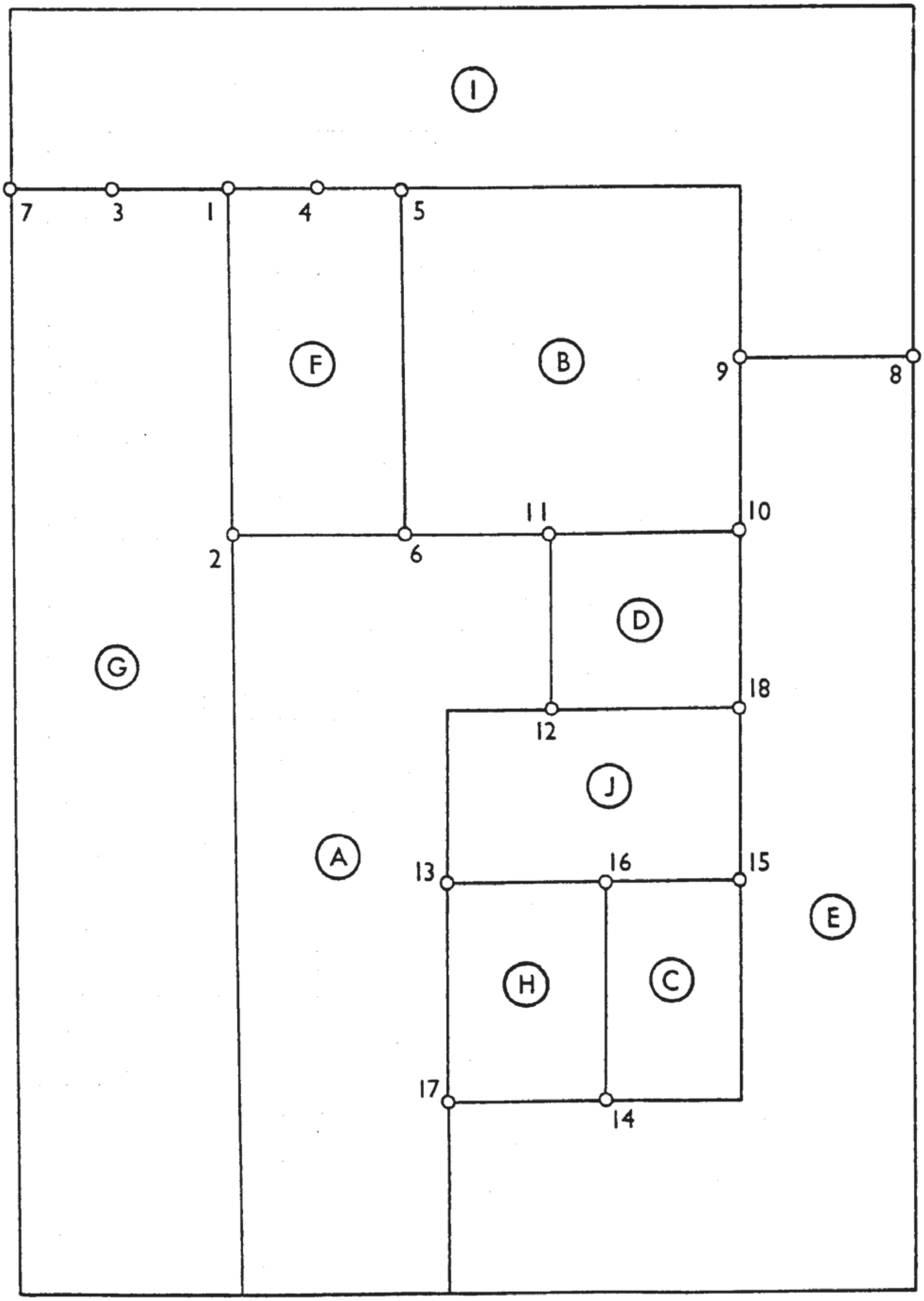


Figure 5.7 Block Diagram for the Example Problem

|  | a | b | c | d | e | f | g | h | i | j |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
| a | - | 0 | 3 | 53 | 33 | 4 | 43 | 55 | 5 | 6 |  |
| b | 0 | - | 44 | 34 | 54 | 45 | 36 | 32 | 42 | 31 |  |
| c | 3 | 44 | - | 60 | 35 | 46 | 39 | 8 | 7 | 49 |  |
| d | 53 | 34 | 60 | - | 9 | 47 | 59 | 10 | 41 | 30 |  |
| e | 33 | 54 | 35 | 9 | - | 25 | 48 | 51 | 26 | 40 |  |
| f | 4 | 45 | 46 | 47 | 25 | - | 62 | 57 | 39 | 29 |  |
| g | 43 | 36 | 39 | 59 | 48 | 62 | - | 28 | 56 | 38 |  |
| h | 55 | 32 | 8 | 10 | 51 | 57 | 28 | - | 37 | 27 |  |
| i | 5 | 42 | 7 | 41 | 26 | 39 | 56 | 37 | - | 50 |  |
| j | 6 | 31 | 49 | 30 | 40 | 29 | 38 | 27 | 50 | - |  |
|  | adg<br>155 | bcf<br>135 | cdg<br>158 | dfg<br>168 | ebg<br>138 | fdg<br>168 | gdf<br>168 | hfg<br>147 | ifg<br>157 | jcd<br>139 | d(1), f(2)<br>g(3) |
| dfg | 100 | 115 | 145 | - | 82 | - | - | 95 | 136 | 97 | c(4), i(5) |
| cdf | 60 | 123 | - | - | 69 | - | - | 75 | 87 | 108 |  |
| cdg | 99 | 114 | - | - | 92 | - | - | 46 | 104 | 117 |  |
| cfg | 50 | 125 | - | - | 108 | - | - | 93 | 102 | 116 | b(6) |
| idf | 62 | 121 | - | - | 60 | - | - | 104 | - | 109 |  |
| idg | 101 | 112 | - | - | 83 | - | - | 75 | - | 118 |  |
| ifg | 52 | 123 | - | - | 99 | - | - | 122 | - | 117 | h(9) |
| bcg | 46 | - | - | - | 137 | - | - | 68 | - | 118 | e(7) |
| bcf | 7 | - | - | - | 113 | - | - | 97 | - | 109 |  |
| bfg | 47 | - | - | - | 127 | - | - | 117 | - | 98 |  |
| ebc | 36 | - | - | - | - | - | - | 91 | - | 120 |  |
| ebg | 76 | - | - | - | - | - | - | 111 | - | 109 |  |
| ecg | 79 | - | - | - | - | - | - | 87 | - | 127 | j(8) |
| jec | 42 | - | - | - | - | - | - | 86 | - | - |  |
| jeg | 82 | - | - | - | - | - | - | 106 | - | - |  |
| jcg | 52 | - | - | - | - | - | - | 63 | - | - |  |
| hif | 64 | - | - | - | - | - | - | - | - | - |  |
| hig | 103 | - | - | - | - | - | - | - | - | - | a(10) |
| hfg | 102 | - | - | - | - | - | - | - | - | - |  |
| ahi | - | - | - | - | - | - | - | - | - | - |  |
| ahg | - | - | - | - | - | - | - | - | - | - |  |
| aig | - | - | - | - | - | - | - | - | - | - |  |

Figure 5.8 Solution to the Problem Presented by Foulds and Robinson by Using the ARP Algorithm

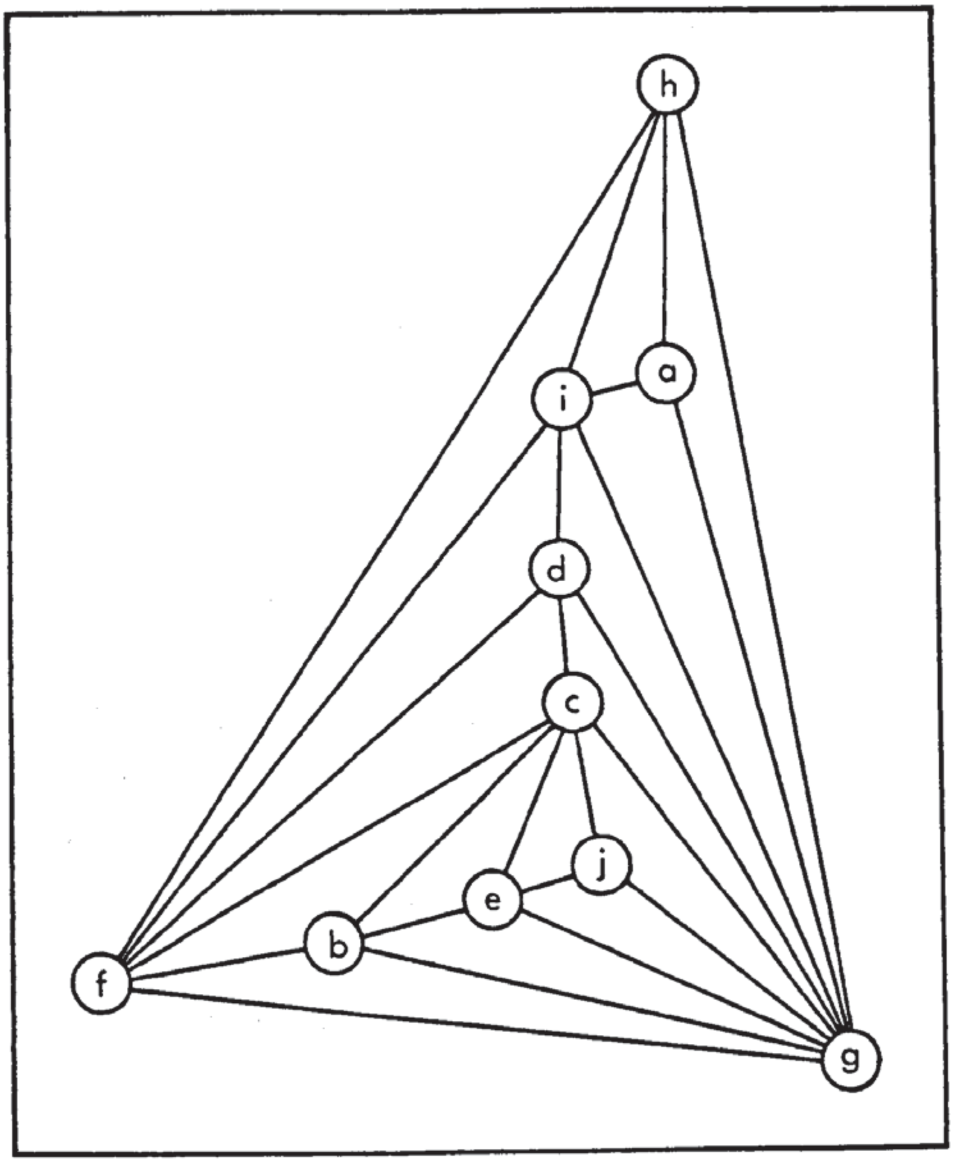


Figure 5.9 Maximal Planar Graph Drawn from Results in Figure 5.8

Figure 5.10 Maximal Planar Graph by Foulds and Robinson

# CHAPTER SIX

# 6. A METHODOLOGY FOR THE INTRODUCTION OF CELLULAR MANUFACTURE

## 6.1 Introduction

The techniques described in the previous chapters can provide a comprehensive approach to the design problems in implementing cellular manufacture. This involves a series of related changes which can take place in three main stages:-

1) The decision regarding the general policy for the change. This will include defining the objectives and planning the necessary preliminary changes in departmental organisations before machine cells are formed.

2) The formation of the machine cells and their associated component families. This will involve the use of the complexity code and the DCA method as already described.

3) The planning of the management and services for the machine cells, and of any necessary changes in the supporting systems. The first part will be concerned with the layout of each machine cell and of the whole system, by making use of the ARP algorithm, to effect an efficient material flow. The second part will be mainly a matter of introducing and adopting a production control system which is compatible to a cell organisation.

These problems will be discussed in the following sections.

## 6.2 General Policy

There are two alternative approaches in selecting the general policy for the introduction and implementation of cellular manufacture. The change can be made in such a way as to retain all the existing machine tools and equipment, production methods and product design, or to start with extensive preliminary changes in manufacturing procedures and product design.

The first approach is generally preferred as the changes in design, production processes and tooling need a long time to complete, and are best left until after the machine cells have been organised. Otherwise the introduction of the GT concept and its associated benefits will be delayed. Preliminary changes in product design are really unnecessary as the planning of an effective reduction in variety will be greatly simplified after the component families are formed. Changes will then be required only by those exceptional components which cannot readily be allocated to a family. Finally, the purchase of machines will mean a substantial increase in capital investment, and should be made after the machine cells are formed. This is because the types of machines desirable with cellular manufacture are likely to be different from those which are attractive with traditional production systems.

The most important changes in the course of introducing cellular manufacture lie in the formation of machine cells and the use of a compatible production control system. It is possible and probably better to make these changes with the existing products, machines and methods, so that savings can be achieved from the earliest date, and then to carry on with other types of development.

The second main policy decision to be made concerns the general approach to the design and implementation. The design of a new system can be based on a comprehensive analysis of all the components, or it can be based on the analysis of a selected sample. The implementation of cellular manufacture in an organisation can follow two different ways. Comprehensive implementation requires a total plan for changes on a company wide basis, with every major system change treated as a separate project and tackled as a whole. Pilot implementation, on the other hand, starts by introducing a trial cell together with its own special supporting systems. When this first cell is running, further cells are planned and installed successively, until the total implementation is complete.

Comprehensive analysis should be adopted wherever possible. A sample analysis may initially save some expense but it may well be more expensive in the long run due to the need to redesign and reorganise cells when the parts not included in the sample become due for production. In addition, from a limited analysis, it is very difficult to make the accurate load checks needed to give a good distribution of common machine types between the production cells. However, in some cases the use of a sample analysis may be unavoidable, for example, in a job shop the parts produced are changing frequently and the only possible basis for analysis is a sample of part orders. Also, when the information is used to make out an overall analysis for the development of a firm or for academic purpose, an analysis on only a limited number of components can be justified.

Similarly, comprehensive implementation is preferable to pilot implementation. The latter can mean operating the production system for a long period with duplicate services, such as wages or production control systems. Until the last machine cell is installed, no system change is completed and most of the potential savings cannot be obtained. With a comprehensive implementation, each major project is finished before the next is started, thus schedules and budgets for change can be more accurate. Also it is possible to install the more important changes first, so that savings can be achieved at an early stage and the capital for further development can be obtained as the result of the early changes.

Finally, it is worth noting that the most successful applications of cellular manufacture have all been supported by the senior directors in the company. The introduction of the GT concept is likely to affect all functions of management in the organisation. If such a change is initiated by a line manager, the full potential benefits of GT would be difficult to achieve because the promoter would have insufficient influences to persuade other functional managers to make the changes necessary to support the new system. It is important that the change should be directed and controlled from the top.

### 6.3 Objectives

A summary of objectives can provide a basis for decision making during both the design and the implementation stages. Theoretically, a cellular manufacturing system comprises of independent production cells, each cell should possess the following characteristics: there should be a set of machines and equipment specifically allocated and laid out in one special area; each cell should be dedicated to the production of a specific family of components or products; the output target and other control functions should be related to the cell as a whole and not separately to individuals in the cell; the sizes of the cell and the worker team in the cell should be designed to obtain social cohesion and benefits. These are the desirable characteristics of a cellular manufacturing system and together they are responsible for the many advantages claimed for such a system. Therefore they must be the objectives of the system design.

One main objective of this thesis is to develop an economic way of implementing cellular manufacture in small firms, therefore a desirable design method would be one which requires a minimum capital investment. Existing resources such as machines, plant and tooling must be utilized wherever possible, and indeed, for firms with limited resources, this may be the only possible way of making the change.

In general, the objective of any innovation is to improve the performance of the organisation. In product design, this would be improved quality and reduced modification lead time.

In marketing, this would be reliable delivery and the ability to meet variations in demand. In personnel this would mean increased job satisfaction and improved motivations. In the production department, this would be reduced set-up times and throughput times, reduced stock and work in progress, and increased material utilisation and capacity. All of these improvements can result from the introduction of cellular manufacture, and must be aimed at in the design of the cell system.

### 6.4 Allocation of Resources

In an ideal cellular manufacturing system, the cells would be designed with all the machines and equipment necessary. However, in practice, this ideal cannot always be achieved in all cells. In the formation of cells there are often some overall physical restrictions imposed by specialist technologies. As has been discussed earlier (sections 2.4 and 5.1), it is sometimes necessary to have a small number of components leaving their own cells for intermediate operations. If the cells have been well designed and the output target for each cell has been calculated correctly, the effect of a controlled component flow between cells can be reduced to a tolerable level. Therefore, it is important at the design stage to detect the odd process routes and exceptional components, and to plan the appropriate steps in minimizing their drawbacks. What should be avoided at all times is to freely transfer work operations from one cell to another in an attempt to keep certain types of machine fully loaded, this will only cause confusion and lead to uncertainty about the work load assigned to each cell.

In general, the production cells should be designed in such a way that the majority of components are tied to those cells where any special machines required to make them are installed. If this is the case, then only the simpler components with very few operations on common types of machines will be made in more than one cell, and the inter-cell component flow will be small and easily controlled.

One of the advantages claimed for cellular manufacture is its sociological benefit. Group working will provide a climate where job satisfaction can grow. For a GT system to work with maximum efficiency, each cell should have its own special team of workers who should remain in the cell and should not normally be transferred. In this way the workers can become specialised with the problems associated with their machines and equipment as well as with the component family which they manufacture. Also the cell environment will provide close social contact between workers who are contributing to a common objective.

However, there are certain situations where some movement of workers between cells can be justified. For example, in a job shop it may be difficult to maintain an even load of work for all the cells, and it is inevitable that workers are moved occasionally from lightly loaded cells to heavily loaded ones. Or in an emergency when one group loses many of its workers, it may be necessary to transfer workers from other cells to maintain production.

In a group layout situation, certain machines will be idle at some time, and some components may have to back track to an earlier machine. Under these conditions any operator in a cell may be moved to any of the machines. This work flexibility is an essential feature in the working of a cell system if the work is to flow smoothly. Some operators must be capable of operating all types of machines within the cell. Nevertheless, the fact that the machines are bound to be unevenly loaded allows an element of choice to the workers. Those who prefer to work mainly with one machine can choose one of the heavily loaded machines while those who prefer a variety of work can move between the machines which are lightly loaded.

Studies on group working by behavioural scientists have suggested that small groups of workers are more likely to derive sociological benefits. However, large cells can usually be formed in existing machine shops without purchasing additional plant, and as the cell size is reduced more machines of the same type will be needed in several cells, consequently there is a likelihood that some new plant must be purchased. In general, machine utilization is better and supervision costs are lower with larger cells. Also the balance of load between cells tend to be more even, period to period, with larger cells. Economic factors tend to contradict sociological factors over this matter.

This thesis aims at finding the most economical way of designing cellular manufacturing systems, in particular, for smaller firms, and so the economic factors are made the dominating criterion. The cells should be designed according to the natural divisions of the machines and components, with the minimum risk of increasing capital investments, even if this means that size of certain cell exceeds that recommended by the sociologists. In practice, the sizes of cells in a small firm will not be too large anyway.

## 6.5 Organising the Existing Production System

The next step is to organise the existing system and to make any changes which are needed before machine cells are introduced. For successful formation of cells in a department, the department itself should have the characteristics of a major group. This means that the inter-departmental material flow system must be rationalised before machine cells can be formed inside the departments. This can be achieved by carrying out an analysis of departments visited by each component. Nevertheless, if the departments involved are not exceptionally large, it will be easier and cheaper to analyse the components in each individual department in an attempt of finding the natural groupings. During this process, the inter-departmental material flow will become apparent and the problem can be solved at the same time.

The basic unreliability of the production data is a major cause of failure in implementing cellular manufacture. The data needed for analysis is usually readily available in most engineering firms. However, the level of accuracy of this information is generally low, and it must be manually checked and corrected before being used for any analysis. This is a very critical stage and if possible an experienced line management staff should be involved in the work so that any incorrect data which may lead to unfavourable results can be identified at an early time.

The data required for analysis can be obtained from various sources in a firm, and when there are more than one source for the same information, a compromise must be reached between the accessibility of the data and its accuracy. The basic data includes the following:

1) Component Identification - It is essential that every component has a unique identification throughout the company. Where multi-part drawings are issued each component included in one drawing must have a separate identifier. Usually this data exists in a company as the part list.

2) Machine Identification - There should be a plant list which identifies each machine or piece of equipment with a specific number. Ideally this identifier should also be a classification by type so that any part produced on a particular type can be transferred, whenever necessary, to any other machine which bears the same identifier.

3) Route Cards - Each component should have a route card which records its actual sequence of manufacture. Every activity from the issue of raw material to receipt of the completed component must be recorded as a separate operation.

Each operation should be denoted by the identifier of the machine on which it is carried out.

4) Product List - A list should be prepared for each product showing its composition by assemblies, sub-assemblies and piece parts. This list is required not only for load checking during the design stage, but also as an essential information for production control of the cell system.

Other relevant information needed for each component include an estimate of the required quantity, the average batch size, the moving cost per batch per unit distance, and finally a complexity code which should be assigned after examining the part drawing.

## 6.6 Data Processing and Group Formation

At this stage the information required for all components and machines involved should be available, ideally on computer files. The analysis is carried out with the aid of a computer.

Initially the components are sorted with respect to their complexity codes. In a listing in ascending order of complexity codes, the components will form large rough groups of specific types, i.e. rotational and non-rotational, with roughly similar dimensions and machining features. Since these rough groups are to be analysed further, it is essential that their sizes match that of the machine/component matrix whose dimension has been pre-determined by the DCA programme. The divisions should be based firstly on the first digit, then the second and third digits, and finally on the last two digits. The rough groups should follow the natural divisional lines and their sizes should always be smaller than the maximum permitted dimension.

After the rough groups are obtained, each one must be analysed separately by using the Direct Clustering Algorithm. A computer programme has been written for doing this work (see Appendix IA). Upon input of data, the programme first generates the machine/component matrix, then it carries out the iterative analysis automatically following a procedure as described in Chapter Four.

At the end of each iteration, a printout showing the final matrix pattern will be produced. It is necessary at this stage to manually examine the printout and to decide whether the result is satisfactory or otherwise. If improvement is required, adjustments to the date file, i.e. specifying the cell and column entries which should be temporarily deleted in the next iteration, can be made before the programme is run again. The programme can be run for as many times as necessary, until a satisfactory solution is finally obtained.

In the solution printout, components and machines will appear as clustering groups. Very often manual refinements of these groups are required in order to obtain a practical solution, e.g. if one type of machine is needed in more than one cell, then a decision must be made as how many machines are to be installed in each cell. A load checking for each machine group will provide useful information for the refinements. If reliable production times are not readily available, then a test production programme should be carried out to obtain the load figure for each group. If this figure exceeds the standard running time of the machines in the group, then it may be necessary to replan some works, to re-allocate some machines, or to buy new machines.

Having checked the load and decided on the allocation of machines to each group, the next step is to eliminate the exceptional components which do not fit into any of the existing machine groups completely. There are five ways of doing this:

(i) By re-routing operations from machines outside the group to other machines in the group which can do the same job.

(ii) By change of production method.

(iii) By change of component design.

(iv) By purchasing the component instead of making it.

(v) By further dividing or merging machine groups.

Sometimes the bad effects of exceptional components can be relatively insignificant, especially when the machine groups are carefully placed to minimize inter-cell material flow, in such cases the above methods should be used only if little effort is involved.

After the machine groups and component families are determined and the production cells are formed, the next stage will be layout planning to effect a smooth material flow within the system.

## 6.7 Group Layout Planning

Layout planning in a cellular manufacturing system includes the layout of production cells within the factory, and also that of individual machines within a production cell. A computer programme has been written to assist this task (see Appendix IB).

The computer programme first reads the basic data, such as number of machines, machine cells and components. Production data for each component, such as the identifier, quantity, batch size and the unit moving cost, are also required. The computer then proceeds to calculate the number of batches to be moved between every two machine cells and the moving cost, and a cross chart showing material moving costs as the weighted factor is produced. Next the programme automatically determines the first optimum triangle from this cross chart, this is the most tedious part of the ARP algorithm which has been discussed in detail in Chapter Five. The other steps in the determination of adjacency requirements are carried out manually in a chart form. This is because for practical problems in small firms, the computation effort involved in this part will be small and can be done satisfactorily with manual method. However, the nature of the ARP algorithm does permit total computerisation if later it is necessary.

The next stage is to redraw the maximal planar graph generated by the ARP algorithm and to construct the block diagram for layout planning, both are done manually as described in section 5.5. The allocation of areas to each cell in the factory will be decided on the basis of this block diagram and the machine sizes. Any constraints limiting the planning should be considered at an early stage, so that techniques such as overwriting the cross chart (section 5.6) can be used.

In choosing the positions for machine cells, it is essential to consider safety, material handling convenience, and easy access to sources of power supply. Each cell should be placed so that there is gangway access to the machines, and if possible, the boundaries between cells should run in straight lines from principal doorways and parallel to the walls and columns of the building.

The layout planning of machines in a cell follows a similar procedure as laying out the cells. The ARP algorithm will still be useful in this case, although the problem will be much simpler. Sometimes heavy machines requiring foundations may be difficult or uneconomical to move, then it may be necessary to accept a less perfect solution and plan the rest of layout to suit the positions of any unmoved machines. In general, a compromise between the simplication of material flow and the economy of making the change has to be reached.

## 6.8 Industrial Application

In the following chapter, the methodology developed so far in this thesis will be applied to solve a real life problem.

This is concerned with the re-organisation of plant layout in a small machine shop. This industrial application also serves the purpose of illustrating further how the techniques developed for introducing cellular manufacture can work.

## CHAPTER SEVEN

## 7. AN INDUSTRIAL APPLICATION OF CELLULAR MANUFACTURE

### 7.1 Introduction

This chapter is concerned with the implementation of cellular manufacture to a small machine shop. The work is intended for demonstrating the application of the methodology and techniques developed in the previous chapters to an industrial situation.

In the present economic climate, finding an industrial firm which is completely suitable for the intended study, and which is willing to give full co-operations to outside investigators is an extremely difficult task. The machine shop chosen was the North Toolroom at the Longbridge car plant of Austin Morris. This workshop is concerned mainly with one-off type production and repair work rather than repeated batch production, but ready documentation was available for the implementation of this methodology.

### 7.2 The North Toolroom at Longbridge

The North Toolroom is part of the overall manufacturing plant at Longbridge, which is one of the major plants of Austin Morris, which in turn is a part of B.L. cars - a subsection of British Leyland as a whole. It is now the only remaining large toolroom operative at Longbridge. The work taken on in this workshop is very varied. It includes tool grindings, fixture repairings, making new fixtures and producing spare parts for machines and part stores. Most jobs are one-off production, which are repeated only occasionally. The current practice in the North Toolroom at the time of study was as follows:-

When a job request was received by the main office and assigned to the planner, the planner would fill in a route card which included the jig or tool number, order number, control number, part name, quantity required, material details, order date and the route of this component through the factory which was given only by sections, e.g. milling, turning or drilling. The route card and job request, together with any other information about the job, were then passed on to the progress department.

Progress department obtained the required material from the store (or the existing item if the job was a repair), and took it to the foreman of the first section who would allocate the job to a suitable machine. After the first operation was finished, the component would be inspected within the same section, and if passed taken by progress to the next section. Upon completion of all operations, the component would be passed to final inspection and then returned to the originator of job request.

At the time of the study, machines in the North Toolroom were laid out in sections by function as shown in the original layout plan in figure 7.1. Since the components had to go from one section to another, the material flow pattern in the factory was very complicated. A discussion with the works manager had revealed that material flow through the workshop could possibly be improved or simplified by changing the plant layout on a cellular manufacture basis. It was decided that only the layout of machines should be changed, the compartments such as the main office, progress department, tool and guage room, etc., should remain unaltered.

### 7.3 Collecting Data

Before the analysis could be carried out, it had to be decided exactly what information was to be collected and in what form. For the purpose of this exercise, the following data was obtained.

#### (1) Plant List

First a list of every specific machine in the workshop was prepared. Initially each machine was given an identification number, with one number representing more than one machine only if they were absolutely identical. A complete plant list of the North Toolroom was compiled which included 199 machines, this is shown in table 7.2.

For the design purpose, machine types instead of machines should be considered. Therefore, it was necessary to compare the sizes, functions and capacities of machines in the plant list, and to classify them by type in such a way that any part processed on a particular machine could be transferred to any other machine of the same type. This classification was done manually and the original plant list was modified to contain 45 machine types. Each type was assigned a number as identification, and the revised plant list is shown in table

7.3. Throughout the analysis, any machine number would be referring to a machine type number in this new plant list.

(2) Component List

Next a component list was prepared. In an ideal case, this list would have been compiled of all components produced in the toolroom. However, this was not practical because the toolroom had produced mainly one-off jobs and no less than 50,000 different parts were made in the past. Given the limited time for data collection, it was decided that a sample of 500 components would probably serve the purpose of this study. The sample was selected from the representative components produced in the last eight months, covering as wide a range as possible.

Initially components in the toolroom were identified by their part names. After being selected as sample, each component was given a unique three-digit number for identification. Its part drawing was examined and a complexity code was assigned. A list of the sample components is shown in table 7.4.

(3) Data Collecting Sheet

The route card and planning sheet of each selected component was retrieved from the factory's filing system. From these the quantity ordered and the production route through the factory were obtained and entered onto a data collecting sheet next to the component number. The production route was represented by a series of identification numbers of machines visited by the component.

For layout planning, it was necessary to know the batch size and moving cost of every component. However, this data was not given in the route card nor readily available from other sources. After discussions with the works manager, it was decided that the practical way of obtaining this data was by estimation. Since most jobs were one-off small batch production, it was assumed the batch size of any component equal to the order quantity and its moving cost equal to unity. This data was also entered onto the data collecting sheet.

A complete list of component information is shown in the printout result of the ARP programme (see Appendix IIC).

## 7.4 Finding Machine Groups and Component Families

The first step of analysis was to divide the components into rough groupings by sorting their complexity codes, so that each rough group could be accommodated in a machine/component matrix. Since the number of components involved in this exercise was small, a sorting based on only the first digit of the code was sufficient. This was done manually during compilation of component information. As a result, two rough groups were formed, one comprised of 267 rotational and the other 233 non-rotational components.

Next the component information was analysed by using the DCA computer programme. Two data files were prepared, one for each rough group, and each was set out in a format specified by the programme (the DCA programme is self explanatory). Then the programme was run in conjunction with these data files in turn, following a procedure as described in the last chapter. The two solution machine/component matrices are shown in Appendices IIA and IIB.

Referring to Appendix IIA, the rotational components were divided into three families, and the machine groups formed were as follows:-

Group A - composed of machines number 3, 4, 6, 8, 11, 13, 18, 22, 28, 29, 31, 35, 36, 40, 43, 44 and 45.

Group B - composed of machines number 1, 5, 9, 19, 20, 21, 23, 24, 25 and 26.

Group C - composed of multiple machines number 2, 10, 27, 33, 39 and 41. These were also used by group A and group B.

Referring to Appendix IIB, the non-rotational components were divided into six families, and their respective machine groups were as follows:-

Group D - composed of machines number 3, 5, 10, 14, 18, 30, 31, 32, 34, 35, 37 and 44.

Group E - composed of machines number 4, 11, 12, 20, 21, 22, 28, 36, 40 and 42.

Group F - composed of machines number 7, 15, 26 and 27.

Group G - composed of machines number 17.

Group H - composed of machines number 16.

Group I - composed of multiple machines number 13, 33, 38, 39 and 41. These were also used by groups D, E, F and G.

A check was carried out to find that for certain machine types, the number of machines available was less than the number of groups requiring them, i.e. some machines had been over allocated. Because it had been decided that no new machine or equipment would be purchased, therefore reallocations of certain machines and modifications to groupings were necessary.

There was only one machine available for each of machine types 21, 35 and 37, these were combined with machines number 8, 30 and 32 to form a new group for heavy machining. Only one machine 22 and one machine 36 were available but were required by both group A and group E, these machines were placed in group A because of higher utilization there. The only two machine 4's were both allocated to group A for the same reason.

Group G and group H were combined to form a new group specializing in tool grinding. Group I was merged into group F to facilitate easier supervision.

Process number 39 was heat treatment and therefore formed a group by itself. Process 38 (mark out) and 41 (bench work) could be carried out in whichever group requiring them, since their installations were inexpensive.

After reallocations and modifications, nine groups were formed, these were as follows:-

Group 1 - composed of machines number 3, 4, 6, 11, 13, 18, 22, 28, 29, 31, 36, 38, 40, 41, 43, 44 and 45.

Group 2 - composed of machines number 1, 5, 9, 19, 20, 23, 24, 25, 26, 38 and 41.

Group 3 - composed of machines number 2, 10, 27, 33, 38 and 41.

Group 4 - composed of machines number 3, 5, 10, 14, 18, 31, 34, 38, 41 and 44.

Group 5 - composed of machines number 11, 12, 20, 28, 38, 40, 41 and 42.

Group 6 - composed of machines number 7, 13, 15, 26, 27, 33, 38 and 41.

Group 7 - composed of machines number 16 and 17.

Group 8 - composed of machines number 8, 21, 30, 32, 35 and 37.

Group 9 - composed of heat treatment plant number 39.

Since there were machine types allocated to more than one group, it was necessary to decide on how many machines were to be placed in which group. The decision was made on the basis of load checking on the machines concerned, the number of machines allocated to a group would be proportional to the number of components in the group using the machine. This was based on figures obtained from the solution machine/component matrices. The final machine distributions and machine group structures were presented in tabular form and is shown in figure 7.5.

## 7.5 Planning the Layout

At this stage, all machine groups had been formed and the problem was to place each of them in a specific area to form a cell. As described in the last chapter, the ARP programme was used to determine the adjacency requirements between these cells. All component information, inclusive of rotational and non-rotational, had to be employed in this analysis. A new data file was prepared for the programme in a specific format (the programme was self-explanatory). For machine types which appeared in more than one group, the machine number was listed with the group number for distinction. Thus number 113 and 613 represented machine number 13 of group 1 and group 6 respectively.

A list of workstation information was shown in the result printout of the ARP programme, this was followed by the cell information and component information, then by the flow value matrix generated by the computer programme (see Appendix IIC).

Because group 9 comprised heat treatment plants and was not situated at the North Toolroom, it would not be placed adjacent to another group in any case. Therefore, the matrix entries of group 9 were overwritten by zero to ensure a very low priority (see section 5.7). This was done automatically by the computer programme and the modified flow value matrix was shown in the printout following the original matrix.

The modified flow value matrix provided the basic data for the Adjacency Requirements Planning algorithm. The optimal triangle in each column and the overall optimum triangle had been determined by the computer. The other steps in applying the algorithm were carried out manually on a chart following a method as described in section 5.4, the solution obtained is shown in figure 7.6. Based on this result, a maximal planar graph showing relative positions of the machine cell was drawn (figure 7.7). Then it was redrawn to a form as shown in figure 7.8 in order to keep lighter material flows to the outer areas of the layout. As indicated by the flow value matrix, there was no material flowing from group 9 to group 6, 7 or 1, also there was no material flows between group 3 and group 4, these were represented by broken lines in figure 7.8, and were disconnected later during the construction of its dual graph (figure 7.9).

Based on the dual graph, a block diagram was constructed. As shown in figure 7.10, this block diagram was drawn to the shape of the toolroom, hence adjacencies between some cells had to be sacrificed to satisfy geographical constraints. By referring to the flow value matrix, the three less important links between 1-4, 1-6 and 2-8 were disconnected. Together with the two connections, 4-5 and 4-7, which were not included in the maximal planar graph, the total flow value lost in the present block diagram was 9 units. With an overall flow value of 769 units, therefore, a plant layout based on this block diagram would result in more than 98% of material flows taking place between adjacent cells, and the problem of inter-cell material flow was practically solved.

After positions of the manufacturing cells had been fixed, the next step was to plan the layout of machines within each cell. The ARP algorithm was not employed at this stage, mainly because the sizes of component families were too small for systematic analysis, and any result obtained would be very unlikely representative. However, since a machine cell was relatively small, its layout problem could well be solved intuitively. Heavily loaded machines were placed near to the cell centre, while machines shared by other cells were located near to the boundaries. If a number of machines of the same type were available in a cell, they would be distributed evenly to minimise back trackings.

Based on the block diagram obtained previously and the machine areas as specified in the original layout plan, a new plant layout diagram for the North Toolroom was constructed (figure 7.11). The machines were laid out by component types in eight cells, which were positioned in such a way to optimise material flows through the factory.

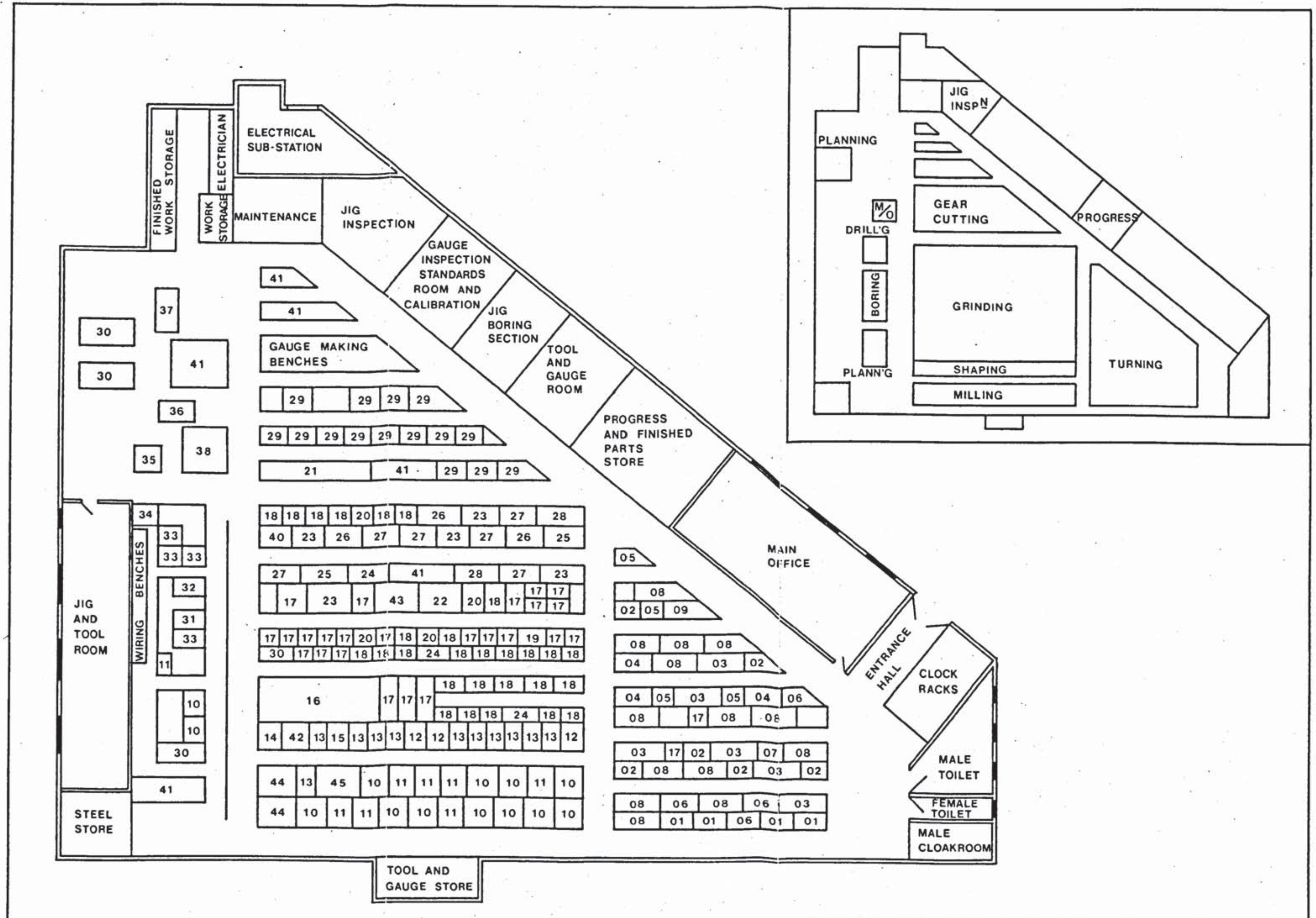
## 7.6 Discussions and Conclusions

It has been shown that the methodology for implementing cellular manufacture can be applied to an industrial situation to obtain satisfactory results. Since the North Toolroom is basically a job shop, the analysis had to be carried out with a sample of parts. The components were chosen from past order, although as randomly as possible, there might still be bias towards similar components. If more time was given for data collection, the sample would have been larger and covering a wider range of components, and more reliable results could be expected. Nevertheless, the results achieved in this study have been satisfactory for academic purpose.

With a large component sample, the complexity code could have been used to obtain several rough groupings prior to use of the DCA programme. Machine groups formed would be smaller and more specific to certain component types, so that upon receiving a job, the planner would be able to decide fairly easily on which cell suitable for making the part. Since a larger number of components would be adhered to each group, the ARP programme could be used to find an optimal layout for machines within each cell, as well as for the whole workshop.

As shown in figure 7.5, the machine groups formed were rather distinct, and it was possible to specify a general component type for each group. The result of adjacency requirements planning was exceptionally good, with more than 98% of material flows being confined to adjacent cells. The final layout plan suggested for the toolroom clearly exhibited the tidiness and good organisation which one would expect from a cellular manufacturing system.

During the study, it was found that the demand on certain machines were low, e.g. large shapers and millers, whilst some machines were heavily loaded, e.g. small and medium lathes. This suggested that the machine mix in the toolroom was probably not well balanced. There was a high demand for works to be done on the four vertical drills, therefore, the purchase of another drilling machine would probably be a worthwhile investment, otherwise this could be eased by re-planning parts to be drilled on lathes.



(Refer to the revised plant list for machine types)

Figure 7.1 Original Layout Plan of the North Toolroom at Longbridge, Austin Morris. Machines are Laid Out by Functions.

TURNING SECTION

| M/C No. | Description | No. Off | Swing & Length | Taper Turn | Metric Screw Cut |
|---|---|---|---|---|---|
| 13001 | Herbert Capstan No. 3 | 1 | 10" x 16" | No | Yes |
| 13002 | Herbert Senior Capstan type No. 4 | 2 | 16" x 12" | No | Yes |
| 13004 | Herbert Junior turret lathe | 1 | 16" x 12" | No | Yes |
| 13005 | Herbert 2D bar feed capstan | 1 | | | |
| 12006 | Churchill 15 ML lathe | 1 | 16" x 42" | Yes | Yes |
| 90007 | Handpress | 1 | | | |
| 12008 | Dean Smith and Grace type 26 lathe | 1 | 26" x 96" | Yes | Yes |
| 11009 | Holbrook Model C No. 16 sliding, surfacing and screwcutting lathe | 1 | | Yes | Yes |
| 12010 | Holbrook Model 17B S, S and SC lathe | 3 | 18½" x 42" | Yes | Yes |
| 11011 | Dean Smith and Grace type 1609 lathe | 1 | 17" x 36" | Yes | Yes |
| 12012 | Dean Smith and Grace type 13/1 lathe, high speed head lathe | 3 | 13" x 42" | Yes | Yes |
| 10013 | Dean Smith and Grace type 13/2 lathe | 3 | 13" x 30" | Yes | Yes |
| 10014 | Monarch Centre lathe | 2 | 16" x 30" | Yes | Yes |
| 12016 | Dean Smith and Grace type 17 Centre lathe | 4 | 17" x 48" | Yes | Yes |
| 10018 | Type 13C Holbrook S, S and SC lathe | 2 | 14" x 30" | Yes | Yes |
| 11020 | Reinker cutter relieving lathe | 1 | | No | No |
| 10021 | Pratt and Whitney Model B toolroom lathe | 3 | 13" x 30" | Yes | No |
| 59023 | Hand held tool grinder | | | | |
| 12025 | Type 17 Dean Smith and Grace | 1 | 17" x 120" | Yes | Yes |
| 10029 | Type 13/1 Dean Smith and Grace | 1 | 16" x 30" | Yes | Yes |
| 10030 | Kaerger Model DL 1 high speed precision turning lathe | 2 | 10" x 19" | No | Yes |
| 10031 | Monarch Centre lathe | 3 | 16" x 30" | No | No |
| 10035 | Hardinge HLV precision lathe | 1 | 7" x 24" | Yes | Yes |
| 12041 | Dean Smith and Grace gap bed centre lathe | 1 | 25" x 60" | Yes | Yes |
| 12042 | Monarch Timkenised lathe Model AA | 1 | 16" x 54" | Yes | No |
| 10043 | Le-Bond lathe | 1 | 15" x 30" | No | No |

MILLING SECTION

| M/C No. | Description | No. Off |
|---|---|---|
| 21001 | Cincinatti vertical miller | 5 |
| 21002 | Kearney and Trecker Milwaukee vertical miller | 4 |
| 21004 | S.H.W. vertical miller | 1 |
| 24005 | Cincinatti horizontal miller | 5 |
| 24009 | Kearney and Trecker Milwaukee horizontal miller | 2 |
| 26011 | Butler slotter with dividing table | 2 |
| 27020 | Asquith HK1 duplex keyseating machine | 1 |

Figure 7.2 Original Plant List of the North Toolroom

SHAPING SECTION

| M/C No. | Description | No. Off |
|---|---|---|
| 30021 | American 18" shaper | 1 |
| 31023 | CR 24" heavy duty shaper | 3 |
| 30024 | CR 18" heavy duty shaper | 6 |
| 30026 | Butler 18" shaper | 4 |
| 30035 | Brook Cam shaper | 1 |
| 30037 | Ormerod 18" shaper | 1 |
| 32038 | CR 32" heavy duty | 1 |
| 40000 | Small sawgrinders | 3 |
| 40001 | Noble sawgrinders | 3 |
| 40002 | Tooth cutter | 1 |
| 40003 | Rivet smoother | 1 |

GEAR CUTTING SECTION

| M/C No. | Description | No. Off |
|---|---|---|
| 90126 | Mills 20 ton press | 1 |
| 90127 | 16 ton press | 1 |
| 60128 | Bradner machine (cuts screws, worms, etc.) | 1 |
| 60129 | Pfauter fobbing machine | 2 |
| 60130 | Bevel gear cutter | 1 |
| 60131 | Maxicut shaper | 1 |
| 60132 | Felbus shaper | 1 |
| 60133 | Press | 1 |
| 60134 | Hurth gear grinders | 3 |
| 60137 | Thiel 117 precision bandsawing and filing machine | 1 |
| 82138 | Planning machine, 2 headed, 10ft stroke | 1 |
| 82139 | Bridgeport vertical miller | 1 |
| 22140 | Cincinatti vertical miller | 1 |
| 24141 | Horizontal miller | 1 |
| 73142 | Horizontal jig borer | 1 |
| 73143 | Kearney-Trecker horizontal jig borer | 1 |
| 75144 | Devlieg horizontal jig mill | 1 |
| 72145 | Archdale vertical spindle swinging head drill | 2 |
| 70147 | Herbert vertical spindle drill | 2 |
| 25148 | Gidding Lewis and Frazer very heavy duty mill borer | 1 |
| 74149 | Numerically controlled cintematic drill | 1 |
| 92150 | Wild-Barfield tip brazing machine | 1 |
| 82151 | Stirk planning machine - 10ft stroke, 2 headed | 1 |
| 82152 | Waldrich Coburg planning machine - 10ft stroke, 2 headed | 1 |
| 12153 | 'Lang' lathe swing 6ft x 1ft in front of headstock 4ft between centres | 1 |

Figure 7.2 Original Plant List (continued)

GRINDING SECTION

| M/C No. | Description | No. Off |
|---|---|---|
| 50039 | Waldrich Siegen-Ingersoll milling cutter grinders | 3 |
| 51043 | Jones and Shipman surface grinder (s) | 19 |
| 51047 | Norton surface grinder | 1 |
| 51046 | Browne and Sharp surface grinder (s) | 4 |
| 56045 | Hudson Lapoint cylindrical grinder (m) | 1 |
| 51059 | Cincinatti surface grinder (s) | 2 |
| 50063 | Fixture for grinding special boring tool | 1 |
| 50064 | With workhead and chuck (cutter grinder) | 2 |
| 59067 | Benon tool grinder, two wheels | 1 |
| 59068 | Lumsden tool grinder, four wheels | 1 |
| 52069 | Cutmaster 'parting off' grinder | 1 |
| 59070 | Hand tool grinder (Abwood) | 2 |
| 50072 | Cincinatti cutter grinder | 7 |
| 52074 | Browne and Sharp surface grinder (m) | 1 |
| 50076 | Jones and Shipman drill grinder | 1 |
| 52077 | Cincinatti surface grinder (m) | 1 |
| 50083 | Bench grinders - drill sharpening | 4 |
| 50087 | Dormer cutter grinder | 1 |
| 51088 | Sparcotron surface grinder (s) | 1 |
| 52089 | Norton Asquith surface grinder (m) | 1 |
| 54090 | Jones and Shipman internal grinder | 1 |
| 52091 | Churchill spline grinder | 1 |
| 50092 | Cincinatti cutter grinder (drills) | 1 |
| 52093 | Lumsden rotary grinder | 1 |
| 50094 | Jones and Shipman cutter grinder | 1 |
| 52096 | Churchill rotary grinder | 1 |
| 58097 | Churchill 24" x 40" universal grinder | 1 |
| 58098 | 14" x 51" Cincinatti universal grinder | 1 |
| 56099 | Jones and Shipman cylindrical grinder | 1 |
| 57100 | Cincinatti cylindrical grinder | 1 |
| 58101 | 12" x 36" Cincinatti universal grinder | 1 |
| 58102 | 10" x 40" Jones and Shipman cylindrical grinder | 1 |
| 58103 | Jones and Shipman 8" x 24" universal grinder | 1 |
| 58104 | Landis type C 14" x 36" universal grinder | 1 |
| 55105 | Cincinatti 7" x 16" cylindrical grinder | 3 |
| 58106 | Browne and Sharp 12" x 30" universal grinder type 2 | 1 |
| 58107 | Browne and Sharp 14" x 30" universal grinder type 2 | 1 |
| 58108 | Churchill 10" x 24" universal grinder | 2 |
| 91110 | Speedhone honing machine | 1 |
| 58111 | Browne and Sharp universal grinder (1) | 1 |
| 58112 | Jones and Shipman universal grinder (m) | 1 |
| 52117 | Abwood surface grinder (m) | 1 |
| 53122 | Marwin grinding machine (not in use) | 1 |
| 53123 | Crystal lake grinder, universal | 1 |
| 65124 | Jones and Lawson automatic thread grinder | 1 |
| 53125 | Large surface grinder, 5ft magnetic chuck | 1 |

Figure 7.2 Original Plant List (continued)

| M/C Type No. | Description | No. off | M/C No. |
|---|---|---|---|
| 01 | Capstan Lathes | 4 | 13001 - 13005 |
| 02 | Small Lathe ( 30" length) taper turn and metric screwcut | 6 | 10013, 10018, 10035 |
| 03 | Small Lathe, taper turn, no metric | 6 | 10014, 10021, 10024 |
| 04 | Small Lathe, metric, no t.t. | 2 | 10030 |
| 05 | Small Lathe, no metric, no t.t. | 4 | 10031, 10043 |
| 06 | Medium Lathe (30" - 40" length) t.t. and metric | 2 | 11009, 11011 |
| 07 | Reinker Cutter Relieving Lathe | 1 | 11020 |
| 08 | Large Lathe ( 41"), taper turn and metric | 14 | 12010, 12012, 12016, 12025, 12006, 12008 |
| 09 | Monarch Lathe 16" x 54", taper turn, no metric | 1 | 12042 |
| 10 | Vertical Miller | 12 | 21001, 21002, 21004, 20139, 20140 |
| 11 | Horizontal Miller | 8 | 24005, 24009, 24141 |
| 12 | 24" Shaper | 3 | 31023 |
| 13 | 18" Shaper | 12 | 30024, 30021, 30026, 30027 |
| 14 | 32" Shaper | 1 | 32038 |
| 15 | Cam Shaper | 1 | 30035 |
| 16 | Saw Grinding Section | 1 | 40000 - 40003 |
| 17 | Cutter Grinders, i.e. Drill Grinders, Milling Cutter Grinders, Ream Grinders, Hand Held Tool Grinders, etc. | 22 | 50039, 50063, 50064, 59067, 59068, 59070, 50072, 50076, 50083, 50087, 50092, 50094 |
| 18 | Small Surface Grinder | 27 | 51043, 51047, 51046, 51059, 51088 |
| 19 | "Parting off" Grinder | 1 | 52069 |
| 20 | Medium Surface Grinder | 3 | 52074, 52077, 52117 |
| 21 | Large Surface Grinder (5ft chuck) | 1 | 53125 |
| 22 | Jones and Shipman Internal Grinder | 1 | 54090 |

Figure 7.3 The Revised Plant List

| M/C Type No. | Description | No. off | M/C No. |
|---|---|---|---|
| 23 | Cylindrical Grinder (small) | 3 | 55105 |
| 24 | Cylindrical Grinder (medium) | 2 | 56045, 56099 |
| 25 | Cylindrical Grinder (large) | 1 | 57100 |
| 26 | Universal Grinder (small 25" length) | 3 | 58103, 58108 |
| 27 | Universal Grinder (medium 25" - 40") | 6 | 58104, 58106, 58107, 58112, 58097, 58101 |
| 28 | Universal Grinder (large 40") | 2 | 58098, 57111 |
| 29 | Gear Cutting Section | 13 | 90126 60137 |
| 30 | Planning machine, 2 heads, 10ft stroke | 3 | 82138, 82151, 82152 |
| 31 | Horizontal Jig-Borer | 2 | 73142, 73143 |
| 32 | Horizontal Jig-Mill | 1 | 75144 |
| 33 | Archdale verticle spindle swinging head drill | 2 | 72145 |
|  | Herbert verticle spindle drill | 2 | 70147 |
| 34 | Gidding Lewis and Frazer very heavy duty mill borer | 1 | 25148 |
| 35 | N/C Cintematic Drill | 1 | 74149 |
| 36 | Wild-Barfield tip brazing machine | 1 | 12150 |
| 37 | 'Lang' lathe, swing 6ft x 1ft in front headstock. 4ft between centres | 1 | 12153 |
| 38 | Mark out | - | - |
| 39 | Heat treat, carbon harden, etc. | - | - |
| 40 | Engrave | - | - |
| 41 | Fraze and Bench operations | - | - |
| 42 | Bandsaw | - | - |
| 43 | Churchill spline grinder | - | - |
| 44 | Butler slotters | - | - |
| 45 | Asquith keyseater | - | - |

Figure 7.3 The Revised Plant List (continued)

| Cpt. No. | Cpt. Type | Cpt. No. | Cpt. Type |
|---|---|---|---|
| 001 | Bush | 064 | Bush |
| 002 | Cap | 065 | Strip |
| 003 | Spindle | 066 | Strip |
| 004 | Gear | 067 | Bush |
| 005 | Spindle | 068 | Retaining Screw |
| 006 | Roller Spindle | 069 | Guide |
| 007 | Slipper Insert | 070 | Drift |
| 008 | Gear | 071 | Locating Pillar |
| 009 | Spacer | 072 | Base |
| 010 | Bush | 073 | Tailstock Centre |
| 011 | Worm | 074 | Headstock Centre |
| 012 | Worm Wheel | 075 | Drift |
| 013 | Location Peg | 076 | Bush |
| 014 | Bush | 077 | Location Spigot |
| 015 | Spacer | 078 | Shim |
| 016 | Spindle | 079 | Drive Gear |
| 017 | Spindle | 080 | Gear |
| 018 | Spindle | 081 | Gear |
| 019 | Roller | 082 | Gear |
| 020 | Spindle | 083 | Gear |
| 021 | Arm | 084 | Gear |
| 022 | Location Ring | 085 | Gear |
| 023 | Location Bung | 086 | Gear |
| 024 | Bush | 087 | Gear |
| 025 | Gear | 088 | Sleeve |
| 026 | Spigot | 089 | Spindle |
| 027 | Centre | 090 | Distance Piece |
| 028 | Drawbar | 091 | Distance Piece |
| 029 | Location Peg | 092 | Intermediate Shaft |
| 030 | Spigot | 093 | Intermediate Shaft |
| 031 | Extension Pad | 094 | Packing Piece |
| 032 | Clamp Screw Pad | 095 | Dowel |
| 033 | Screw Location Pad | 096 | Dowel |
| 034 | Clamp Handle | 097 | Dowel |
| 035 | Clamp | 098 | Plate |
| 036 | Clamp Stud | 099 | Spacer |
| 037 | Locating Peg | 100 | Spacer |
| 038 | Location Pad | 101 | Spindle |
| 039 | Location Pad | 102 | Spindle |
| 040 | Strengthening Fillet | 103 | Top Casting |
| 041 | Vertical Face of Fixture | 104 | Intermediate Casting |
| 042 | Retaining Screw | 105 | Location Bung |
| 043 | Slip Brush | 106 | Shaft |
| 044 | Locking Screw | 107 | Drive Gear |
| 045 | Liner Brush | 108 | Sleeve |
| 046 | Drill Brush Head | 109 | Bush |
| 047 | Sub Assy. of Fixture | 110 | Gear |
| 048 | Location Peg | 111 | Spindle |
| 049 | Bracket | 112 | Jaw Inserts |
| 050 | Base | 113 | Jaw Body |
| 051 | Location Shoe | 114 | Jaw Body |
| 052 | Dowel | 115 | Centre |
| 053 | 'Destago' Clamp | 116 | Snug |
| 054 | Locator Housing | 117 | Clamp |
| 055 | 'Vee' Block | 118 | Clamp |
| 056 | Locator | 119 | Stud |
| 057 | Peg | 120 | Wing Nut Shank |
| 058 | 'Vee' Block | 121 | Wing Nut Blade |
| 059 | Steady | 122 | Locator |
| 060 | Base Plate | 123 | Headstock Centre |
| 061 | Clamping Bracket | 124 | Bush |
| 062 | Body Housing | 125 | Drive Key |
| 063 | Plunger | 126 | Drive Pin |

Figure 7.4 The Component List

| Cpt. No. | Cpt. Type |
|---|---|
| 127 | Drive Block |
| 128 | End Bush |
| 129 | Mandrel |
| 130 | Sleeve |
| 131 | Spinella |
| 132 | Moving Jaw |
| 133 | Fixed Jaw |
| 134 | Bush |
| 135 | Bush |
| 136 | Drive Gear |
| 137 | Gear |
| 138 | Spindle Gear |
| 139 | Idler/Gear |
| 140 | Vee Locator RH |
| 141 | Vee Locator LH |
| 142 | Raising Block |
| 143 | Locating Peg |
| 144 | Raising Block |
| 145 | Vee Block LH |
| 146 | Vee Block RH |
| 147 | Clamp Block |
| 148 | Locator |
| 149 | Chuck Jaws |
| 150 | Eccentril Shaft |
| 151 | Ram |
| 152 | Splined Shaft |
| 153 | Pinion |
| 154 | Clamp Ram |
| 155 | Gear |
| 156 | Gear |
| 157 | Thrust Washer |
| 158 | Bush |
| 159 | Shaft |
| 160 | Tailstock Centre |
| 161 | Workhead Centre |
| 162 | Workhead Centre |
| 163 | Tailstock Centre |
| 164 | End Cap |
| 165 | Spindle Quill |
| 166 | End Cap |
| 167 | Driving Key |
| 168 | Housing |
| 169 | Main Spindle |
| 170 | Main Spindle |
| 171 | Spherical Locator |
| 172 | Rest Pad |
| 173 | Spherical Washer |
| 174 | Clevis Pin |
| 175 | Clamp |
| 176 | Link Arm |
| 177 | Knuckle |
| 178 | Location Bung |
| 179 | Location Bung |
| 180 | Spring Housing |
| 181 | Knuckle |
| 182 | Clamp Arm |
| 183 | Bush |
| 184 | Clamp Arm |
| 185 | Bush |
| 186 | Drive Key |
| 187 | Drive Key |
| 188 | End Stop Bush |
| 189 | End Stop Bush |
| 190 | Centre |
| 191 | End Plate |
| 192 | Bush |
| 193 | Insert |
| 194 | Chuck Jaws |
| 195 | Insert |
| 196 | Chuck Jaws |
| 197 | Locating Peg |
| 198 | Locating Peg |
| 199 | Locator |
| 200 | Pin |
| 201 | Lever |
| 202 | Arm |
| 203 | Locator |
| 204 | Clamp |
| 205 | Collar |
| 206 | Broach |
| 207 | Arbor Spindle |
| 208 | Arbor |
| 209 | Collar |
| 210 | Circular Form Tool |
| 211 | Circular Form Tool |
| 212 | Boring Bar |
| 213 | Cutter |
| 214 | Dove-Tail Shaving Tool |
| 215 | Part-Off Tool |
| 216 | Cam |
| 217 | Tip |
| 218 | De-Burring Tool |
| 219 | Chamfer Tool |
| 220 | Tool Holder |
| 221 | Turning Tool |
| 222 | Key |
| 223 | Dummy Laygear Shaft |
| 224 | Chamfer Tool |
| 225 | Facing Tool |
| 226 | Tool Holder Body |
| 227 | Holder |
| 228 | Change Gear |
| 229 | Copy Template |
| 230 | Push Rod Sleeve |
| 231 | Splined Shaft |
| 232 | Blow Bush |
| 233 | Blow Bush |
| 234 | Trip Dog |
| 235 | Trip Dog |
| 236 | Reaction Pad |
| 237 | Bung |
| 238 | Extractor |
| 239 | Bush |
| 240 | Guide |
| 241 | Guide |
| 242 | Locator |
| 243 | Slide Block |
| 244 | Stop Pad |
| 245 | Stop Pad |
| 246 | Yoke |
| 247 | Slide Jack |
| 248 | Pillar |
| 249 | Keeper |
| 250 | Tee Nut |
| 251 | Clip |
| 252 | Nut |
| 253 | Nut |
| 254 | Cam |

Figure 7.4 The Component List (continued)

| Cpt. No. | Cpt. Type | Cpt. No. | Cpt. Type |
|---|---|---|---|
| 255 | Bracket | 319 | Rod Adaptor |
| 256 | Cover | 320 | Setting Block |
| 257 | Stop | 321 | Mounting Plate |
| 258 | Stop | 322 | Spacer |
| 259 | Packer | 323 | Adaptor |
| 260 | Thrust Block | 324 | Tailstock Block |
| 261 | Packing | 325 | Bush |
| 262 | Packing Block | 326 | Spindle |
| 263 | Bracket | 327 | Centre |
| 264 | Bracket | 328 | Cam Locator |
| 265 | Bracket | 329 | Journal Locator |
| 266 | Base Plate | 330 | Centre Block |
| 267 | Insert | 331 | Centre Block |
| 268 | Insert | 332 | Base Plate |
| 269 | Spacer Bar | 333 | Top Casting |
| 270 | Pin | 334 | Body Casting |
| 271 | Collar | 335 | Body Casting |
| 272 | Nut | 336 | Body Casting |
| 273 | Jaw | 337 | Top Plate |
| 274 | Bolt | 338 | Bush Plate |
| 275 | Fixed Saw | 339 | Outer Tube Housing |
| 276 | Plate | 340 | Support Bracket |
| 277 | Exhaust Flange | 341 | Location Casting |
| 278 | End Plates | 342 | Top Bolster |
| 279 | Carriage Plate | 343 | Adaptor Plate |
| 280 | Carriage Plate | 344 | Intermediate Plate |
| 281 | Bearing Housing | 345 | Top Casting |
| 282 | Output Dr. Gear | 346 | Body Casting |
| 283 | Idler Gear | 347 | Location Pad |
| 284 | Copy Template | 348 | Block |
| 285 | Copy Template | 349 | Fixture Base |
| 286 | Handle | 350 | Top Casting |
| 287 | Support Guidearm | 351 | Intermediate Casting |
| 288 | Support Plate | 352 | Body Casting |
| 289 | Fillet Support | 353 | Top Plate |
| 290 | Stud | 354 | Base Plate |
| 291 | Setting Master | 355 | Washer |
| 292 | Support Block | 356 | Body Casting |
| 293 | Feed Template | 357 | Body Casting |
| 294 | Spool Plate | 358 | Jig Body |
| 295 | Dowel | 359 | Main Spindle |
| 296 | Dowel | 360 | Bush |
| 297 | Tennon | 361 | Body Casting |
| 298 | Setting Block | 362 | Fixture Body Casting |
| 299 | Bush | 363 | Base Plate |
| 300 | Location Block | 364 | Body Casting |
| 301 | Special Dowel | 365 | Turning Tool |
| 302 | Rough Location Block | 366 | Turning Tool |
| 303 | Valve Striker | 367 | Turning Tool |
| 304 | Side Plate | 368 | Part-Off Tool |
| 305 | Location Screw | 369 | Chamfer Tool |
| 306 | Spacer | 370 | Turning Tool |
| 307 | Side Plate | 371 | Milling Cutter |
| 308 | Valve Mounting Plate | 372 | Milling Cutter |
| 309 | Valve Mounting Plate | 373 | Chamfer Tool |
| 310 | Mounting Bracket | 374 | Milling Cutter |
| 311 | Cylinder Rod Adaptor | 375 | Milling Cutter |
| 312 | Adaptor Plate | 376 | Milling Cutter |
| 313 | Guide Strip | 377 | Drill |
| 314 | Locator | 378 | Drill |
| 315 | Location Roller | 379 | Drill |
| 316 | Radial Locator | 380 | Drill |
| 317 | Side Plate | 381 | End Mill |
| 318 | Location Block | 382 | Turning Tool |

Figure 7.4 The Component List (continued)

| Cpt. No. | Cpt. Type |
|---|---|
| 383 | Part-Off Tool |
| 384 | Shaping Tool |
| 385 | Shaping Tool |
| 386 | Shaping Tool |
| 387 | Chamfer Tool |
| 388 | End Mill |
| 389 | End Mill |
| 390 | Turning Tool |
| 391 | Turning Tool |
| 392 | Circular Saw |
| 393 | Circular Saw |
| 394 | Circular Saw |
| 395 | Circular Saw |
| 396 | Circular Saw |
| 397 | Circular Saw |
| 398 | Circular Saw |
| 399 | Circular Saw |
| 400 | Circular Saw |
| 401 | Circular Saw |
| 402 | Spindle |
| 403 | Arm |
| 404 | Gear |
| 405 | Location Pad |
| 406 | Clamp Handle |
| 407 | Dowel |
| 408 | Base Plate |
| 409 | Bush |
| 410 | Dowel |
| 411 | Spacer |
| 412 | Bolt |
| 413 | Centre |
| 414 | Drive Key |
| 415 | Idler Gear |
| 416 | Pinion |
| 417 | Housing |
| 418 | Pin |
| 419 | Collar |
| 420 | Pin |
| 421 | Nut |
| 422 | Jaw |
| 423 | Bolt |
| 424 | Fixed Jaw |
| 425 | Plate |
| 426 | Exhaust Flange |
| 427 | End Plates |
| 428 | Carriage Plate |
| 429 | Bearing Housing |
| 430 | Output Drive Gear |
| 431 | Idler Gear |
| 432 | Copy Template |
| 433 | Gear Shaft |
| 434 | Locator Rack |
| 435 | Change Gear |
| 436 | Plate |
| 437 | Spigot |
| 438 | Bearing Cover |
| 439 | Bearing Housing |
| 440 | Cam |
| 441 | Former Plate |
| 442 | Change Gear |
| 443 | Brass Pad |
| 444 | Stop Screw |
| 445 | Bush |
| 446 | Bush |
| 447 | Shoe |
| 448 | Jaw |
| 449 | Jaw |
| 450 | Sleeve |
| 451 | Tee Nut |
| 452 | Retaining Plate |
| 453 | Stud |
| 454 | Key |
| 455 | Key Piece |
| 456 | Bung |
| 457 | Retaining Plate |
| 458 | Sleeve |
| 459 | Adjusting Screw |
| 460 | Bush |
| 461 | Lever |
| 462 | Adjusting Screw |
| 463 | Location Block |
| 464 | Sliding Block |
| 465 | Base |
| 466 | Top Gear |
| 467 | Coupling Shaft |
| 468 | Feed Pinion |
| 469 | Loading Arm Shaft |
| 470 | Boss |
| 471 | Pinion Bush |
| 472 | Driving Gear |
| 473 | Intermediate Gear |
| 474 | Tie Bar |
| 475 | Probe |
| 476 | Mouting Block |
| 477 | Gauge Plate |
| 478 | Changing Gear |
| 479 | Block |
| 480 | Stud Adaptor |
| 481 | Drive Peg |
| 482 | Drive Flange |
| 483 | Splined Drive Shaft |
| 484 | Upper Ejector Pin |
| 485 | Pin Base (small) |
| 486 | Pin Base (large) |
| 487 | Slip Bolt |
| 488 | Packing Block |
| 489 | Bracket |
| 490 | Base Plate |
| 491 | Tool Holder |
| 492 | Gear Spanner Handle |
| 493 | Gear Spanner End |
| 494 | Guide Plate |
| 495 | Cap |
| 496 | Locating Pillar |
| 497 | Gear |
| 498 | Spacer |
| 499 | Spindle |
| 500 | Drive Pin |

Figure 7.4 The Component List (continued)

| GROUP NUMBER AND GENERAL COMPONENT TYPE | M/C NO. | M/C TYPE | NO. ALLOCATED |
|---|---|---|---|
| <u>GROUP 1</u><br>Small to medium rotational components. Components with screw threads, flats, slots, keyways, splines, gear teeth, internal ground surfaces and engravings. | 3 | lathe (s) | 4 |
| | 4 | metric lathe (s) | 2 |
| | 6 | metric lathe (m) | 2 |
| | 11 | horizontal miller | 5 |
| | 13 | 18" shaper | 6 |
| | 18 | surface grinder (s) | 10 |
| | 22 | internal grinder | 1 |
| | 28 | universal grinder (l) | 1 |
| | 29 | gear cutter | 13 |
| | 31 | horizontal jig borer | 1 |
| | 36 | tip brazing machine | 1 |
| | 38 | mark out table | 1 |
| | 40 | engraving machine | 1 |
| | 41 | bench | 1 |
| | 43 | spline grinder | 1 |
| | 44 | slotter | 1 |
| | 45 | keystation | 1 |
| <u>GROUP 2</u><br>Shafts and other rotational components requiring fine finishes, large batch of rotational components. | 1 | capstan lathe | 4 |
| | 5 | lathe (s) | 2 |
| | 9 | monarch lathe (l) | 1 |
| | 19 | part-off grinder | 1 |
| | 20 | surface grinder (m) | 1 |
| | 23 | cylindrical grinder (s) | 3 |
| | 24 | cylindrical grinder (m) | 2 |
| | 25 | cylindrical grinder (l) | 2 |
| | 26 | universal grinder (s) | 1 |
| | 38 | mark out table | 1 |
| | 41 | bench | 1 |
| <u>GROUP 3</u><br>General machining. | 2 | metric lathe (s) | 6 |
| | 10 | vertical miller | 8 |
| | 27 | universal grinder (m) | 4 |
| | 33 | vertical drill | 2 |
| | 38 | mark out table | 1 |
| | 41 | bench | 1 |

Figure 7.5 The Final Machine Group Structures

| | | | |
|---|---|---|---|
| GROUP 4<br>Blocks, rectangular bars, flat components, non-rotational components requiring boring. | 3 | lathe (s) | 2 |
| | 5 | lathe (s) | 2 |
| | 10 | vertical miller | 4 |
| | 14 | 32" shaper | 1 |
| | 18 | surface grinder (s) | 17 |
| | 31 | horizontal jig-borer | 1 |
| | 34 | mill borer | 1 |
| | 38 | mark out table | 1 |
| | 41 | bench | 1 |
| | 44 | slotters | 1 |
| GROUP 5<br>Flat strips, small blocks, non-rotational components requiring fine finishes. | 11 | horizontal miller | 3 |
| | 12 | 24" shaper | 3 |
| | 20 | surface grinder (m) | 2 |
| | 28 | universal grinder (l) | 1 |
| | 38 | mark out table | 1 |
| | 40 | engraving machine | 1 |
| | 41 | bench | 1 |
| | 42 | bandsaw | 1 |
| GROUP 6<br>All cam productions, general machining. | 7 | relieving lathe | 1 |
| | 13 | 18" shaper | 6 |
| | 15 | cam shaper | 1 |
| | 26 | universal grinder (s) | 2 |
| | 27 | universal grinder (m) | 2 |
| | 33 | vertical drill | 2 |
| | 38 | mark out table | 1 |
| | 41 | bench | 1 |
| GROUP 7<br>All saw and cutter grinding. | 16 | saw grinders | 8 |
| | 17 | cutter grinders | 22 |
| GROUP 8<br>Heavy duty machining and very large components. Components requiring processing on NC drill. | 8 | metric lathe (l) | 14 |
| | 21 | surface grinder (l) | 1 |
| | 30 | planning machine | 3 |
| | 32 | horizontal jig-mill | 1 |
| | 35 | NC cintematic drill | 1 |
| | 37 | long lathe (l) | 1 |
| GROUP 9<br>All heat treated components. | 39 | heat treating plants | 1 |

Figure 7.5 The Final Machine Group Structures (continued)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 9 | 327 | 2 | 12 | 4 | 0 | 59 | 0 | |
| 2 | 9 | 0 | 16 | 0 | 0 | 0 | 0 | 1 | 0 | |
| 3 | 327 | 16 | 0 | 0 | 0 | 0 | 0 | 10 | 0 | |
| 4 | 2 | 0 | 0 | 0 | 1 | 164 | 1 | 73 | 0 | |
| 5 | 12 | 0 | 0 | 1 | 0 | 58 | 3 | 11 | 0 | |
| 6 | 4 | 0 | 0 | 164 | 58 | 0 | 5 | 13 | 0 | |
| 7 | 0 | 0 | 0 | 1 | 3 | 5 | 0 | 0 | 0 | |
| 8 | 59 | 1 | 10 | 73 | 11 | 13 | 0 | 0 | 0 | |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | 138 | 213 | 318 | 413 | 513 | 613 | 713 | 813 | 913 | 1(1), 3(2) |
| | 396 | 352 | 396 | 329 | 339 | 331 | 327 | 396 | 327 | 8(3) |
| 138 | - | 26 | - | 75 | 23 | 17 | 0 | - | 0 | 4(4), 2(7) |
| 413 | - | 25 | - | - | 13 | 168 | 1 | - | 0 | |
| 418 | - | 10 | - | - | 24 | 181 | 1 | - | 0 | 6(5) |
| 438 | - | 17 | - | - | 12 | 177 | 1 | - | 0 | |
| 641 | - | 9 | - | - | 71 | - | 6 | - | 0 | |
| 648 | - | 1 | - | - | 70 | - | 6 | - | 0 | |
| 618 | - | 10 | - | - | 81 | - | 5 | - | 0 | 5(6) |
| 561 | - | 9 | - | - | - | - | 8 | - | 0 | 7(8) |
| 568 | - | 1 | - | - | - | - | 8 | - | 0 | |
| 518 | - | 10 | - | - | - | - | 3 | - | 0 | |
| 213 | - | - | - | - | - | - | 0 | - | 0 | |
| 218 | - | - | - | - | - | - | 0 | - | 0 | |
| 238 | - | - | - | - | - | - | 0 | - | 0 | |
| 756 | - | - | - | - | - | - | - | - | 0 | |
| 751 | - | - | - | - | - | - | - | - | 0 | |
| 761 | - | - | - | - | - | - | - | - | 0 | 9(9) |
| 976 | - | - | - | - | - | - | - | - | - | |
| 971 | - | - | - | - | - | - | - | - | - | |
| 961 | - | - | - | - | - | - | - | - | - | |

Figure 7.6 Solution After Applying the Adjacency Requirements Planning Algorithm

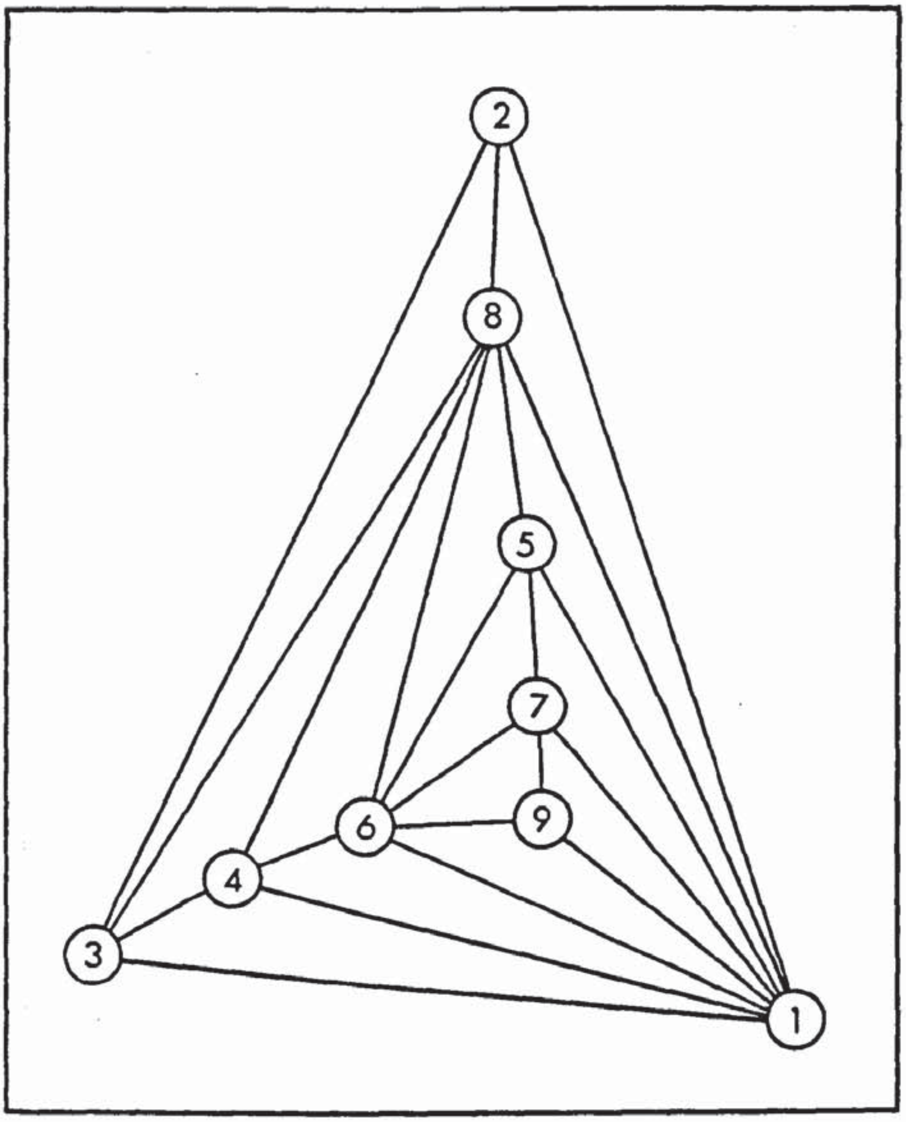


Figure 7.7 Maximal Planar Graph Drawn from Results in Figure 7.6

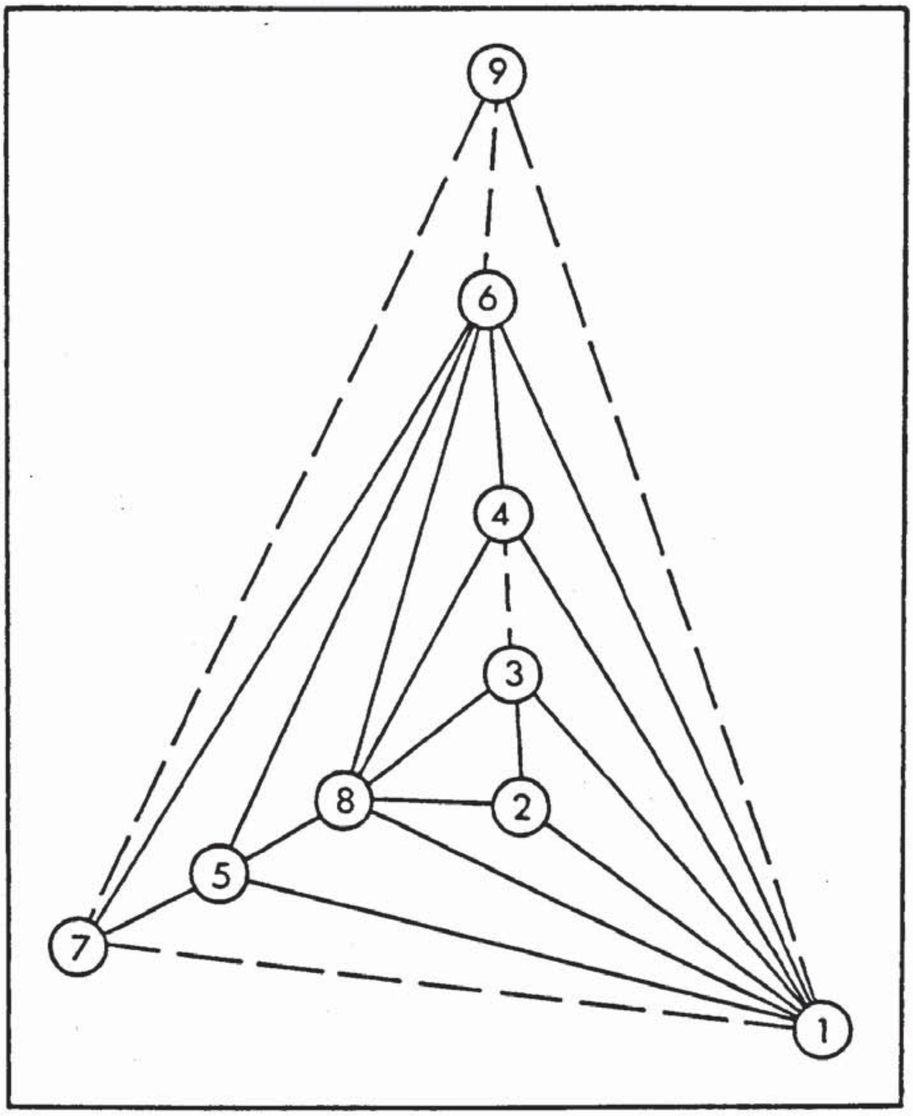


Figure 7.8 The Redrawn Maximal Planar Graph of Figure 7.7

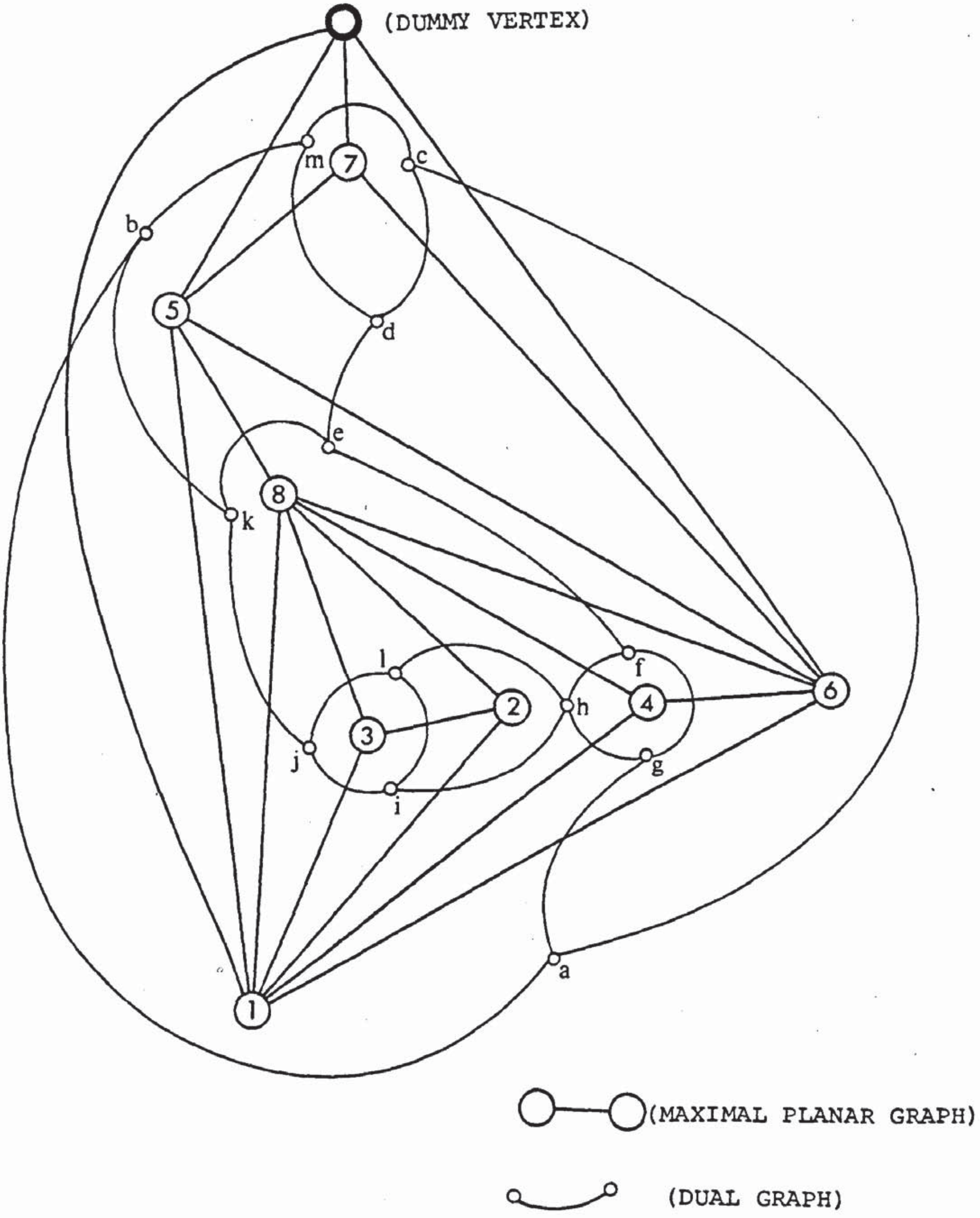


Figure 7.9 The Dual Graph of Figure 7.8

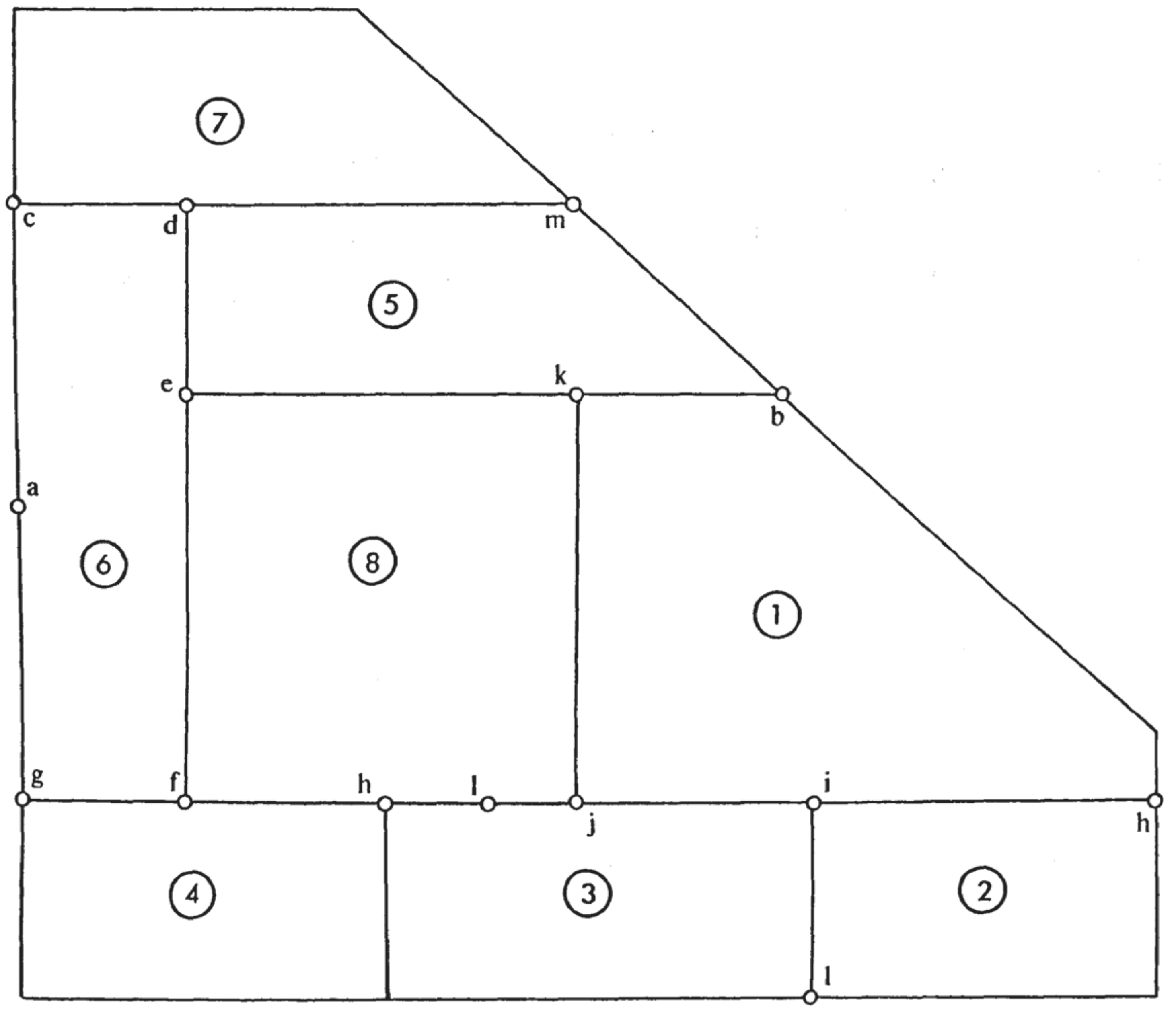
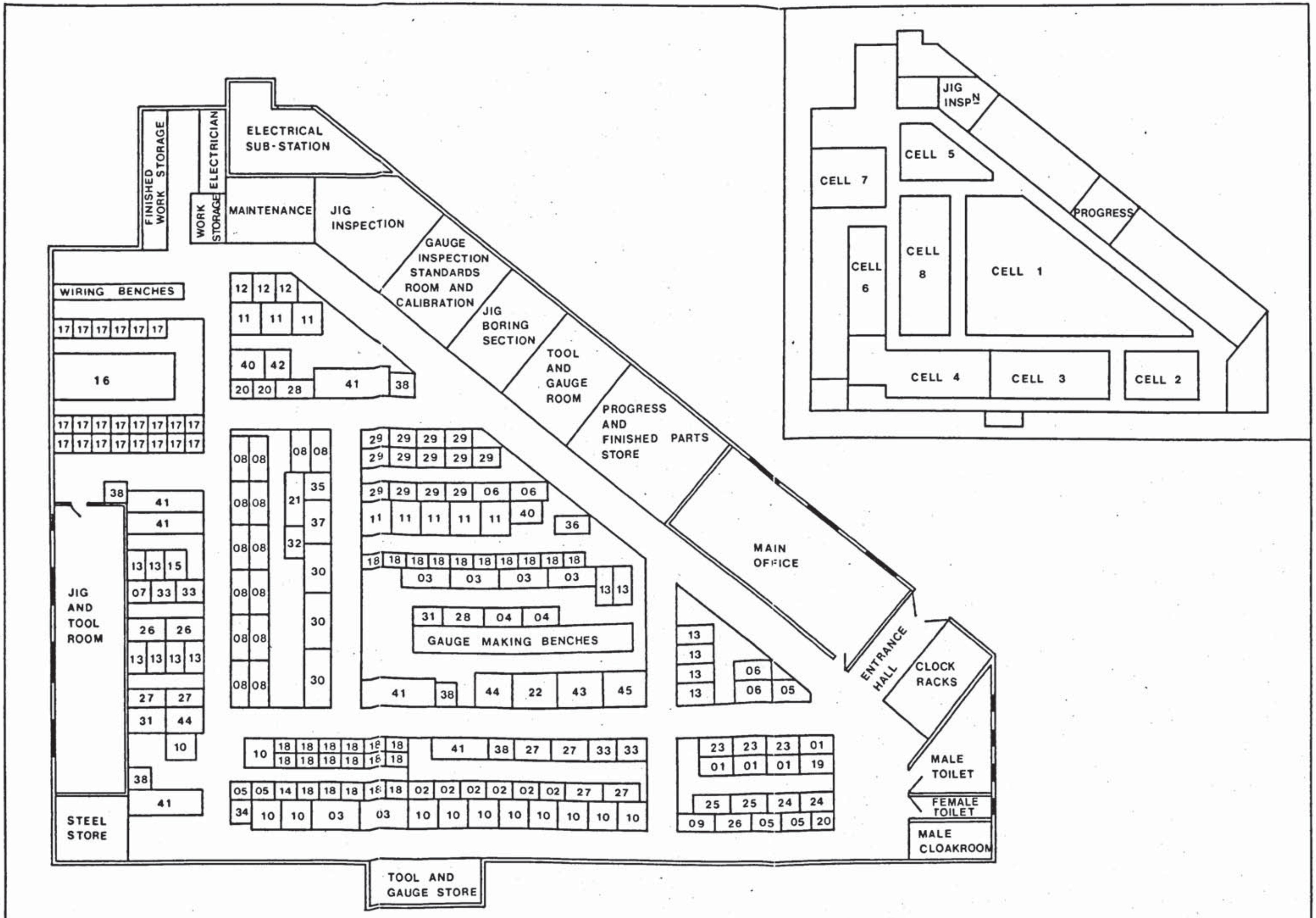


Figure 7.10 Block Diagram for Layout Planning in the North Toolroom



(Refer to the revised plant list for machine types)

Figure 7.11 The Final Layout Plan of the North Toolroom at Longbridge, with 98% of Inter-Cell Material Flows Between Adjacent Cells.

# CHAPTER EIGHT

# 8. PRODUCTION CONTROL IN CELLULAR MANUFACTURING SYSTEMS

## 8.1 Introduction

In a shop laid out on functional basis production control is very complex in nature, and in solving the problem a large amount of work in progress is usually maintained which is undesirable. In a cellular manufacturing system where the flow of materials is very much simplified, the size of the problem is reduced, involving only a family of components and a small group of machines, therefore production control should be simpler and more efficient. Unfortunately the methods which have been designed to suit the traditional form of organisations tend to be inefficient when used in cellular manufacture situations, mainly because they were not designed for that type of system, and a special approach needs to be adopted.

This and the following chapters are concerned with the methods of production control necessary for obtaining the full advantages of cellular manufacture. In particular, emphases are given to the two major tasks of production control: ordering and operations scheduling.

## 8.2 Flow Control Ordering for Cellular Manufacture

The pre-requisite of an effective production control system is the planning of production programmes. These programmes should show the quantities to be produced in a series of equal periods, based on the information provided by marketing in the form of sales forecasts. The aim of the controller is to plan production programmes at regular intervals to ensure the supply of finished product at the time required to meet the sales forecast. At the same time, he will seek to smooth out random and seasonal variations in demand so as to provide the production system with as even a load of work as possible, period after period.

The essential features of production programming have been summarised by Burbidge (72) and are shown in figure 8.1. It is impossible to plan the input of materials efficiently without information about the quantities to be produced. The forecast of sales, however, can hope to be accurate only for short periods of time ahead. Therefore, an ideal production system would plan a series of production programmes at frequent period intervals, and these would have short material throughput times. Also it would use purchasing methods allowing only short lead times for changes in the rate of deliveries. This can be achieved in a cellular manufacturing system coupled with a suitable ordering system.

There are two main systems used to control the issuing of orders, these are the "Stock Control" and "Flow Control" ordering systems. Traditionally, most companies use a stock control ordering system, but in recent years there are many reported evidences showing that a flow control ordering system is more suitable for batch manufactuing organisations (15, 16). With a flow control system the quantities to be ordered and the delivery dates are calculated directly from a series of production programmes. A typical flow control ordering system is that known as "Material Requirements Planning" (17, 18), this has been widely used for many years in the U.S.A. with traditional forms of organisation. However, the MRP technique is much more efficient with cellular manufacturing systems because the shorter throughput times make it possible to work with much shorter periods, and in turn these increase its reliability and accuracy. This will be discussed in the following section.

## 8.3 Material Requirements Planning

Material Requirements Planning is a short cycle flow control technique which ties production inventory requirements to the actual production programme. It functions by exploding the product requirements on the production programme through a bill of materials to result in a time phased list of material requirements. These requirements are then compared with the inventory stock status to determine the planned and released orders. The released orders are despatched to the workshop, and by maintaining progress records of orders through the workshop, shortages may be predicted and steps taken so as to produce items as they are needed.

In figure 8.2, a typical bill of material is used to illustrate the structural relationship of a multi-component product and its component parts. Level by level the product can be exploded into assemblies, sub-assemblies and piece parts. All the items used in an end product can be related through their final due dates. If the delivery date of the end product is extended, then all the due dates for the component items can be amended relative to their positions in the bill of materials, and the available resources and equipment can be used for other jobs with higher priorities. This is the fundamental concept of MRP.

The demands for the lower levels of product structure, such as the piece parts, are always dependent on the demands for the higher level assemblies or end products. This dependent demand is not uniform but random over time, as will be shown later. It is this non-uniformity which makes the traditional stock control system so inefficient, and the MRP approach superior in dealing with such situations.

To illustrate the mechanism of the MRP technique, a numerical example is used. Figure 8.3 shows the ordering requirements of three products A, B and C, two assemblies D and E, and one piece part F. The structural relationship between them has been defined that products A and B each contains one assembly D, that product C contains one assembly E, and that D and E each requires one part F for assembly. Therefore, the demand for F is dependent on the demands for D and E, which in turn are dependent on demands for A, B and C.

In figure 8.3, only the gross requirements of the three products are given, these may be from customers' orders or forecasts. The second line shows the current inventory status of each item, and the third line shows the lead time required for each item to be delivered. The optimal order quantity in line four can be calculated by the part period balancing method which will be explained later.

Figure 8.4 shows the processing logic of MRP. Products A, B and C are the highest level items in the bill of materials and their gross requirements, 1, 6 and 3 units per week respectively, are entered into the first row of table I as shown. This table covers a period of six weeks, each week being represented by one column.

At the beginning of the planned period, there are five units of product A on hand, which is reduced to four units after the first week and so on. At the fifth week the quantity of product A on hand is zero and at the sixth week this becomes negative. In order to maintain the production level, more product A are needed at week six. Therefore, the order for five units of product A, which is the optimal order quantity, must be released at week five to allow one week lead time for delivery. This same logic applies to product B and C, and therefore the order for eighteen product B should be released at the first and fourth weeks, and the order for nine product C should be released at the second and fifth weeks of the planned period.

By the principle of the bill of materials, the planned order release quantities of the products in table I become the gross requirements of assemblies D and E at the corresponding weeks in table II. This is illustrated by the lines joining the two tables in figure 8.4. The same processing logic as that used in table I is now applied to table II, and the planned order release of assemblies D and E are obtained. These now become the gross requirements of part F in table III as shown.

The planned order release in table III shows that thirty units of part F should be ordered at week one and week two. Therefore, the production of thirty part F should be completed at the end of the first and second weeks and no production is required for the other weeks, although the average demand for part F is ten units per week.

The non-uniform demand pattern for part F is called "lumpy demand", and it is because of this lumpy demand that the conventional stock control technique cannot work efficiently in such a shop. The problem is that stock control ordering systems rely on the calculation of the Economic Ordering Quantity (EOQ), which assumes constant usage and independent demand for all components. Suppose, for example, that there is an assembly which is made in batches of 500, and that the EOQ for one component is 350 and that for another is 800. Then it is not difficult to see that there will be a large residual inventory of components which are not used at all.

In MRP, the optimal ordering quantity for each item can be calculated by a technique called part period balancing (86), and this is illustrated by the example shown in figure 8.5. In this instance, the quantity of a component required for each week is known, together with the set-up cost, unit cost and inventory carrying cost. If the requirements for weeks two and three were combined, for example, then the cumulative lot size would be 2,200 units, and 2,000 units would be carried in inventory for one extra week. The inventory carrying costs would be (2,000 x £5 x 0.004 =) £40, which would not quite balance the set-up cost of £50. By combining the requirements for weeks two, three and four, and making them together, the cumulative inventory cost comes closest to balancing the set-up costs. Therefore, the optimal ordering quantity should be the cumulative lot size at week four, which is 2,450 units.

It is important to note that the calculation of the optimal ordering quantity is only an approximation at best. Requirements of any component will change, since they are usually based on some kind of forecast, the unit cost and set-up cost are only as accurate as good estimations, and the inventory carrying cost is usually a guess. However, the result of this calculation can be expected to be more accurate than the EOQ since it is geared to the demand forecast, and its accuracy should increase as the forecast period shortens.

Material Requirements Planning is a well-developed inventory timetable method of optimizing material flow. Although the feasibility of this technique did once arouse an argument among some British engineers (87, 88), it has become so widespread, especially in the United States, that some manufacturers consider it to be the standard computer based system in production and inventory management fields. One major advantage of using the MRP method is that there are very well developed and readily available computer programme packages commercially on offer. The use of a computer allows recalculation as often as necessary and this greatly increases the effectiveness and efficiency of the system.

It would appear that MRP is the right ordering system for use in a cellular manufacturing environment, and the merits of integrating the two have been widely publicised in recent years (56, 57, 58). Even so, a careful study of all aspects of a particular situation is necessary for a successful implementation.

## 8.4 Cellular Manufacture and Material Requirements Planning

Cellular Manufacture is an overall philosophy of manufacturing, whereas Material Requirements Planning is a production management system. MRP, in fact, performs the same functions as does a short cycle flow control system, and therefore can be considered as an essential part of a practical cellular production system. Integrating MRP with cellular manufacture not only can generate savings because of their individual merits, but also can mutually compensate for their weaknesses. The benefits of some composite GT-MRP systems have been found to be even greater than the sum of the benefits of the two systems.

By introducing the GT concept to a production system, the "efficiency" of manufacturing can be greatly improved. This is achieved by reducing part design costs, by allowing group planning for component families, by reducing tooling and set-up requirements. The major aim of cellular manufacture is to produce parts at the lowest possible cost. MRP, on the other hand, does not concentrate on the "efficiency" but rather on the "effectiveness" of a production system. It determines when components should be made and is not altogether concerned with how efficiently they are produced. The major aim of MRP is to produce parts so as to allow final products to be delivered according to schedule while minimizing inventories. Thus these two principles have to be integrated to result in the overall balance of an efficient and effective manufacturing system.

Now suppose a MRP system is used for production control in a cellular manufacturing system. The production functions at the product design stage would remain very much the same. The only difference would be that when the item master file is constructed, instead of employing a parts list, a structured bill of material is required. The layout of the production cells in the factory, as one would expect, would not be affected. At the scheduling stage a master production schedule would be constructed according to the production programme or the production requirements, and this would be exploded into a bill of material form just as in any MRP system.

A variation would occur, however, at the ordering stage. When the MRP system indicates that the order of an item should be released, instead of being released immediately, this order would be carried back to the item master file and the part family in which the item is contained would be determined. When the families of all the items needed for this planning period are known, the items in these families together with those required for the next and the following periods would be examined. Then a decision is made as to whether the item quantity in a particular part family is sufficient to warrant the release of that family for this planning period. In this way, order releases of individual items can be translated into family orders.

When the order for an item is of insufficient importance to initiate a family order release, the order has to be transferred from the original planned period to another, either forward or backward in time. This indicates that it is economically sound to produce efficiently rather than effectively. If it is decided that the order should be released even though a family release is not justified, then the indication is that it is economically sound to produce effectively rather than efficiently.

The above steps are for determining any similar items which can be produced at the same time in order to increase the lot sizes and reduce the setting times over a certain period. One question unresolved is how many parts should be produced in that period and which parts in a family should be produced first. A simple example can be used to illustrate the operation of a composite GT-MRP system in solving this problem.

Suppose five components named P, Q, R, S and T are to be produced, the number of each item required in a certain month is known. By referring to the item master file, these components are found to belong to two families, as shown in figure 8.6.a. Because of the lumpy demand effect, it would be difficult, without the MRP system, to decide on the precise production quantity of each component for a short period, say one week. With the MRP system, however, it is possible to determine this short term quantity of production by following a similar procedure to that described in the last section. For this example, the planned order release of each component for each of the four weeks is determined and is shown in figure 8.6.b.

It is readily apparent that figures 8.6.a and 8.6.b can be combined to form figure 8.6.c. Here, the components are divided into two families and the requirements for each component are divided into four periods, each period being one week. This schedule will neither violate the due date constraint nor miss the benefits which can be obtained from the cellular manufacture concept.

### 8.5 Implementation Considerations for a Composite GT-MRP System

It may appear that a GT-MRP system can be implemented simply by including MRP in the implementation plan of a cellular manufacturing system. However, in preparing the plan, two important considerations can ensure the probability of success as well as a likely return on the investment made.

Successful implementation of a MRP system depends on top managements understanding and commitment, and these must be reflected in the analysis, design and installation of the system. The three tests of Pre-MRP Planning as described by Quigley (89) may serve as indicators to how much work the organisation needs before MRP can be implemented. It often takes one or two years for the system to function after it is launched, and there is no way of running a parallel system. Therefore, strict discipline is needed to maintain the MRP system and to keep it from degenerating. Just one negligence or a delayed computer record may result in enough inertia to destroy the credibility of a formal MRP system. Perhaps this is responsible for the high failure rate of MRP installations.

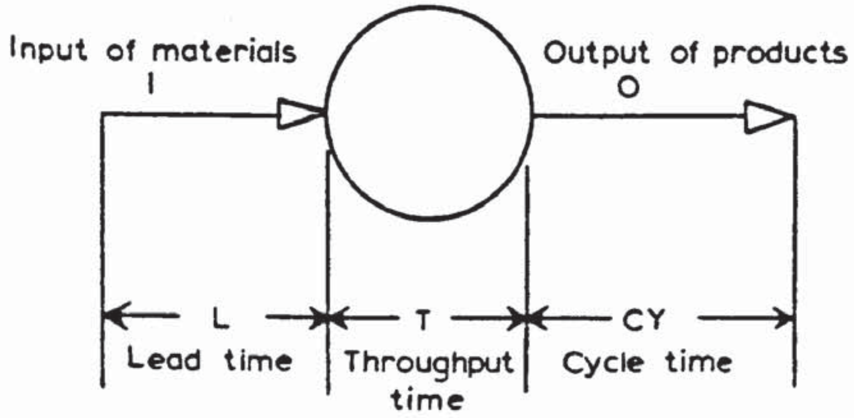
In comparison with MRP, GT has many areas of application, each area is self-contained and can be launched independently. With careful planning, a successful application of GT in one department can be unaffected by the progress of implementation in any other departments. Hence the probability of success with GT is greater than with MRP. Implementation of a MRP system is generally easier if the company's data files have been standardised according to the cellular manufacture concept. This is particularly true for companies with relatively little computer experience, in such cases the GT project should always be implemented prior to MRP.

Because cellular manufacture can be implemented by parts at different rates, the first area of implementation can begin generating benefits in a relatively short time. Although a full installation may also take up to two years, partial benefits can be expected at an early stage. In comparison, MRP does not generate partial benefits and a slower return on investment can be expected. This is another indication that GT should be implemented before MRP.

It is generally not advisable to implement GT and MRP jointly as both systems require substantial changes in the organisation. Strategically, GT should be introduced first and then once the system is fully accepted, the MRP system can be initiated.

However, for those companies which have already installed MRP systems successfully, there will be very little difficulty in implementing the system of cellular manufacture.

Finally, the MRP programmes developed by the computer companies are usually designed to accommodate different batch frequencies for different components. Since research works have shown that cellular systems can work with maximum efficiency with a fixed cycle, single phase ordering system, it is necessary to modify the programme packages before adopting them. This is because the MRP programmes are not initially written for Group Technology applications, but for a wider scope of industry. Nevertheless, the introduction of these computer packages has been of enormous benefit as far as ordering is concerned in cellular manufacturing systems.



1. To plan 'I' one must forecast 'O'.
2. The forecast must be made for any cycle, at least (L+T) days before it starts.
3. The accuracy of 'O' depends on the time ahead for which the forecast is made.
4. 'T' (the throughput time) is a function of the complexity of the Material Flow System and of the cycle.
5. 'L' (the lead time for materials) is a function of Purchasing and Stocking policy.
6. REDUCING THE CYCLE INCREASES FLEXIBILITY.

Figure 8.1 Features of Production Programming (after Burbidge)

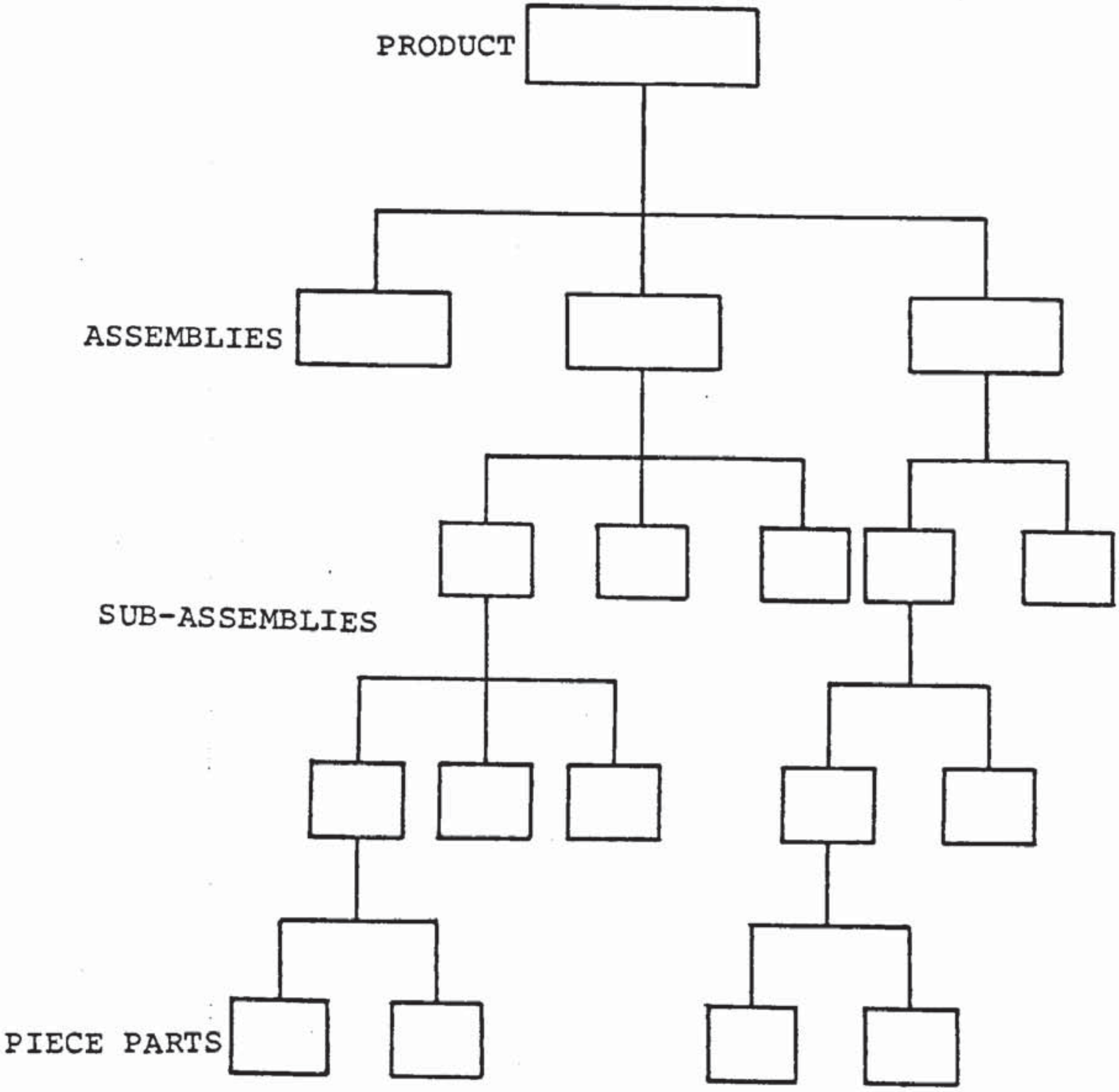


Figure 8.2 A Typical Bill of Materials

| | Product A | Product B | Product C | Assembly D | Assembly E | Part F |
|---|---|---|---|---|---|---|
| Gross Requirement | 1 | 6 | 3 | | | |
| On Hand | 5 | 10 | 7 | 20 | 15 | 22 |
| Lead Time (weeks) | 1 | 1 | 1 | 2 | 1 | 2 |
| Optimal Order Quantity | 5 | 18 | 9 | 20 | 15 | 30 |

Figure 8.3 Basic Data for the Numerical Example Illustrating MRP

| Table I | Product A | | | | | | | Product B | | | | | | | Product C | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Week Number | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
| Gross Requirement | | 1 | 1 | 1 | 1 | 1 | 1 | | 6 | 6 | 6 | 6 | 6 | 6 | | 3 | 3 | 3 | 3 | 3 | 3 |
| On Hand | 5 | 4 | 3 | 2 | 1 | 0 | -1 | 10 | 4 | -2 | 10 | 4 | -2 | 10 | 7 | 4 | 1 | -2 | 4 | 1 | -2 |
| Net Requirement | | | | | | | 5 | | | 18 | | | 18 | | | | | 9 | | | 9 |
| Planned Order Release | | | | | | ⑤ | | | 18 | | | 18 | | | | | 9 | | | ⑨ | |

| Table II | Assembly D | | | | | | | Assembly E | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Week Number | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
| Gross Requirement | | 18 | 0 | 0 | 18 | ⑤ | 0 | | 0 | 9 | 0 | 0 | ⑨ | 0 |
| On Hand | 20 | 2 | 2 | 2 | -16 | -1 | 19 | 15 | 15 | 6 | 6 | 6 | -3 | 8 |
| Net Requirement | | | | | 20 | 20 | | | | | | | 15 | |
| Planned Order Release | | | 20 | 20 | | | | | | | | 15 | | |

| Table. III | Part F | | | | | | |
|---|---|---|---|---|---|---|---|
| Week Number | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
| Gross Requirement | | 0 | 20 | 20 | 15 | 0 | 0 |
| On Hand | 22 | 22 | 2 | -18 | -3 | 27 | 27 |
| Net Requirement | | | | 30 | 30 | | |
| Planned Order Release | | 30 | 30 | | | | |

Figure 8.4 Processing Logic of MRP

| Week | Amount Required | Cumulative Lot Size | Excess Inventory | Weeks Carried | Carrying Cost | | Set Up Cost |
|---|---|---|---|---|---|---|---|
| | | | | | Per Period | Cumulative | |
| 2 | 200 | 200 | 2000 | 0 | 0 | 0 | |
| 3 | 2000 | 2200 | 2000 | 1 | £40 | £40 | £50 |
| 4 | 250 | 2450 | 250 | 2 | £10 | £50 | £50 |
| 5 | 100 | 2550 | 100 | 3 | £6 | £56 | £50 |
| 6 | 1000 | 3550 | 1000 | 4 | £80 | £136 | £50 |

Set up cost = £50
Unit cost = £5
Inventory cost = £0.004 per week

Figure 8.5 Example Showing the Principle of Part Period Balancing

| Family Name | Component Name | Quantity Required |
|---|---|---|
| G | P | 60 |
| | Q | 60 |
| | S | 30 |
| H | R | 60 |
| | T | 50 |

Figure 8.6.a Planned Order Release for the Two Part Families in the Scheduled Month

| Component Name | Planned Order Release Per Week | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| P | 30 | 30 | 0 | 0 |
| Q | 15 | 15 | 15 | 15 |
| R | 20 | 20 | 10 | 10 |
| S | 10 | 10 | 5 | 5 |
| T | 15 | 15 | 10 | 10 |

Figure 8.6.b Planned Order Release for the Five Components Using MRP Technique

| Family Name | Component Name | Planned Order Release Per Week | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| G | P | 30 | 30 | 0 | 0 |
| | Q | 15 | 15 | 15 | 15 |
| | S | 10 | 10 | 5 | 5 |
| H | R | 20 | 20 | 10 | 10 |
| | T | 15 | 15 | 10 | 10 |

Figure 8.6.c Planned Order Release for the Two Part Families in a Composite GT-MRP System

# CHAPTER NINE

## 9. OPERATIONS SCHEDULING FOR CELLULAR MANUFACTURE

### 9.1 Introduction

In the last chapter, a short cycle flow control method was used to decide the ordering policy for cellular manufacuture, so that the demand forecast could be met and the production capacity could be used to the best advantage. There is however, one other factor highly significant to the efficiency of the system. This is operations scheduling, and its function is to determine the best loading sequence for parts on the machine in a manufacturing cell.

It is generally agreed that, in a cellular organisation, the foreman in each cell should be responsible for drawing up the schedule of work, possibly with some delegations of decision to the workers in his group. One obvious advantage is that the foreman can react quickly to incidents such as machine or tooling breakdowns. Also there is social benefit in that options to plan and control their own work are usually valued by foremen and workers, and that such arrangement will make an important contribution to job satisfaction.

This chapter is concerned with finding a suitable operations scheduling method which can provide the foreman with a systematic and quantitative approach to schedule his work. The method must be simple and suitable for use at the shopfloor level. Also it should contribute to the benefits to be obtained in a cellular manufacturing environment.

The problems of operations scheduling associated with Group Technology applications have been defined by Hitomi (15) as "Group Scheduling". He and other writers (16, 23) suggested that in any cellular system, each cell can be considered as an individual flow shop, and the scheduling problem can be treated with specific methods derived from flow shop scheduling. A group scheduling method of this kind is the "Flowline Group Production Planning" proposed by Petrov (23). This method is adopted here because of the advantage of its simple computational requirements. However, since Petrov assumed an ideal flowline production pattern to exist in every machine cell, it is necessary to modify his method to make it work with cells which do not incorporate flowlines. Petrov's method and the suggested modifications will be discussed in the following sections, but first the flowline scheduling problem is revealed.

## 9.2 Heuristic Scheduling Methods

In searching for a method of determining the optimal sequence of jobs, one must take into account the practical and economical aspects of the solution technique. Many optimisation algorithms can solve flow shop problems effectively, but must be considered as non-practical because of the computational effort involved. In contrast, the heuristic approaches are very much simpler and usually easily computerised, and they give results very close to the optimal solution. Since the scheduling problems in machine cells are always small, they can be solved with a heuristic method and obtain reasonably accurate results.

Flowline production is characterised by a continuance of operations. It is not necessary to have every component processed on each machine, but all movements between machines must be in the same direction. If "n" jobs are to be allocated to "m" different machines in a flowline, the permutation of possible sequences is $(n!)^m$. Fortunately, it is not necessary to examine all these possibilities to find a near optimal solution. The number of schedules to be considered is greatly reduced by two dominant properties of these problems (90):-

1) To determine any regular measure of performance, only those schedules in which the same job sequence occurs on the first two machines need to be considered.

2) To determine the completion time of all jobs, or the maximum flow time, only those schedules in which the same job sequence occurs on the last two machines need to be considered.

Based on these two considerations. several heuristic algorithms have been developed. These include the most frequently cited Johnson's Rule, which is used for sequencing n jobs to minimize the maximum flow time in a two machine flow shop. Campbell, Dudek and Smith (91) presented a significant heuristic method for scheduling n jobs on m machines, and this employed a multi-stage use of Johnson's Rule. Other algorithms for flowshop scheduling have been developed by various researchers, for example, Gupta (92) and Palmer (93).

## 9.3 Petrov's Group Scheduling Method

Petrov (23) in his "Flowline Group Production Planning" presented a systematic accounting of group production organisation and planning, and showed a way to obtain a good schedule. His method also employs maximum flow time as the scheduling criterion, and is based on several assumptions and heuristic rules. Although it is not specifically designed for group scheduling, a near optimal job sequence within a cell can be found by a slightly modified version of his method. An important significance which makes Petrov's method preferable to the others is that the computational efforts involved are small. As the conditions affecting scheduling may change from time to time, it is necessary to check and modify the plans at intervals, therefore a feasible scheduling algorithm must be simple and easy to operate. Petrov's method can work efficiently, in particular, in a cell system where scheduling is carried out at the shopfloor level without the support from a main frame computer. It is effective too, in that the solutions obtained by its heuristic approach will be close to the optimal because the problems to be dealt with in a cell system are relatively small.

Petrov's method is based on the following assumptions:-

1) Setting-up and processing times are known in advance for all jobs.

2) Setting-up time is included in processing time.

3) All jobs are available at the same time.

4) All jobs follow the same technological sequence.

The first three assumptions can be satisfied readily in a well-established cellular system. The setting-up and processing times for each operation can be determined by workstudy techniques. And by using a short cycle flow control ordering method as described in the last chapter, the jobs allocated to a machine cell can be clearly defined at the beginning of each period, and all should be available at the same time. However, not all the components in a part family would follow the same technological sequence, even though they are made in the same cell. To satisfy the last requirement, therefore, it is necessary to divide the components in a part family into smaller sub-families. The method and its procedures will be suggested in the next section. For the moment, it is accepted that all the required assumptions can be satisfied in a system of machine cells.

Group scheduling using Petrov's method considers the maximum flow time for processing the assigned components in a machine cell. The relations of the total cycle time, processing time and idle time of n parts and m operations are represented by the following mathematical expression:-

$$A = \begin{pmatrix} P_{11} & P_{12} & P_{13} & \cdots & P_{1m} \\ P_{21} & P_{22} & P_{23} & \cdots & P_{2m} \\ P_{31} & P_{32} & P_{33} & \cdots & P_{3m} \\ \vdots & & & & \\ P_{n1} & P_{n2} & P_{n3} & \cdots & P_{nm} \end{pmatrix}$$

where $A$ = operation time matrix for a group

$n$ = number of parts to be processed

$m$ = number of operations in the process

$P_{ik}$ = processing time for one operation.

This group operation time matrix A can be represented by a Gantt Chart as shown in figure 9.1. As can be seen, there are waiting times between jobs, and the objective of an optimal schedule is to minimise the total of these times.

Referring to figure 9.1, the maximum flow time for processing n parts through m operations (machines) can be expressed mathematically as follows:-

$$F_{max} = \sum_{k=1}^{m-1} P_{1k} + \sum_{i=1}^{n} P_{im} + \sum_{i=1}^{n} W_{im}$$

where $F_{max}$ = total time for processing n parts through m operations (machines), i.e. the maximum flow time.

$\sum_{k=1}^{m-1} P_{1k}$ = sum of processing times for the first part on (m-1) operations (machines).

$\sum_{i=1}^{n} P_{im}$ = sum of processing times for n parts on the last or mth operation (machine).

$\sum_{i=1}^{n} W_{im}$ = sum of machine idle times (the time which the final process waits until the next part arrives).

Petrov's method will schedule the n parts in such a sequence that the maximum flow time is the closest to minimum. The algorithm is as follows:-

1) Calculate the sum of processing times $Q_i$ for part i.

   (i) For groups with even number of operations (machines), i.e. m is even

$$Q_i(1) = \sum_{k=1}^{h} P_{ik}$$

$$Q_i(2) = \sum_{k=h+1}^{m} P_{ik}$$

where $h = {}^{m}/_{2}$, $i = 1,2,3,\dots,n$

   (ii) For groups with odd number of operations (machines), i.e. m is odd

$$Q_i(1) = \sum_{k=1}^{h} P_{ik}$$

$$Q_i(2) = \sum_{k=h}^{m} P_{ik}$$

where $h = {}^{(m+1)}/_{2}$, $i = 1,2,3,\dots,n$

2) Plan the sequence of jobs.

   (i) First make a sequence in ascending order of $Q_i(1)$ for those parts that have $(Q_i(2) - Q_i(1) \geqslant 0)$. Then make a sequence in descending order of $Q_i(2)$ for those parts that have $(Q_i(2) - Q_i(1) < 0)$.

   (ii) Sequence all the parts in descending order of $(Q_i(2) - Q_i(1))$.

3) Calculate the maximum flow time of each sequence obtained in step (2), then choose the better sequence as the one with a shorter total time.

Petrov's method can be illustrated with a numerical example. Suppose there are eight parts to be processed on three machines in a cell, all parts following the same technological order. The processing time, which includes the setting up time, is known for each job (figure 9.2). Since m is odd, algorithm (1)(ii) applies:-

$$h = {}^{(m+1)}/_{2} = {}^{(3+1)}/_{2} = 2$$

hence,

$$Q_i(1) = \sum_{k=1}^{h} P_{ik}$$

$$= P_{i1} + P_{i2}$$

and

$$Q_i(2) = \sum_{k=h}^{m} P_{ik}$$

$$= P_{i2} + P_{i3}$$

Referring to figure 9.2, the sums of processing times for each part are calculated:-

$Q_1(1) = 5+5 = 10$

$Q_1(2) = 5+3 = 8$

$Q_1(2) - Q_1(1) = -2$

$Q_2(1) = 7+1 = 8$

$Q_2(1) = 1+8 = 9$

$Q_2(2) - Q_2(1) = 1$

$Q_3(1) = 2+3 = 5$

$Q_3(2) = 3+1 = 4$

$Q_3(2) - Q_3(1) = 1$

$Q_4(1) = 4+2 = 6$

$Q_4(2) = 2+6 = 8$

$Q_4(2) - Q_4(1) = 2$

$Q_5(1) = 3+8 = 11$

$Q_5(2) = 8+5 = 13$

$Q_5(2) - Q_5(1) = 2$

$Q_6(1) = 2+2 = 4$

$Q_6(2) = 2+7 = 9$

$Q_6(2) - Q_6(1) = 5$

$Q_7(1) = 1+8 = 9$

$Q_7(2) = 8+4 = 12$

$Q_7(2) - Q_7(1) = 3$

$Q_8(1) = 9+2 = 11$

$Q_8(2) = 2+5 = 7$

$Q_8(2) - Q_8(1) = -4$

Now applying step (2), $J_2$ to $J_7$ are sequenced in ascending order of $Q_i(1)$, then $J_1$ and $J_8$ are sequenced in descending order of $Q_i(2)$. The first sequence obtained is:-

$J_6, J_3, J_4, J_2, J_7, J_5, J_1, J_8$

The second sequence is obtained by arranging the jobs in descending order of $(Q_i(2) - Q_i(1))$ as follows:-

$J_6, J_7, J_4, J_5, J_2, J_3, J_1, J_8$

The Gantt Charts for these two sequences are shown in figure 9.3. The total maximum flow time for each sequence can be calculated by the following formula:-

$$F_{max} = \sum_{k=1}^{2} P_{6k} + \sum_{i=1}^{8} P_{i3} + \sum_{i=1}^{8} W_{i3}$$

$F_{max}$ for the first sequence is 45 and that for the second is 44. Therefore, the second sequence should be employed.

## 9.4 Modifications to Petrov's Method

In machine cells with flowline production, Petrov's method can be used to achieve good job sequences. However, there are often some cells in which production flowlines cannot be installed, and Petrov's method cannot be employed because its basic assumptions are violated. Under these circumstances the part families in these cells should be divided into smaller sub-groups in such a way that all components in a sub-group follow the same or similar technological sequence. These sub-groups can be established on the basis of the cutting tools used to manufacture the components.

A method of forming tooling families has been described in section 4.7.2. Since machine tools are clearly designated to their machine cells, it is relatively easy to list all the cutting tools to be used in a cell. By considering the materials and workholding methods for any part family, and by analysing the cutting tools used on each component, it is possible to divide the part family into several smaller subfamilies, each one being composed of parts which are processed on the same machines with similar or identical tooling. It is now logical and reasonably accurate to assume that components in a tooling family will follow the same technological sequence.

Hence, Petrov's method can be applied.

Once the tooling families are formed, machines in a cell can be divided into smaller sub-groups with respect to these sub-families. If all machine sub-groups are independent, then each sub-family can be scheduled individually and the scheduling problem for the whole machine cell will be solved. However, in practice, several sub-groups may have to share some machine tools, then it is necessary to plan the processing sequence of the sub-families on these machines. With some modifications, Petrov's method can be applied to this situation to obtain a good schedule for the tooling families.

In the modified method, sub-families are considered instead of individual components. All assumptions for Petrov's method must be satisfied for the components within each sub-family. It is also assumed that sub-families and the relevant components follow the same sequence on all machines involved.

Suppose there are j components in sub-family i, then the total processing time for this tooling family on machine k will be as follows:-

$$T_{ik} = S_{ik} + \sum_{h=1}^{j} P_{hik}$$

where $T_{ik}$ = Total processing time for the sub-family.

$S_{ik}$ = Average setting up time for the sub-family.

$\sum_{h=1}^{j} P_{hik}$ = Processing time for all parts in sub-family i on machine k.

If there are n tooling families to be processed on m machines, then the total maximum flow time will be as follows:-

$$F_{max} = \sum_{i=1}^{n} T_{i1} + \sum_{k=2}^{m} P_{jnk} + \sum_{k=2}^{m} W_{jnk}$$

where $F_{max}$ = Total maximum flow time through the m machines.

$\sum_{i=1}^{n} T_{i1}$ = Sum of total processing times for n sub-families on the first machine.

$\sum_{k=2}^{m} P_{jnk}$ = Sum of processing times for the last (jth) part in the last (nth) sub-family to be processed on all machines except the first one.

$\sum_{k=2}^{m} W_{jnk}$ = Sum of waiting times for the last (jth) part in the last (nth) sub-family.

Using this total maximum flow time as the scheduling criterion and by considering $T_{ik}$'s instead of $P_{ik}$'s, Petrov's algorithm is modified to schedule tooling families instead of piece parts. This is best illustrated with a numerical example.

Suppose a part family has been divided into four sub-families, and Petrov's method has been employed to find the job sequence for each of them. It is now necessary to schedule these sub-families because some components in different sub-families use the same machines. Altogether, there are fourteen components to be processed on five machines, following the same machine order. The basic data required for group scheduling is shown in figure 9.4. The jobs in each sub-family have been arranged in a sequence pre-determined by Petrov's method, and the sub-family processing times ($T_{ik}$'s) have been calculated.

Applying step (1)(ii) of Petrov's method, using $T_{ik}$'s instead of $P_{ik}$'s, the sum of processing time for each sub-family can be calculated as follows:-

$$h = {}^{(m+1)}/_{2} = {}^{(5+1)}/_{2} = 3$$

$$\text{hence, } Q_i(1) = \sum_{k=1}^{3} T_{ik}$$

$$\text{and } Q_i(2) = \sum_{k=3}^{5} T_{ik}$$

Referring to figure 9.4, the following are obtained:-

$Q_1(1) = 178+180+194 = 552$

$Q_1(2) = 194+253+177 = 624$

$Q_1(2) - Q_1(1) = 72$

$Q_2(1) = 208+143+182 = 533$

$Q_2(2) = 182+202+258 = 642$

$Q_2(2) - Q_2(1) = 109$

$Q_3(1) = 142+166+153 = 461$

$Q_3(2) = 153+155+131 = 439$

$Q_3(2) - Q_3(1) = -22$

$Q_4(1) = 199+257+189 = 645$

$Q_4(2) = 189+280+162 = 631$

$Q_4(2) - Q_4(1) = -14$

Applying either rule in step (2) of Petrov's method, the sequences obtained are the same as follows, hence it is the solution sequence:-

$F_2, F_1, F_4, F_3$

The Gantt Chart for this group sequence is shown in figure 9.5. Its total maximum flow time is 1091. This is very close to the optimal value of 1031 which can be obtained by a very tedious branch and bound method (15).

## 9.5 Operations Scheduling in Cellular Manufacturing Systems

Operations scheduling can be operated at the factory, departmental or machine cell levels. With the introduction of cellular manufacture to a production system, the point of control has been moved closer to the operational level. It has been shown that the best way of controlling a machine cell is to give the cell foreman the responsibility for detail scheduling. The only problem is to provide the foreman with suitable facilities to plan the schedule.

The rapidly falling price of computer hardware has presented the opportunity to make scheduling decisions on shop floor with computer assistance. Computer manufacturers have developed control packages for such applications. However, these universal systems inevitably have some shortcomings in particular environments, and the capital investment related to their implementations are too large for small firms. Consequently, the rejection of such systems and the availability of desk-top computers have led to the consideration of using simple heuristic methods on micro-computers. Petrov's method and the modified algorithm are both easily computerised and can be used on small capacity computers. Therefore they are suitable for use in cellular manufacturing systems, in particular, in small firms.

It is anticipated that scheduling efficiency in cellular systems can be improved by installing in every cell a desk-top computer, together with the software support based on heuristic algorithms such as Petrov's and the modified methods. With such facilities, the foreman can obtain a good initial schedule rapidly, and can make any necessary modifications to cope with practical constraints so that the best benefits are achieved. In this way, not only the components can be machined in the most efficient sequence, but the effect of any production interruptions, such as machine or tooling breakdowns, can also be monitored.

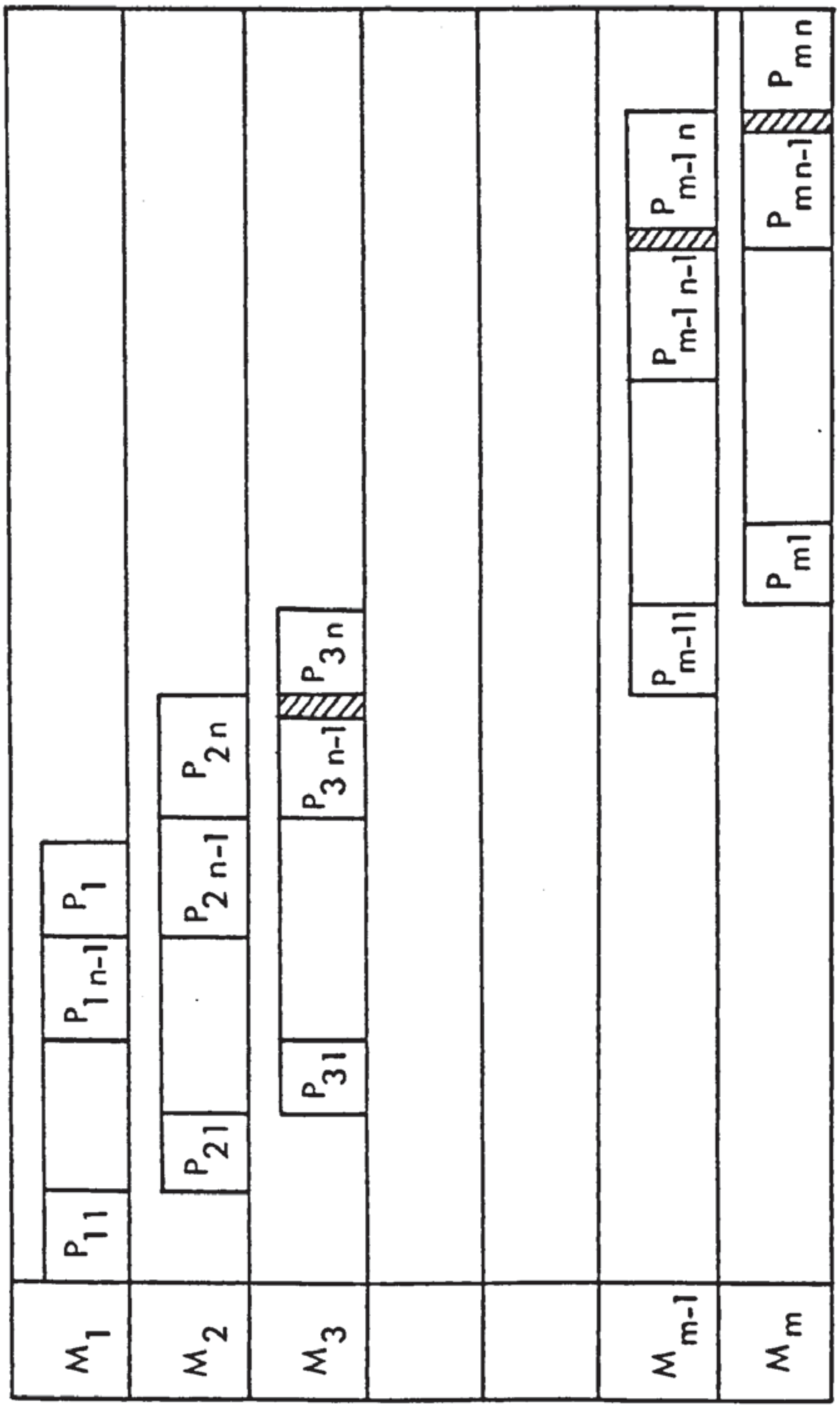


Figure 9.1 Gantt Chart for the Operation Time Matrix

| Component Name | Processing Time | Machine Number (k) | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| $J_1$ | $P_{1k}$ | 5 | 5 | 3 |
| $J_2$ | $P_{2k}$ | 7 | 1 | 8 |
| $J_3$ | $P_{3k}$ | 2 | 3 | 1 |
| $J_4$ | $P_{4k}$ | 4 | 2 | 6 |
| $J_5$ | $P_{5k}$ | 3 | 8 | 5 |
| $J_6$ | $P_{6k}$ | 2 | 2 | 7 |
| $J_7$ | $P_{7k}$ | 1 | 8 | 4 |
| $J_8$ | $P_{8k}$ | 9 | 2 | 5 |

Figure 9.2 Basic Data for the Numerical Example Illustrating Petrov's Algorithm

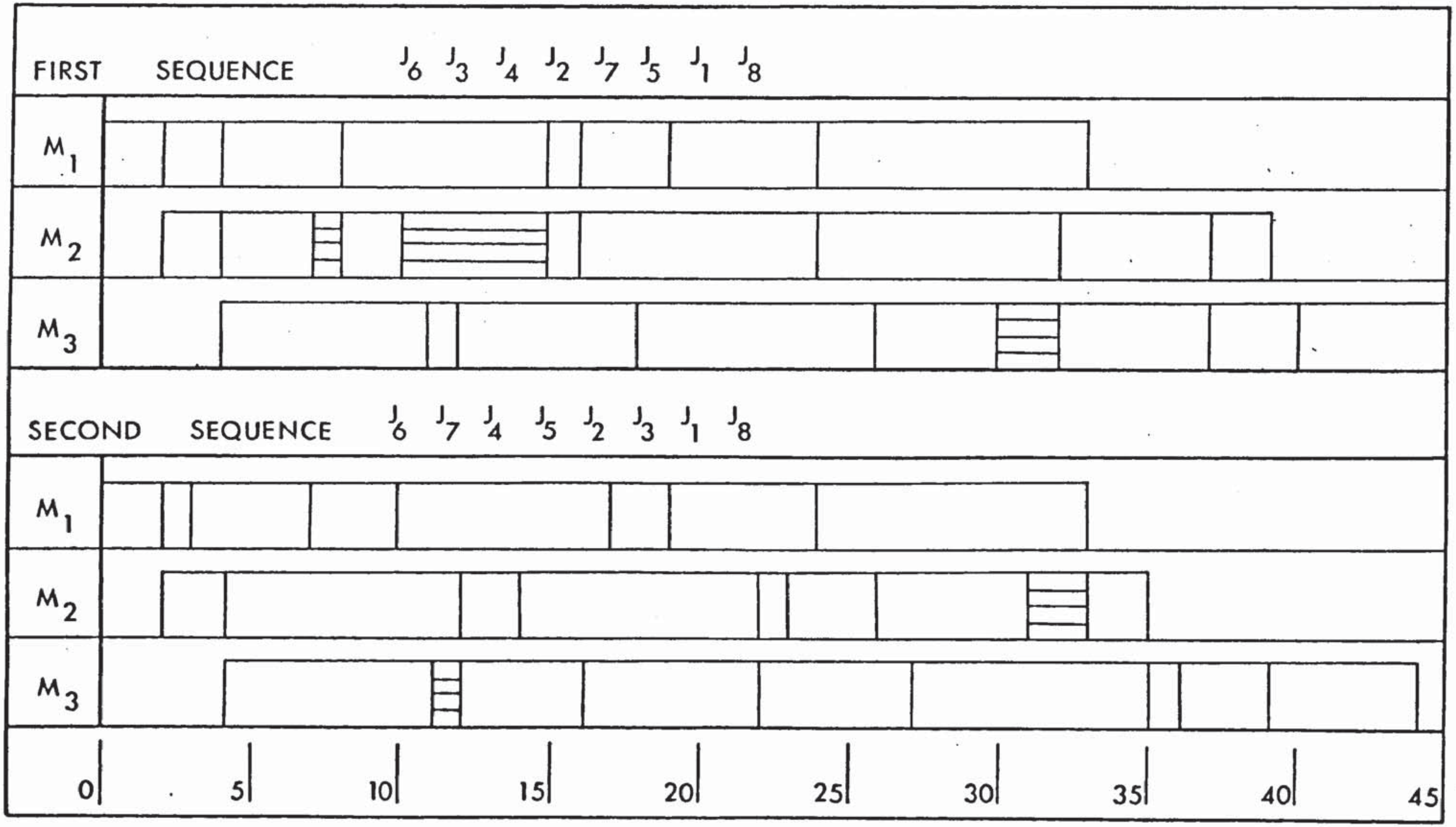


Figure 9.3 Gantt Chart for the Two Sequences Obtained by Petrov's Method

| Sub-Family Name | Component Name | Setting Up and Processing Times | Machine Number (k) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 |
| $F_1$ | | $S_{1k}$ | 30 | 15 | 25 | 30 | 10 |
| | $J_{11}$ | $P_{11k}$ | 32 | 25 | 62 | 73 | 54 |
| | $J_{12}$ | $P_{12k}$ | 41 | 85 | 39 | 79 | 52 |
| | $J_{13}$ | $P_{13k}$ | 75 | 75 | 68 | 71 | 61 |
| | | $T_{1k}$ | 178 | 180 | 194 | 253 | 177 |
| $F_2$ | | $S_{2k}$ | 10 | 20 | 15 | 30 | 25 |
| | $J_{21}$ | $P_{21k}$ | 50 | 41 | 22 | 41 | 55 |
| | $J_{22}$ | $P_{22k}$ | 30 | 28 | 41 | 48 | 64 |
| | $J_{23}$ | $P_{23k}$ | 70 | 20 | 56 | 54 | 62 |
| | $J_{24}$ | $P_{24k}$ | 48 | 34 | 48 | 29 | 52 |
| | | $T_{2k}$ | 208 | 143 | 182 | 202 | 258 |
| $F_3$ | | $S_{3k}$ | 15 | 25 | 30 | 20 | 10 |
| | $J_{31}$ | $P_{31k}$ | 72 | 66 | 40 | 47 | 62 |
| | $J_{32}$ | $P_{32k}$ | 26 | 20 | 37 | 51 | 28 |
| | $J_{33}$ | $P_{33k}$ | 29 | 55 | 46 | 37 | 31 |
| | | $T_{3k}$ | 142 | 166 | 153 | 155 | 131 |
| $F_4$ | | $S_{4k}$ | 25 | 30 | 10 | 25 | 35 |
| | $J_{41}$ | $P_{41k}$ | 22 | 42 | 35 | 68 | 17 |
| | $J_{42}$ | $P_{42k}$ | 27 | 69 | 42 | 75 | 57 |
| | $J_{43}$ | $P_{43k}$ | 78 | 45 | 73 | 74 | 29 |
| | $J_{44}$ | $P_{44k}$ | 47 | 71 | 29 | 38 | 24 |
| | | $T_{4k}$ | 199 | 257 | 189 | 280 | 162 |

Figure 9.4 Basic Data for the Group Scheduling Example

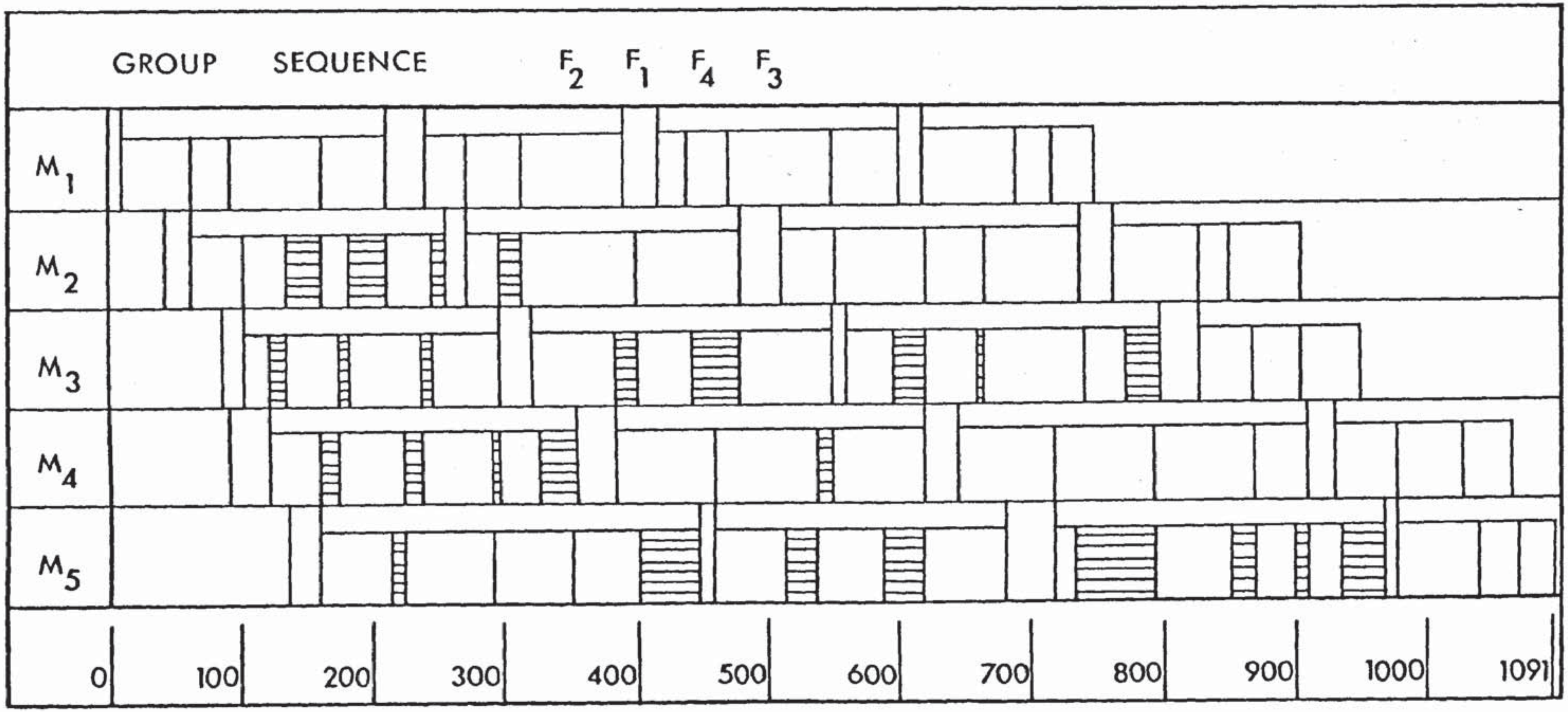


Figure 9.5 Gantt Chart for the Group Scheduling Sequence

## CHAPTER TEN

## 10. CONCLUSIONS ( * author's original contributions )

1. Cellular manufacture may not be a universal panacea for manufacturing industry, but it can provide major benefits if implementations are carefully planned.

2. The application of cellular manufacture to a traditional production system can result in simpler material flow and easier production planning and control functions.

3. In small firms with limited resources, cellular manufacture can provide an economic approach to improve productivity.

4. Group layout cells are flexible and are preferable to small firms.

*5. A controlled inter-cell material flow can be tolerated in group layout cells.

6. To motivate small firms to adopt cellular manufacture and to justify the change, a simpler and cheaper method of implementation is needed.

7. Classification and coding systems are in general costly and time consuming to install.

8. Material flow analysis techniques are easier to implement, but the information produced is sometimes too complex to handle.

*9. A compromise of classification and material flow techniques is the feasible approach to designing manufacturing cells.

*10. The non-manual complexity code is useful for initial sorting of components and for improving communications throughout the company.

11. In group analysis, there is a lack of general procedures to convert a machine/component matrix into clustering form.

*12. The Direct Clustering Algorithm provides a simple and effective way of clustering data directly from any given machine/component matrix.

*13. DCA can be used manually as well as on the computer. It allows an interactive approach offering greater flexibility and is preferable to a completely mechanistic process.

*14. The DCA method can effectively deal with exceptional elements and bottleneck machines.

*15. DCA can be used in conjunction with a data field to serve the purpose of a universal classification and coding system.

*16. The facilities layout problem in a cellular manufacturing system is similar to the classical plant layout problem and can be solved by a heuristic approach.

*17. Graph theory can be the basis of computerised plant layout methods.

*18. The Adjacency Requirements Planning algorithm provides an easy and effective way of solving the cell layout planning problem.

*19. ARP can be used manually or with computer aids to determine the relative positions of facilities for optimal material movement.

*20. A near optimal plant layout block diagram can be constructed from a maximal planar graph obtained from an ARP analysis.

*21. Implementation of cellular manufacture in small firms should be made in such a way as to utilize currently available resources.

22. When introducing cellular manufacture, comprehensive analysis and implementation should be adopted wherever possible, and the change should be directed and controlled from high level management.

*23. The methodology developed in this thesis was sucessfully applied to implement cellular manufacture to the North Toolroom at the Longbridge plant of Austin Morris.

*24. Machine groups formed by the complexity code sorting and DCA analysis were distinct, and each could be associated with a general component type.

*25. A cell layout plan constructed after the ARP analysis resulted in more than 98% of material flows being confined to adjacent cells.

*26. The machine mix in the North Toolroom was probably not well balanced.

27. Special methods of production control are needed for cellular manufacturing systems.

*28. Material Requirements Planning is fully compatible with cellular manufacture, and is a desirable ordering method for cell systems.

*29. MRP can be easily installed with well developed computer packages readily available.

*30. When implementing a composite GT-MRP system, cellular manufacture should be initiated first, MRP can be introduced after the GT system is fully accepted.

31. Operations scheduling in cell systems can be treated with methods derived from flow-shop scheduling techniques.

32. Petrov's scheduling algorithm can be used to find good job sequences in flowline cells.

*33. Production control in cells can be improved by sub-dividing the affected component families into smaller sub-families on the basis of machining methods and tooling.

*34. Good job sequences in non-flowline cells can be obtained by a modified method of Petrov's algorithm.

35. In cellular manufacturing systems, production control functions should be operative at the cell level.

*36. The feasible solution to operations scheduling in a cell system is to install in every cell a desk top computer supported by simple algorithmic softwares.

# CHAPTER ELEVEN

## 11. RECOMMENDATIONS FOR FUTURE WORKS

The present work has shown a way of implementing cellular manufacture in small firms, the future works will be mainly concerned with detailed development and applications of the methodology.

The complexity code has verified the possibility of coding components without a manual. Based on the same concept, other coding systems can be developed for various types of components and products.

The Direct Clustering Algorithm (DCA) is a powerful tool for group formation, its application is not confined to manufacturing industries. The potential use of DCA as a means of universal classification should be investigated. Special attention should be given to its application to stock keeping.

The Adjacency Requirements Planning (ARP) gives near optimal results, its effectiveness can possibly be improved by employing some sort of improvement algorithms on the solution obtained. Efficiency can be improved by developing the ARP programme to draw the layout block diagram.

The design methodology should be verified further, if possible, with a batch manufacturing firm. Comprehensive analysis and implementation should be adopted wherever possible. The DCA and ARP programmes can be combined together to form the basis of a comprehensive computer package for cellular manufacture.

Composite GT-MRP systems have been installed in some companies, the performance of such systems should be investigated.

The operations scheduling algorithm developed is not yet tested, its application to real life problems should be investigated.

The possibility of developing a computer package specifically for production control at the cell level should be examined. Attention should be given to the use of desk top computers in cellular manufacturing systems.

# APPENDIX I

## I. COMPUTER PROGRAMMES

## IA. The DCA Programme

```
      MASTER DCA

C     THE DCA PROGRAMME TO DETERMINE MACHINE GROUPS AND COMPONENT
C     FAMILIES BY DIRECT CLUSTERING ANALYSIS

      DIMENSION IMACH(50),ICOMP(500),ICARD(500,46),NMACH(50),
     1NEWMAT(500,46),NCOMP(500),
     2MEXCH(500),MATRIX(500,46)
      INTEGER DUMMY(500,46),RSUM(500),CSUM(50),
     1B,C,D,E,XX(50),YY(50),X(50),Y(50)
      EQUIVALENCE (DUMMY(1),ICARD(1))
      DATA B/1H /,C/1HX/,D/1H*/,E/1H+/

C     IMACH=MACHINE NUMBER                ICOMP=COMPONENT NUMBER
C     ICARD=MACHINING SEQUENCE            MATRIX=MACHINE COMPONENT MATRIX
C     M=NUMBER OF ROWS IN MATRIX          N=NUMBER OF COLUMNS IN MATRIX
C     RSUM=NO. OF X ENTRIES IN ROW        CSUM= NO. OF X ENTRIES IN COLUMN
C     XX=ROW NO. TO BE DELETED            YY=COLUMN NO. TO BE DELETED
C     X,Y=CELL NO. TO BE DELETED          IEXCH=DUMMY SINGLE VARIABLE
C     MEXCH=DUMMY ROW VARIABLE            DUMMY=DUMMY MATRIX
C     NEWMAT=NEW MATRIX                   NMACH=MACHINE NO. IN NEW MATRIX
C     'X'=POSITIVE ENTRY                  ' '=NEGATIVE ENTRY
C     '+'=MULTIPLE MACHINE ENTRY          '*'=EXCEPTIONAL CELL ENTRY
C     NCOMP=COMPONENT NO. IN NEW MATRIX

C     INPUT DATA

      READ(1,112)(XX(K),K=1,20)
      READ(1,112)(YY(K),K=1,20)
      READ(1,112)(X(K),Y(K),K=1,13)
      READ(1,112)(X(K),Y(K),K=14,26)
      READ(1,112)(X(K),Y(K),K=27,39)
      READ(1,110)M,N
      READ(1,111)(IMACH(J),J=1,N)
      DO 10 I=1,M
   10 READ(1,112)(ICOMP(I)),NZ1,NZ2,NZ3,(ICARD(I,K),K=1,20)
  110 FORMAT(2I3)
  111 FORMAT(50I3)
  112 FORMAT(26I3)

C     TRANSFER DATA TO MATRIX
C     CALCULATE ROW SUM AND COLUMN SUM
C     PRINT ORIGINAL MATRIX

      DO 11 I=1,M
      DO 11 J=1,N
      MATRIX(I,J)=B
      DO 12 K=1,25
   12 IF(ICARD(I,K).EQ.IMACH(J))MATRIX(I,J)=C
   11 CONTINUE
      WRITE(2,114)
  114 FORMAT(1H1,' ***** CLUSTER FORMATION *****',///' ORIGINAL MATRIX')
      CALL SUMMING(MATRIX,RSUM,CSUM,M,N)
      CALL PRINTABLE(IMACH,ICOMP,MATRIX,RSUM,CSUM,M,N)

C     TEMPORARILY DELETE UNWANTED ROW AND COLUMNS
C     PRINT MATRIX

      IF(XX(1).EQ.00)GO TO 94
      DO 46 K=1,20
      IF(XX(K).EQ.00)GO TO 95
      DO 47 I=1,M
      IF(XX(K).NE.ICOMP(I))GO TO 47
      DO 48 J=1,N
      IF(MATRIX(I,J).NE.C)GO TO 48
      MATRIX(I,J)=E
   48 CONTINUE
   47 CONTINUE
   46 CONTINUE

   94 IF(YY(1).EQ.00)GO TO 97
```

```
   95 DO 43 K=1,20
      IF(YY(K).EQ.00)GO TO 96
      DO 44 J=1,N
      IF(YY(K).NE.IMACH(J))GO TO 44
      DO 45 I=1,M
      IF(MATRIX(I,J).NE.C)GO TO 45
      MATRIX(I,J)=E
   45 CONTINUE
   44 CONTINUE
   43 CONTINUE
   96 WRITE(2,113)(XX(K),K=1,20),(YY(K),K=1,20)
  113 FORMAT(///' MATRIX AFTER DELETING ROWS',3X,20(I3,1H;),
     114X/' AND COLUMNS',3X,20(I3,1H;))
      CALL SUMMING(MATRIX,RSUM,CSUM,M,N)
      CALL PRINTABLE(IMACH,ICOMP,MATRIX,RSUM,CSUM,M,N)

C     TEMPORARILY DELETE UNWANTED CELLS
C     PRINT MATRIX

   97 IF(X(1).EQ.00)GO TO 99
      DO 40 K=1,39
      IF(X(K).EQ.00)GO TO 98
      DO 41 I=1,M
      IF(X(K).NE.ICOMP(I))GO TO 41
      DO 42 J=1,N
      IF(Y(K).NE.IMACH(J))GO TO 42
      MATRIX(I,J)=D
   42 CONTINUE
   41 CONTINUE
   40 CONTINUE
   98 WRITE(2,115)(X(K),Y(K),K=1,39)
  115 FORMAT(///' MATRIX AFTER DELETING CELLS',/2X,39(I3,1X,I3,1H;))
      CALL SUMMING(MATRIX,RSUM,CSUM,M,N)
      CALL PRINTABLE(IMACH,ICOMP,MATRIX,RSUM,CSUM,M,N)

C     REARRANGE ROWS IN INCREASING ORDER,COLUMNS IN DECREASING ORDER
C     PRINT MATRIX

   99 DO 36 I=1,M
   36 IF(RSUM(I).EQ.0)RSUM(I)=9999
      DO 30 I=1,M-1
      DO 31 J=I+1,M
      IF(RSUM(I).LT.RSUM(J)) GO TO 31
      IEXCH=ICOMP(I)
      ICOMP(I)=ICOMP(J)
      ICOMP(J)=IEXCH
      IEXCH=RSUM(I)
      RSUM(I)=RSUM(J)
      RSUM(J)=IEXCH
      DO 32 K=1,N
      MEXCH(K)=MATRIX(I,K)
      MATRIX(I,K)=MATRIX(J,K)
   32 MATRIX(J,K)=MEXCH(K)
   31 CONTINUE
   30 CONTINUE
C
      DO 33 I=1,N-1
      DO 34 J=I+1,N
      IF(CSUM(I).GT.CSUM(J))GO TO 34
      IEXCH=IMACH(I)
      IMACH(I)=IMACH(J)
      IMACH(J)=IEXCH
      IEXCH=CSUM(I)
      CSUM(I)=CSUM(J)
      CSUM(J)=IEXCH
      DO 35 K=1,M
      MEXCH(K)=MATRIX(K,I)
      MATRIX(K,I)=MATRIX(K,J)
   35 MATRIX(K,J)=MEXCH(K)
   34 CONTINUE
```

```
   33 CONTINUE
      WRITE(2,120)
  120 FORMAT(///' MATRIX REARRANGED, ROWS INCREASE, COLUMNS DECREASE')
      CALL SUMMING(MATRIX,RSUM,CSUM,M,N)
      CALL PRINTABLE(IMACH,ICOMP,MATRIX,RSUM,CSUM,M,N)

C     APPLY THE DIRECT CLUSTERING ALGORITHM
C     PRINT MATRIX

  903 K=1
      DO 16 I=1,M
      DO 16 J=1,N
   16 DUMMY(I,J)=MATRIX(I,J)
      DO 17 J=1,N
      DO 17 I=1,M
      IF(MATRIX(I,J).NE.C)GO TO 17
      DO 18 L=1,N
      NEWMAT(K,L)=MATRIX(I,L)
   18 MATRIX(I,L)=B
      NCOMP(K)=ICOMP(I)
      K=K+1
   17 CONTINUE
      IF(K.EQ.M+1)GO TO 904
      DO 19 I=K,M
      NCOMP(I)=ICOMP(I)
      DO 19 J=1,N
   19 NEWMAT(I,J)=MATRIX(I,J)
  904 DO 20 J=1,N
      DO 20 I=1,M
      IF(NEWMAT(I,J).NE.DUMMY(I,J))GO TO 901
   20 CONTINUE
      GO TO 999
  901 DO 21 I=1,M
      ICOMP(I)=NCOMP(I)
      DO 21 J=1,N
   21 MATRIX(I,J)=NEWMAT(I,J)

      K=1
      DO 22 I=1,M
      DO 22 J=1,N
   22 DUMMY(I,J)=MATRIX(I,J)
      DO 23 I=1,M
      DO 23 J=1,N
      IF(MATRIX(I,J).NE.C)GO TO 23
      DO 24 L=1,M
      NEWMAT(L,K)=MATRIX(L,J)
   24 MATRIX(L,J)=B
      NMACH(K)=IMACH(J)
      K=K+1
   23 CONTINUE
      IF(K.EQ.N+1)GO TO 905
      DO 25 J=K,N
      NMACH(J)=IMACH(J)
      DO 25 I=1,M
   25 NEWMAT(I,J)=MATRIX(I,J)
  905 DO 26 I=1,M
      DO 26 J=1,N
      IF(NEWMAT(I,J).NE.DUMMY(I,J)) GO TO 902
   26 CONTINUE
      GO TO 999
  902 DO 27 J=1,N
      IMACH(J)=NMACH(J)
      DO 27 I=1,M
   27 MATRIX(I,J)=NEWMAT(I,J)
      GO TO 903

C     PRINT THE FINAL MATRIX

  999 WRITE(2,119)
  119 FORMAT(///' THIS IS THE FINAL MATRIX')
```

```
      CALL SUMMING(NEWMAT,RSUM,CSUM,M,N)
      CALL PRINTABLE(IMACH,ICOMP,NEWMAT,RSUM,CSUM,M,N)

      WRITE( 2,122)
  122 FORMAT(///' *****  END OF OUTPUT  *****')
      STOP
      END

C     THIS SUBROUTINE CALCULATES THE SUM OF ENTRIES
C     IN EACH ROW AND COLUMN

      SUBROUTINE SUMMING(MATRIX,RSUM,CSUM,M,N)
      INTEGER RSUM(500),B,C,CSUM(50),D,E
      DIMENSION MATRIX(500,48)
      DATA B/1H /,C/1HX/,D/1H*/,E/1H+/
      DO 1 I=1,M
      RSUM(I)=0
      DO 1 J=1,N
    1 IF(MATRIX(I,J).EQ.C)RSUM(I)=RSUM(I)+1
      DO 2 J=1,N
      CSUM(J)=0
      DO 2 I=1,M
    2 IF(MATRIX(I,J).EQ.C )CSUM(J)=CSUM(J)+1
      RETURN
      END

C     THIS SUBROUTINE PRINTS THE MATRIX WITH ROW AND COLUMN LABELS
C     ALSO THE ROW SUM AND COLUMN SUM

      SUBROUTINE PRINTABLE(IMACH,ICOMP,MATRIX,RSUM,CSUM,M,N)
      DIMENSION IMACH(50),ICOMP(500),MATRIX(500,48)
      INTEGER RSUM(500),CSUM(50)
      WRITE(2,10)(IMACH(J),J=1,N-1,2)
      WRITE(2,15)(IMACH(J),J=2,N,2)
      DO 1 I=1,M
    1 WRITE(2,11)(ICOMP(I)),(MATRIX(I,J),J=1,N),(RSUM(I))
      WRITE(2,12)(CSUM(J),J=1,N)
   10 FORMAT(//7X,'M/C NO,',/' CPT',2X,50I4)
   15 FORMAT(' NO.',4X,50I4)
   11 FORMAT(I4,5X,46A2,I6)
   12 FORMAT(/4X,24I4,/4X,24I4)

      RETURN
      END
      FINISH
```

## IB. The ARP Programme

```
      MASTER ARP

C     THE ARP PROGRAMME TO DETERMINE FLOW VALUE MATRIX AND OPTIMUM
C     TRIANGLE FOR ADJACENCY REQUIREMENTS PLANNING

      INTEGER WSN(100),TYPE(100),CPN(500),CPQ(500),BSZ(500),TRI,
     1 SUM(20,20),SEQ(500,12),WSC(100,100),VERTEX(3),BMC(500)
      DIMENSION NWC(100),NFW(100),MAX(20),MATRIX(50,50),NJ(20),NK(20),
     1 MCN(100),MX(20),MY(20),NX(20),NY(20)

C     NMC=NO. OF MACHINE CELLS          SEQ=WORK SEQUENCE
C     NCP=NO. OF COMPONENTS             NWC=NO. OF WORKSTATIONS IN CELL
C     WSN=WORKSTATION NO.               NFW=NO. OF FIXED WORSTATIONS
C     MCN=MACHINE CELL NO.              WSC=WORSTATIONS IN CELL
C     CPN=COMPONENT NO.                 NOB=NO. OF BATCHES
C     CPQ=COMPONENT QUANTITY            MATRIX=FLOW VALUE MATRIX
C     BSZ=BATCH SIZE                    M=ROW NUMBER IN MATRIX
C     BMC=BATCH MOVING COST             N=COLUMN NUMBER IN MATRIX
C     TYPE 1=FIXED 0=MOVABLE            SUM=TOTAL EDGE LENGTH OF TRIANGLE
C     MAX=OPTIMAL TRIANGLE IN COLUMN    TRI=OPTIMUM TRIANGLE
C     NWS=NO. OF WORKSTATIONS
C     MX,MY=MATRIX ENTRIES TO BE OVERWRITTEN BY 000
C     NX,NY=MATRIX ENTRIES TO BE OVERWRITTEN BY 999
C     I,NJ,NK=VERTICES OF OPTIMAL TRIANGLE IN COLUMN
C     VERTEX=VERTICES OF OPTIMUM TRIANGLE

C     INPUT DATA

      READ(1,101)NWS,NMC,NCP
      DO 10 I=1,NWS
      READ(1,101)WSN(I),MCN(I),TYPE(I)
   10 CONTINUE
      DO 11 I=1,NCP
      READ(1,102)CPN(I),CPQ(I),BSZ(I),BMC(I),(SEQ(I,J),J=1,12)
   11 CONTINUE
      READ(1,201)(MX(K),MY(K),K=1,13)
      READ(1,201)(NX(K),NY(K),K=1,13)
  201 FORMAT(26I3)
  101 FORMAT(3I0)
  102 FORMAT(16I3)
  103 FORMAT(20I0)

C     PRINT WORKSTATION INFORMATION
C     PRINT CELL INFORMATION
C     PRINT COMPONENT INFORMATION

      DO 12 I=1,NWS
      NWC(MCN(I))=NWC(MCN(I))+1
      NFW(MCN(I))=NFW(MCN(I))+TYPE(I)
   12 CONTINUE
      DO 13 I=1,NMC
      K=0
      DO 93 J=1,NWS
      IF(MCN(J).NE.I) GO TO 93
      K=K+1
      WSC(I,K)=WSN(J)
   93 CONTINUE
   13 CONTINUE
      WRITE(2,105)
      WRITE(2,106)NWS,NMC
      WRITE(2,107)
      DO 14 I=1,NWS
   14 WRITE(2,108) WSN(I),MCN(I),TYPE(I)
      WRITE(2,109)
      DO 15 I=1,NMC
   15 WRITE (2,110) I,NWC(I),NFW(I),(WSC(I,K),K=1,NWC(I))
      WRITE (2,111)
      DO 16 I=1,NCP
   16 WRITE(2,112) CPN(I),CPQ(I),BSZ(I),BMC(I),(SEQ(I,J),J=1,10)
  105 FORMAT(1H1///,1X,'ADJACENCY REQUIREMENTS PLANNING ',
     1 'FOR CELL LAYOUT')
```

```
  106 FORMAT(//' NUMBER OF WORKSTATIONS',I9//,' NUMBER OF ',
     1 'MANUFACTURING CELLS',I9)
  107 FORMAT(//' WORKSTATION INFORMATION:-',//1X,'W/S NO.',
     1 8X,'CELL NO.',8X,'TYPE(0=MOV;1=FXD)')
  108 FORMAT(I7,8X,I7,8X,I9)
  109 FORMAT(//' CELL INFORMATION:-',//1X,'CELL NO.',3X,
     1 'NO. OF W/S',3X,'NO. FIXED',3X,'WORKSTATION NUMBERS')
  110 FORMAT(I6,5X,I6,8X,I5,6X,12I4/,36X,15I4)
  111 FORMAT(///' COMPONENT INFORMATION:-',//1X,'CPT. NO.',3X,
     1 'QUANTITY',3X,'B/SIZE',3X,'MOV. COST',3X,'W/S SEQUENCE')
  112 FORMAT(I7,5X,I6,4X,I6,3X,I6,6X,12I4)

C     CALCULATE NO. OF BATCHES
C     FORM FLOW VALUE MATRIX
C     PRINT FLOW VALUE MATRIX

      DO 20 I=1,NCP
      NOB=CPQ(I)/BSZ(I)
      IF((CPQ(I)-NOB*BSZ(I)).NE.0)NOB=NOB+1
      DO 21 J=2,12
      IF(SEQ(I,J).EQ.0)GO TO 21
      DO 22 K=1,NWS
      IF(SEQ(I,J).EQ.WSN(K))M=MCN(K)
      IF(SEQ(I,J-1).EQ.WSN(K))N=MCN(K)
   22 CONTINUE
      MATRIX(M,N)=MATRIX(M,N)+NOB*BMC(I)
      IF(M.EQ.N)MATRIX(M,N)=0
      MATRIX(N,M)=MATRIX(M,N)
   21 CONTINUE
   20 CONTINUE
      WRITE(2,113)(I,I=1,NMC)
      DO 25 I=1,NMC
      MCN(I)=I
   25 WRITE(2,114) MCN(I),(MATRIX(I,J),J=1,NMC)
  113 FORMAT(///' FLOW MATRIX BETWEEN CELLS',///5X,20I7//)
  114 FORMAT(I4,1X,30I7)

C     MODIFY FLOW VALUE MATRIX
C     PRINT FLOW VALUE MATRIX

      IF(MX(1).EQ.0)GO TO 99
      DO 40 K=1,13
      IF(MX(K).EQ.0)GO TO 99
      DO 41 M=1,NMC
      IF(M.NE.MX(K))GO TO 41
      DO 42 N=1,NMC
      IF(N.NE.MY(K))GO TO 42
      MATRIX(M,N)=0
      MATRIX(N,M)=MATRIX(M,N)
   42 CONTINUE
   41 CONTINUE
   40 CONTINUE

   99 IF(NX(1).EQ.0)GO TO 98
      DO 50 K=1,13
      IF(NX(K).EQ.0)GO TO 98
      DO 51 M=1,NMC
      IF(M.NE.NX(K))GO TO 51
      DO 52 N=1,NMC
      IF(N.NE.NY(K))GO TO 52
      MATRIX(M,N)=999
      MATRIX(N,M)=MATRIX(M,N)
   52 CONTINUE
   51 CONTINUE
   50 CONTINUE

   98 WRITE(2,202)(I,I=1,NMC)
      DO 60 I=1,NMC
      MCN(I)=I
   60 WRITE(2,114)MCN(I),(MATRIX(I,J),J=1,NMC)
```

```
  202 FORMAT(//' MODIFIED FLOW VALUE MATRIX',//5X,20I7//)

C     FIND OPTIMAL TRIANGLE IN EACH COLUMN
C     PRINT OPTIMAL TRIANGLE IN EACH COLUMN

      WRITE(2,115)
      DO 30 I=1,NMC
      MAX(I)=0
      DO 31 J=1,NMC-1
      IF(I.EQ.J)GO TO 31
      DO 32 K=J+1,NMC
      IF(I.EQ.K)GO TO 32
      SUM(J,K)=MATRIX(I,J)+MATRIX(I,K)+MATRIX(J,K)
      IF(MAX(I).GE.SUM(J,K)) GO TO 32
      MAX(I)=SUM(J,K)
      NJ(I)=J
      NK(I)=K
   32 CONTINUE
   31 CONTINUE
      WRITE(2,116) I,I,NJ(I),NK(I),MAX(I)
   30 CONTINUE
  115 FORMAT(///' THE OPTIMAL TRIANGLE IN COLUMN ',8X,'IS',
     1 8X,' WITH TOTAL FLOW VALUE ')
  116 FORMAT(24X,I4,7X,3I3,10X,I7)

C     FIND OPTIMUM TRIANGLE
C     PRINT OPTIMUM TRIANGLE

      TRI=MAX(1)
      DO 33 I=1,NMC
      IF(TRI.GT.MAX(I)) GO TO 33
      TRI=MAX(I)
      VERTEX(1)=I
      VERTEX(2)=NJ(I)
      VERTEX(3)=NK(I)
   33 CONTINUE
      WRITE(2,117) VERTEX(1),VERTEX(2),VERTEX(3),TRI
  117 FORMAT(///' THE OPTIMUM TRIANGLE IS',2X,3I3,'  WITH TOTAL FLOW',
     1 ' VALUE OF ',I7)

      STOP
      END
      FINISH
```

# APPENDIX II

## II. COMPUTER OUTPUT FOR THE INDUSTRIAL APPLICATION

## IIA. The Final Matrix for Rotational Components

| M/C NO. | A | | | | | | | | | | | | | | | | | B | | | | | | | | | | C | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CPT NO. | 40 | 8 | 6 | 3 | 4 | 11 | 36 | 18 | 31 | 22 | 28 | 44 | 45 | 35 | 43 | 13 | 29 | 23 | 1 | 19 | 24 | 20 | 9 | 26 | 25 | 5 | 21 | 41 | 39 | 38 | 33 | 27 | 10 | 2 |
| 462 | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ |
| 458 | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ |
| 456 | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ |
| 453 | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ |
| 446 | x | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | ◆ | ◆ | | ◆ |
| 445 | x | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | ◆ | ◆ | | ◆ |
| 413 | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | | | ◆ | | ◆ |
| 325 | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | ◆ | | ◆ |
| 238 | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ |
| 115 | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | | | ◆ | | ◆ |
| 43 | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | ◆ | | ◆ |
| 481 | x | x | | | | | | | | | | | | | | | | | | | | | | | ★ | | | | ◆ | | | | | |
| 457 | x | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | ◆ | | | |
| 450 | x | | | x | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | | | ◆ | | |
| 444 | x | | | | x | | | | | | | | | | | | | | | | | | | | | | | | ◆ | | | | ◆ | |
| 311 | x | | | | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ |
| 230 | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | ◆ | | ◆ | |
| 212 | x | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | | ◆ | ◆ | |
| 180 | x | | x | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | ◆ | ◆ | |
| 179 | x | | x | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | ◆ | ◆ | |
| 174 | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | ◆ | | | |
| 163 | x | | | | | | x | | | | | | | | | | | | | | | | | | | | | | ◆ | | | ◆ | | ◆ |
| 157 | x | | | | | | | x | | | | | | | | | | | | | | | | | | | | | ◆ | | | | | |
| 106 | x | | | | | x | | | | | | | | | | | | | | | | | | | | | | ◆ | | | | ◆ | | ◆ |
| 74 | x | | | | | | x | | | | | | | | | | | | | | | | | | | | | | ◆ | | | ◆ | | ◆ |
| 73 | x | | | | | | x | | | | | | | | | | | | | | | | | | | | | | ◆ | | | ◆ | | ◆ |
| 37 | x | | | | x | | | | | | | | | | | | | | | | | | | | | | | | ◆ | | | ◆ | ◆ | |
| 6 | x | | | | | x | | | | | | | | | | | | | | | | | | | | | | ◆ | ◆ | | | ◆ | | ◆ |
| 499 | x | x | | | | x | | | | | | | | | | | | | | | | | | | | | | ◆ | | | | ◆ | | |
| 463 | x | | x | | | | | | x | | | | | | | | | | | | | | | | | | | | ◆ | | ◆ | ◆ | | |
| 440 | x | | | | x | | | | | x | | | | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | | | ◆ | |
| 248 | x | x | | | | | | | | | x | | | | | | | | | | | | | | | | | | | | | | | |
| 239 | x | x | | | | x | | | | | | | | | | | | | | | | | | | | | | | ◆ | | | ◆ | | |
| 217 | x | | x | | | | | x | | | | | | | | | | | | | | | | | | | | | ◆ | | | ◆ | ◆ | |
| 200 | x | x | | | | | | | | | x | | | | | | | | | | | | | | | | | | ◆ | | | | | |
| 171 | x | | | | x | | | x | | | | | | | | | | | | | | | | | | | | | ◆ | | | | | |
| 111 | x | x | | | | x | | | | | | | | | | | | | | | | | | | | | | ◆ | | | | ◆ | | |
| 102 | x | | | | | x | | | | | | x | | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | ◆ | ◆ | | ◆ |
| 101 | x | | | | | x | | | | | | x | | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | ◆ | ◆ | | ◆ |
| 89 | x | | | | | x | | | | | | x | | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | ◆ | ◆ | | ◆ |
| 18 | x | x | | | | | | | | | | | x | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | ◆ | ◆ | | |
| 17 | x | x | | | | | | | | | | | x | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | ◆ | ◆ | ◆ | |
| 439 | x | | x | | | | | x | | | x | | | | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | | | |
| 355 | x | | | | x | | | x | | | | | | x | | | | | | | | | | | | | | | | | | | | |
| 207 | x | x | | | | | | | | | x | x | | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | ◆ | | | |
| 150 | x | | | | | x | | | x | | | | | | x | | | | | | | | | | | | | | ◆ | | | ◆ | | ◆ |
| 199 | x | | | | x | | | x | x | | | x | | | | | | | | | | | | | | | | ◆ | | | | ◆ | ◆ | |
| 20 | x | x | | | | | | x | | | | x | x | | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | ◆ | | |
| 492 | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 486 | | x | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | | | | | ◆ | |
| 485 | | x | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | | | | | ◆ | |
| 484 | | x | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | | | | | | |
| 474 | | x | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | | ◆ | ◆ | | | |
| 421 | | x | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | | | | | ◆ | |
| 339 | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 270 | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 233 | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | | ◆ | | | ◆ |
| 232 | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | | ◆ | | | ◆ |
| 151 | | x | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | ◆ | ◆ | ◆ | |
| 28 | | x | | | | | | | | | | | | | | | | | | | | | | | | | | ◆ | | | | | | |
| 3 | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 467 | | x | | | | x | | | | | | | | | | | | | | | | | | | | | | ◆ | | | | | | |
| 402 | | x | | | | | | | | | | | x | | | | | | | | | | | | | | | ◆ | ◆ | ◆ | | ◆ | | |
| 359 | | x | | | | x | | | | | | | | | | | | | | | | | | | ★ | | | ◆ | ◆ | ◆ | ◆ | | | |
| 347 | | x | | | | x | | | | | | | | | | | | | | | | | | | | | | ◆ | ◆ | | | ◆ | | |
| 274 | | x | | | | x | | | | | | | | | | | | | | | | | | | | | | ◆ | | | | | | |
| 272 | | x | | | | x | | | | | | | | | | | | | | | | | | | | | | ◆ | | | | | | |
| 228 | | x | | | | | | | | | | x | | | | | | | | | | | | | | | | ◆ | | | | | ◆ | |
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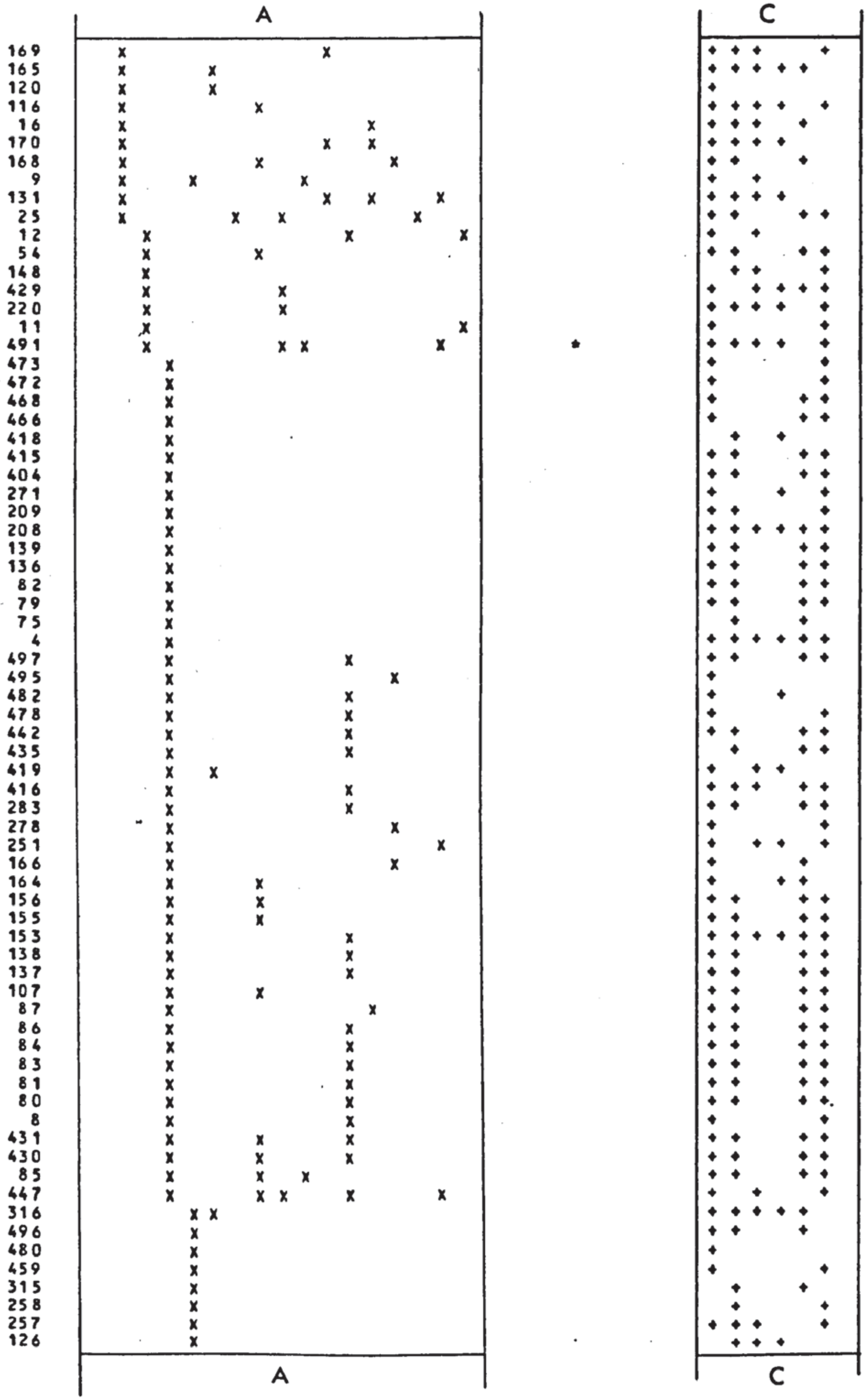
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A
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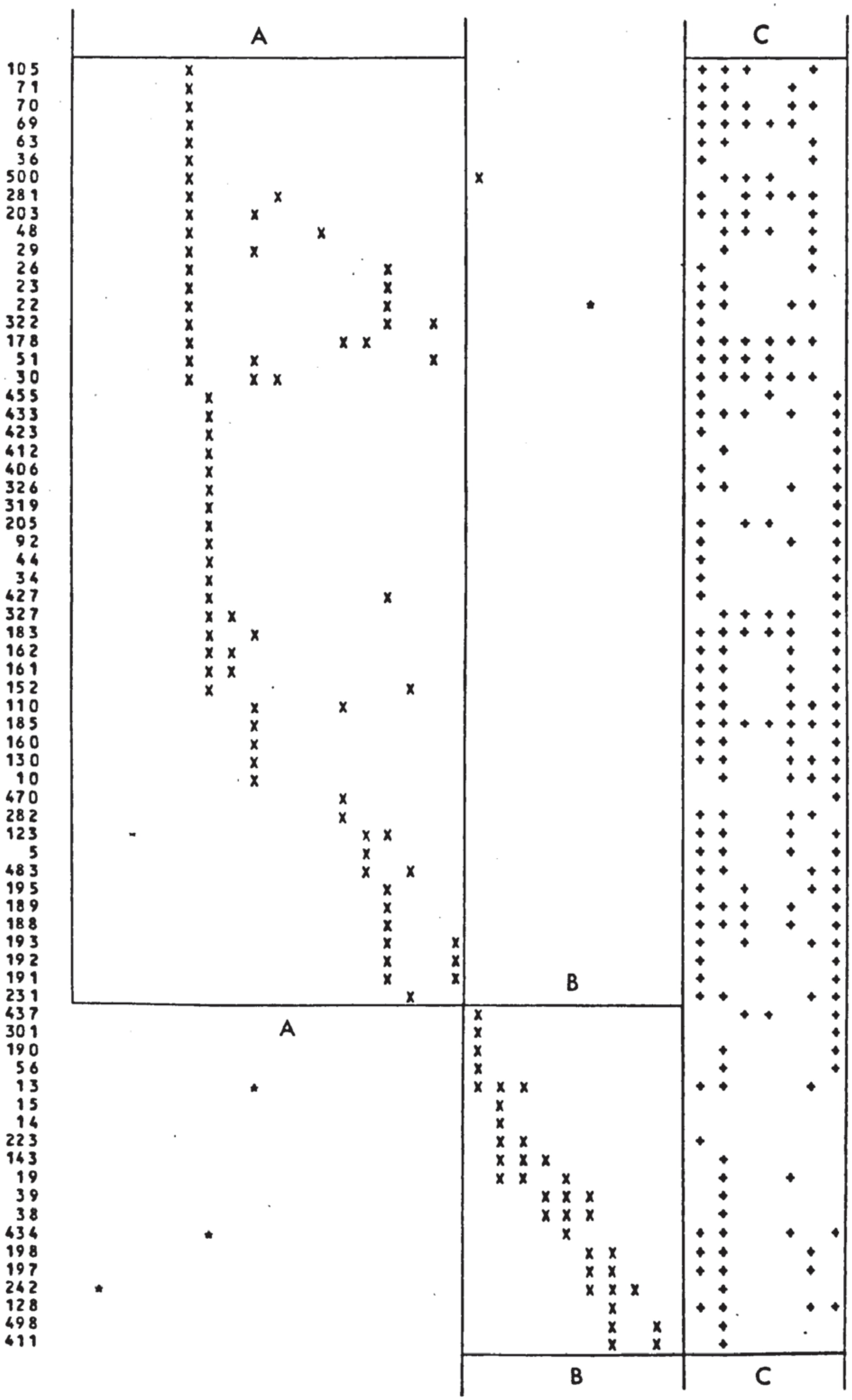
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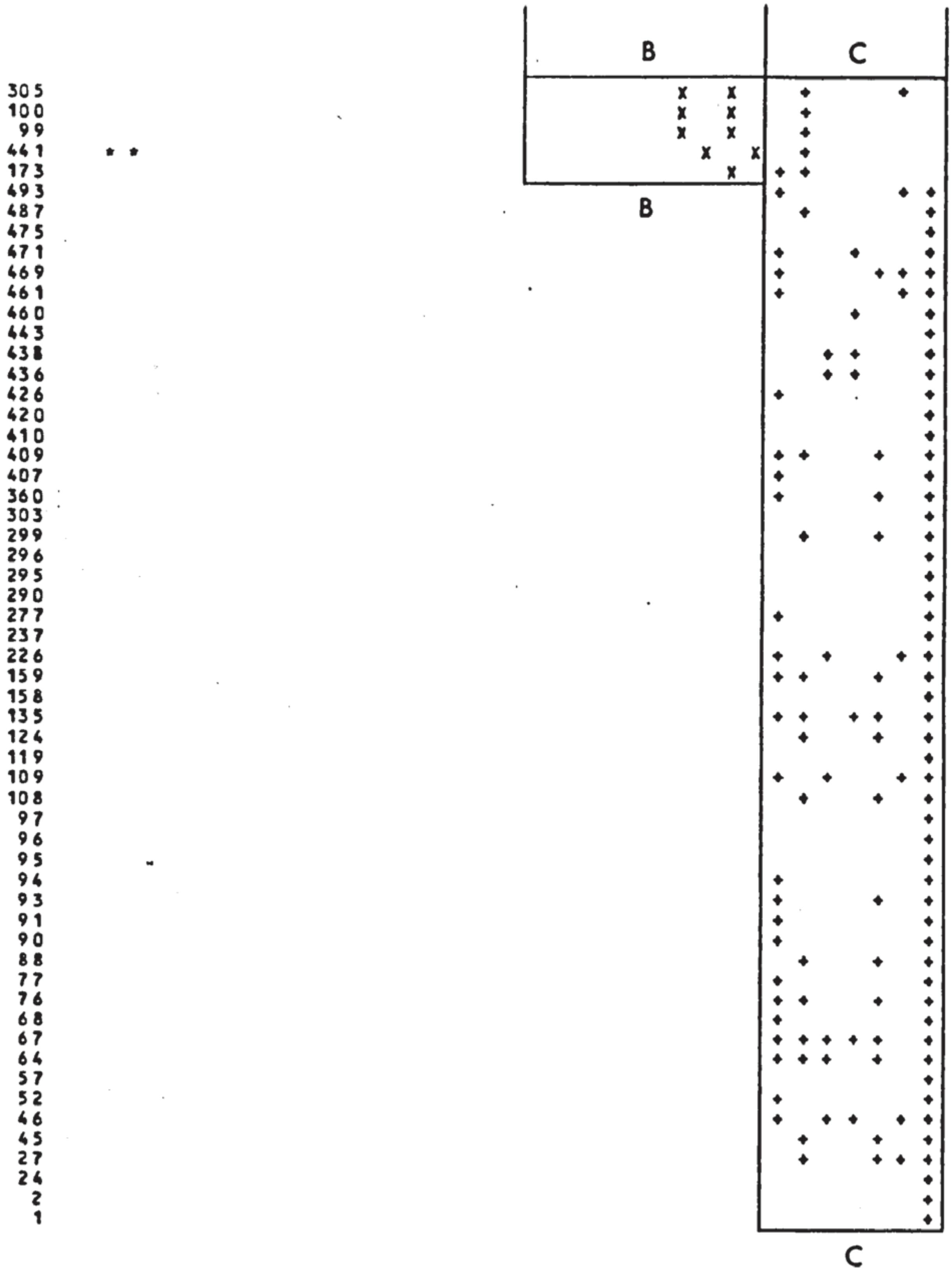
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## IIB. The Final Matrix for Non-Rotational Components

| M/C NO. | D | | | | | | | | | | | | G | | E | | | | | | | | H | | F | | | | I | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CPT NO. | 31 | 30 | 32 | 18 | 14 | 10 | 44 | 35 | 37 | 34 | 3 | 5 | 17 | 20 | 40 | 12 | 22 | 36 | 42 | 11 | 21 | 28 | 4 | 16 | 26 | 15 | 27 | 7 | 41 | 39 | 38 | 33 | 13 | |
| 202 | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | | ✦ | 00 |
| 349 | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | | | | | 00 |
| 342 | x | | x | | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | | | 00 |
| 338 | x | | x | | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | | 00 |
| 324 | x | | | x | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | | | ✦ | ✦ | 00 |
| 318 | x | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | | 00 |
| 245 | x | | | x | | | | | | | | | | | * | | | | | | | | | | | | * | | | ✦ | | | ✦ | 00 |
| 244 | x | | | x | | | | | | | | | | | * | | | | | | | | | | | | * | | | ✦ | | | ✦ | 00 |
| 184 | x | | | x | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | | ✦ | 00 |
| 182 | x | | | x | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | | ✦ | 00 |
| 104 | x | | | | x | | | | | | | | | | | | | | | | | | | | | | | | ✦ | | | ✦ | | 00 |
| 103 | x | | | | x | | | | | | | | | | | | | | | | | | | | | | | | ✦ | | | ✦ | | 00 |
| 98 | x | | | x | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | ✦ | 00 |
| 464 | x | | | x | | x | | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | ✦ | 00 |
| 449 | x | | | | | x | x | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | ✦ | 00 |
| 425 | x | | | | | x | x | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | | ✦ | 00 |
| 424 | x | | | x | | x | | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | ✦ | 00 |
| 363 | x | | x | | | | | x | | | | | | | | | | | | | | | | | | | | | ✦ | | | | | 00 |
| 358 | x | | x | | | | | | x | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | | | 00 |
| 356 | x | | | | | | | x | | x | | | | | | | | | | | | | | | | | | | ✦ | | | | | 00 |
| 350 | x | x | | | | | | x | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | | | 00 |
| 346 | x | x | | | | | | x | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | | 00 |
| 345 | x | x | | | | | | x | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | | 00 |
| 344 | x | x | | | | | | x | | | | | | | | | | | | | | | | | | | | | ✦ | | | | | 00 |
| 341 | x | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | | 00 |
| 336 | x | | x | | | | | x | | | | | | | | | | | | | | | | | | | | | ✦ | | | | | 00 |
| 333 | x | x | | | | | | x | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | | | 00 |
| 330 | x | | | x | | x | | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | ✦ | 00 |
| 317 | x | | x | | x | | | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | | 00 |
| 304 | x | | x | | x | | | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | | 00 |
| 276 | x | | | | | x | x | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | | ✦ | 00 |
| 275 | x | | | x | | x | | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | ✦ | 00 |
| 247 | x | | | x | | x | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | ✦ | ✦ | 00 |
| 147 | x | | x | | x | | | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | | 00 |
| 47 | x | | | | | x | | x | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | | 00 |
| 465 | x | | | x | x | x | | | | | | | | | * | | | | | | | | | | | | | | ✦ | ✦ | ✦ | ✦ | | 00 |
| 428 | x | | x | | x | | | | | | x | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | | 00 |
| 362 | x | | | | | | | x | x | x | | | | | | | | | | | | | | | | | | | ✦ | | | | | 00 |
| 352 | x | x | x | | | | | x | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | | 00 |
| 348 | x | | | x | x | x | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | ✦ | | 00 |
| 280 | x | | x | | x | | | | | | | x | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | | 00 |
| 279 | x | | | | x | x | | | | | | x | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | | 00 |
| 41 | x | | | x | x | x | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | | | 00 |
| 490 | | x | | | | | | x | | | | | | | | | | | | | | | | | | | | | ✦ | | | | | 00 |
| 351 | | x | | | | | | x | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | | | 00 |
| 266 | | x | | | | | | x | | | | | | | | | | | | | | | | | | | | | ✦ | | | | | 00 |
| 357 | | x | | | | | | x | | x | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | | | 00 |
| 332 | | x | x | | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | | 00 |
| 364 | | x | | | | | | | | x | | | | | | | | | | | | | | | | | | | ✦ | | | ✦ | | 00 |
| 335 | | | x | | | | | x | | | | | | | | | | | | | | | | | | | | | ✦ | | | | | 00 |
| 334 | | | x | | | | | x | | | | | | | | | | | | | | | | | | | | | ✦ | | | | | 00 |
| 340 | | | x | | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | | 00 |
| 408 | | | x | | | | | | x | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | | 00 |
| 494 | | | | x | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | ✦ | ✦ | 00 |
| 329 | | | | x | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | ✦ | ✦ | 00 |
| 328 | | | | x | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | ✦ | ✦ | 00 |
| 313 | | | | x | | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | ✦ | 00 |
| 298 | | | | x | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | | ✦ | 00 |
| 241 | | | | x | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | ✦ | ✦ | 00 |
| 236 | | | | x | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | ✦ | ✦ | 00 |
| 222 | | | | x | | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | ✦ | 00 |
| 175 | | | | x | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | ✦ | ✦ | 00 |
| 172 | | | | x | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | ✦ | ✦ | 00 |
| 154 | | | | x | | | | | | | | | | | | | | | | | | | | | | | * | | ✦ | ✦ | | | | 00 |
| 58 | | | | x | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | ✦ | ✦ | 00 |
| 49 | | | | x | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | | ✦ | ✦ | ✦ | 00 |
| 42 | | | | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 00 |
| 7 | | | | x | | | | | | | | | | | | | | | | | | | | | | | | | | ✦ | ✦ | ✦ | ✦ | 00 |
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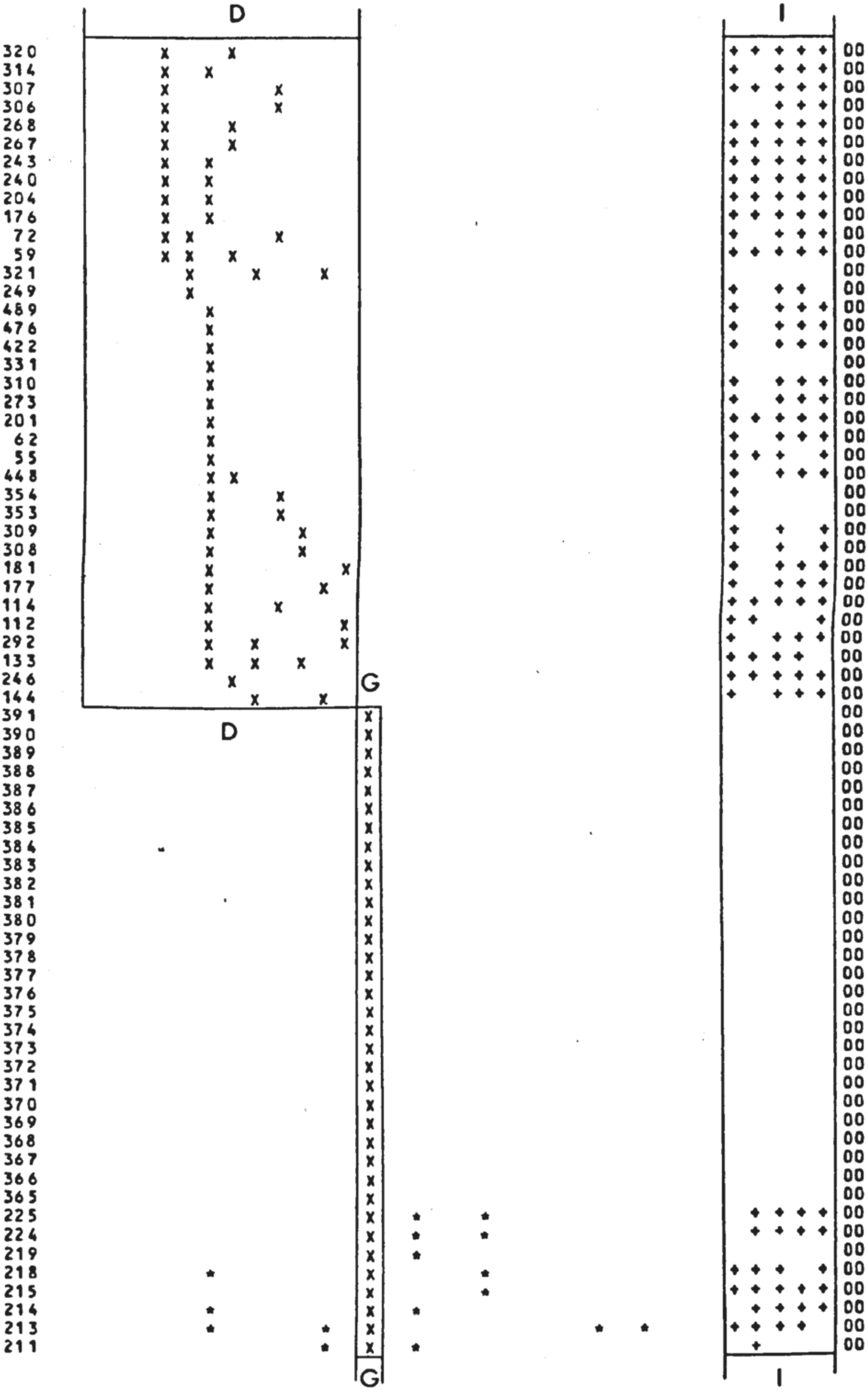
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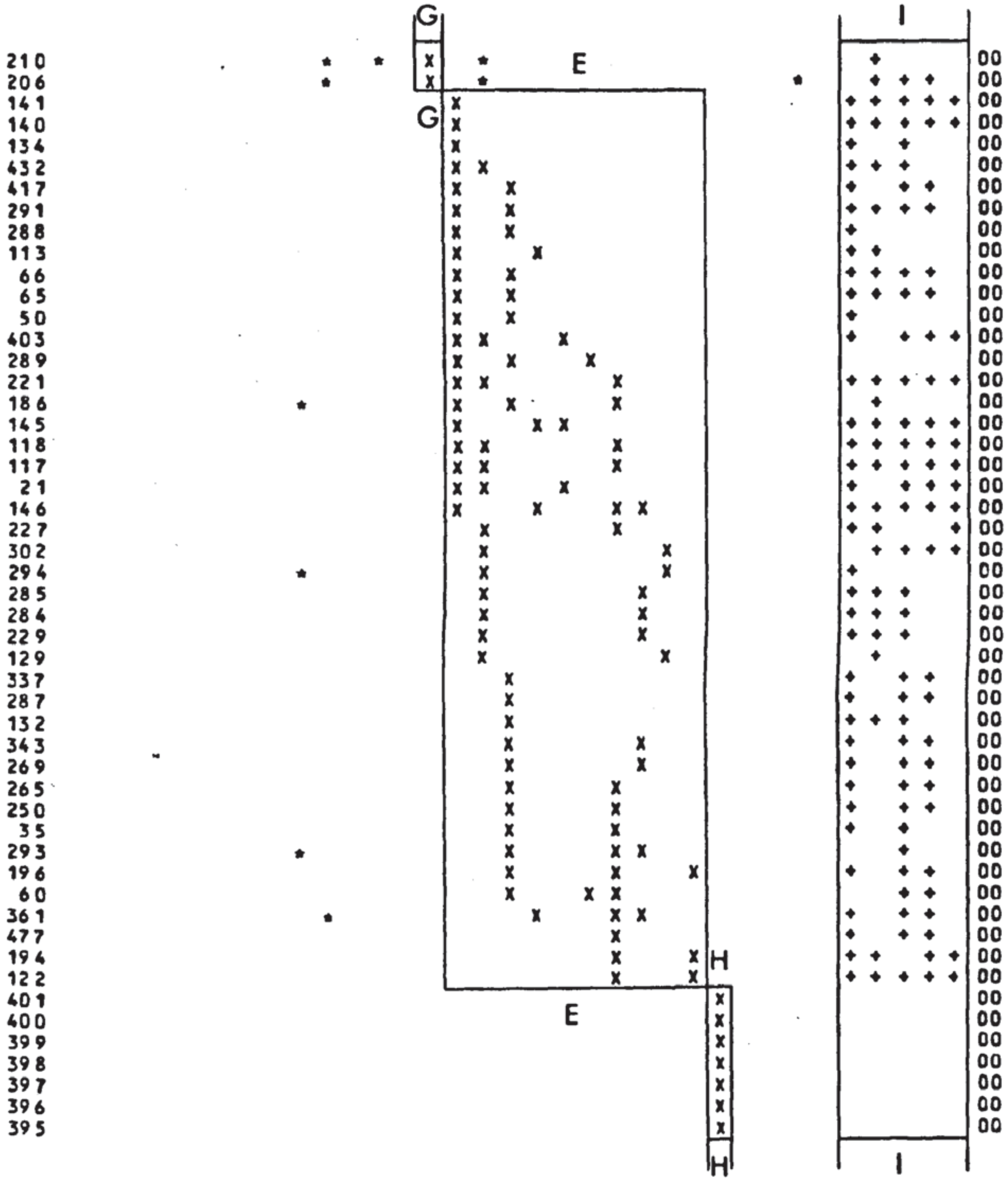
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| 393 | x | | | | | | | | | | 00 |
| 392 | x | | | | | | | | | | 00 |
| 235 | | x | | | | + | + | + | + | + | 00 |
| 234 | | x | | | | + | + | + | | + | 00 |
| 216 | | x | | | | + | + | + | + | + | 00 |
| 254 | | x | x | x | | + | + | + | + | | 00 |
| 414 | | | x | | | + | + | + | + | + | 00 |
| 127 | | | x | | | + | + | + | + | + | 00 |
| 125 | | | x | | | + | + | + | + | + | 00 |
| 187 | | | | x | x | + | + | | | + | 00 |
| 149 | | | | x | x | + | + | | | | 00 |
| 488 | | | | | | + | | + | + | + | 00 |
| 479 | | | | | | + | | + | + | + | 00 |
| 454 | | | | | | + | | + | + | + | 00 |
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| 451 | | | | | | + | | + | + | + | 00 |
| 405 | | | | | | + | | + | + | + | 00 |
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| 78 | | | | | | + | | | | | 00 |
| 61 | | | | | | + | | | + | + | 00 |
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| 33 | | | | | | + | | + | + | + | 00 |
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| 31 | | | | | | + | | + | + | + | 00 |

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## IIC. Results of the ARP Analysis

```
ADJACENCY REQUIREMENTS PLANNING FOR CELL LAYOUT

NUMBER OF WORKSTATIONS         69

NUMBER OF MANUFACTURING CELLS        9

WORKSTATION INFORMATION:-

W/S NO.          CELL NO.         TYPE(0=MOV;1=FXD)
     1              2                   0
     2              3                   0
   103              1                   0
   403              4                   0
     4              1                   0
   205              2                   0
   405              4                   0
     6              1                   0
     7              6                   0
     8              8                   0
     9              2                   0
   310              3                   0
   410              4                   0
   111              1                   0
   511              5                   0
    12              5                   0
   113              1                   0
   613              6                   0
    14              4                   0
    15              6                   0
    16              7                   0
    17              7                   0
   118              1                   0
   418              4                   0
    19              2                   0
   220              2                   0
   520              5                   0
    21              8                   0
    22              1                   0
    23              2                   0
    24              2                   0
    25              2                   0
   226              2                   0
   626              6                   0
   327              3                   0
   627              6                   0
   128              1                   0
   528              5                   0
    29              1                   0
    30              8                   0
   131              1                   0
   431              4                   0
    32              8                   0
   333              3                   0
   633              6                   0
    34              4                   0
    35              8                   0
    36              1                   0
    37              8                   0
   138              1                   0
   238              2                   0
   338              3                   0
   438              4                   0
   538              5                   0
   638              6                   0
    39              9                   0
   140              1                   0
   540              5                   0
   141              1                   0
   241              2                   0
```

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   341               3                  0
   441               4                  0
   541               5                  0
   641               6                  0
    42               5                  0
    43               1                  0
   144               1                  0
   444               4                  0
    45               1                  0

CELL INFORMATION:-

CELL NO.    NO. OF W/S     NO. FIXED    WORKSTATION NUMBERS
    1           17              0        103   4   6 111 113 118  22 128  29 131  36 138
                                         140 141  43 144  45
    2           11              0          1 205   9  19 220  23  24  25 226 238 241
    3            6              0          2 310 327 333 338 341
    4           10              0        403 405 410  14 418 431  34 438 441 444
    5            8              0        511  12 520 528 538 540 541  42
    6            8              0          7 613  15 626 627 633 638 641
    7            2              0         16  17
    8            6              0          8  21  30  32  35  37
    9            1              0         39


COMPONENT INFORMATION:-

CPT. NO.    QUANTITY    B/SIZE    MOV. COST    W/S SEQUENCE
    1             20        20        1          2   0   0   0   0   0   0   0   0   0
    2             20        20        1          2   0   0   0   0   0   0   0   0   0
    3             20        20        1          8   0   0   0   0   0   0   0   0   0
    4              2         2        1        103 138 333 310 141  39 327   0   0   0
    5              6         6        1          2  39  45 141 327   0   0   0   0   0
    6              6         6        1          2  39 111 141 327 140   0   0   0   0
    8              1         1        1        103 144 310 141   0   0   0   0   0   0
    9            250       250        1        138 141  22   4   8   0   0   0   0   0
   10              1         1        1          2  39 310 327 118   0   0   0   0   0
   11              2         2        1          6 310  29 141   0   0   0   0   0   0
   12              2         2        1          6 138 144  29 141   0   0   0   0   0
   13              8         8        1          1  39 310 241 118  23  19   0   0   0
   14             50        50        1          1   0   0   0   0   0   0   0   0   0
   15            300       300        1          1   0   0   0   0   0   0   0   0   0
   16              1         1        1          8  39 138  45 141 327   0   0   0   0
   17             16        16        1          8  39  45 138 333 310 141 327 140   0
   18             20        20        1          8  39  45 138 333 140 327 141   0   0
   19             46        46        1          1  39 220 327  19   0   0   0   0   0
   20              9         9        1          8  39  45 138 333 144 140 327 118   0
   22              2         2        1          4 310 141  39  35 327   0   0   0   0
   23              2         2        1          4  39  35 141   0   0   0   0   0   0
   24              2         2        1          2   0   0   0   0   0   0   0   0   0
   25              2         2        1          8 310 141  43  36 131  39 327   0   0
  626              2         2        1          4  35 310 141   0   0   0   0   0   0
  627              3         3        1          2 310  39 327   0   0   0   0   0   0
   28            633        33        1          8 141   0   0   0   0   0   0   0   0
   29              1         1        1          4 310  39 118   0   0   0   0   0   0
   30             10        10        1          4  39 138 310 333 141 327 118 131   0
   34              5         5        1          2 111 141   0   0   0   0   0   0   0
   36              1         1        1          4 310 141   0   0   0   0   0   0   0
   37              4         4        1          4  39 310 327 140   0   0   0   0   0
   38              3         3        1          9  39  24 220   0   0   0   0   0   0
   39              1         1        1          9  39  24 220   0   0   0   0   0   0
   43              1         1        1          2 138 333  39 327 140   0   0   0   0
   44              1         1        1          2 111 141   0   0   0   0   0   0   0
   45              2         2        1          2  39 327   0   0   0   0   0   0   0
   46              2         2        1          2 310 338 333 341   0   0   0   0   0
   48              1         1        1          4  39 310 138 333 128   0   0   0   0
   51              2         2        1          4  39 113 138 333 141 118   0   0   0
   52              2         2        1          2 341   0   0   0   0   0   0   0   0
   54              1         1        1          6  39 310 141 327 118   0   0   0   0
```

```
  56                 2               2             1              2   39   23    0    0    0    0    0    0    0
  57                20              20             1              2    0    0    0    0    0    0    0    0    0
  63                 1               1             1              4   39  310  141    0    0    0    0    0    0
  64                 2               2             1              2   39  338  341  327    0    0    0    0    0
  67                 3               3             1              2   39  338  333  341  327    0    0    0    0
  68                 1               1             1              2  341    0    0    0    0    0    0    0    0
  69                 2               2             1              4   39  138  333  141  327    0    0    0    0
  70                 3               3             1              4   39  138  310  141  327    0    0    0    0
  71                 1               1             1             64  141   39  327    0    0    0    0    0    0
  73                 2               2             1              2   36   39  327  140    0    0    0    0    0
  74                 1               1             1              2   36   39  327  140    0    0    0    0    0
  75                 4               4             1            103   39  327    0    0    0    0    0    0    0
  76                 4               4             1              2  341   39  327    0    0    0    0    0    0
  77                 3               3             1              2  341    0    0    0    0    0    0    0    0
  79                 1               1             1            103  310  141   39  327    0    0    0    0    0
  80                 1               1             1            103  144  310  141   39  327    0    0    0    0
  81                 1               1             1            103  144  310  141   39  327    0    0    0    0
  82                 2               2             1            103  310  141   39  327    0    0    0    0    0
  83                 3               3             1            103  144  310  141   39  327    0    0    0    0
  84                 3               3             1            103  144  310  141   39  327    0    0    0    0
  85                 2               2             1            103  310  141  118   22   39  327    0    0    0
  86                 1               1             1            103  144  310  141   39  327    0    0    0    0
  87                 2               2             1            103  310  141   45   39  327    0    0    0    0
  88                 1               1             1              2   39  327    0    0    0    0    0    0    0
  89                 3               3             1              2   39  111  138  333  144  140  327  141    0
  90                 1               1             1              2  341    0    0    0    0    0    0    0    0
  91                 3               3             1              2  341    0    0    0    0    0    0    0    0
  92                 1               1             1              2  111  141  327    0    0    0    0    0    0
  93                 1               1             1              2  341  327    0    0    0    0    0    0    0
  94                 5               5             1              2  341    0    0    0    0    0    0    0    0
  95                 4               4             1              2    0    0    0    0    0    0    0    0    0
  96                 2               2             1              2    0    0    0    0    0    0    0    0    0
  97                 1               1             1              2    0    0    0    0    0    0    0    0    0
  99                 2               2             1            205   39  226    0    0    0    0    0    0    0
 100                 1               1             1            205   39  226    0    0    0    0    0    0    0
 101                 1               1             1              2   39  111  138  333  144  140  327  141    0
 102                 2               2             1              2   39  111  138  333  144  140  327  141    0
 105                 1               1             1              4   39  310  138  141    0    0    0    0    0
 106                 3               3             1              2  140  111  141  327    0    0    0    0    0
 107                 1               1             1            103  310  141   39  327  118    0    0    0    0
 108                 1               1             1              2   39  327    0    0    0    0    0    0    0
 109                 1               1             1              2  338  310  341    0    0    0    0    0    0
 110                 2               2             1              2  310  144  141   39  327  118    0    0    0
 111                 2               2             1              8  140  111  141  327    0    0    0    0    0
 115                 1               1             1              2   39  327  140    0    0    0    0    0    0
 116                 3               3             1              8  138  310  141   39  333  118    0    0    0
 119                 3               3             1              2    0    0    0    0    0    0    0    0    0
 120                 1               1             1              8  111  141    0    0    0    0    0    0    0
 123                 6               6             1              2   45   35  141   39  327    0    0    0    0
 124                 1               1             1              2   39  327    0    0    0    0    0    0    0
 126                12              12             1              4   39  138  333    0    0    0    0    0    0
 128                 4               4             1              2   39  310  241  226    0    0    0    0    0
 130                 4               4             1              2   39  310  141  327  118    0    0    0    0
 131                 1               1             1              8   39   45  138  333  113  141  128    0    0
 135                 9               9             1              2   39  333  341  327    0    0    0    0    0
 136                 1               1             1            103  310  141   39  327    0    0    0    0    0
 137                 1               1             1            103  144  310  141   39  327    0    0    0    0
 138                 1               1             1            103  144  310  141   39  327    0    0    0    0
 139                 6               6             1            103  310  141   39  327    0    0    0    0    0
 143                52              52             1              1   39   24   19    0    0    0    0    0    0
 148                 1               1             1              6   39  138  310    0    0    0    0    0    0
 150                 5               5             1              2   39  131  111  327   43  140    0    0    0
 151                 4               4             1              8   39  310  138  333  141  327    0    0    0
 152                 4               4             1              2  111  141   39  327   43    0    0    0    0
 153                 2               2             1            103  310  144  138  333  141   39  327    0    0
 155                 4               4             1            103  310  141   39  327  118    0    0    0    0
 156                 4               4             1            103  310  141   39  327  118    0    0    0    0
 157                10              10             -             39  118  140    0    0    0    0    0    0    0
 158                10              10             1              2    0    0    0    0    0    0    0    0    0
 159                10              10             1              2  341   39  327    0    0    0    0    0    0
 160                 2               2             1              2  141   39  327  118    0    0    0    0    0
```

```
161          2         2        1         2 111 141  36  39 327   0   0   0   0
162          2         2        1         2 111 141  36  39 327   0   0   0   0
163          2         2        1         2  36  39 327 140   0   0   0   0   0
164          4         4        1       103 333 141 118 327   0   0   0   0   0
165          4         4        1         8  39 138 333 111 141 327   0   0   0
166          2         2        1       103  35 141 327   0   0   0   0   0   0
168          1         1        1         8  39  35 141 118 327   0   0   0   0
169          1         1        1         8  39 138 310 141 128   0   0   0   0
170          1         1        1         8  39  45 138 333 141 128   0   0   0
171          1         1        1         4  39 118 140   0   0   0   0   0   0
173          4         4        1       205  39 241   0   0   0   0   0   0   0
174          6         6        1         8 138 333 140   0   0   0   0   0   0
178          4         4        1         4  39 144  45 138 310 333 141 327   0
179          6         6        1         6  39 310 138 333 327 140   0   0   0
180          4         4        1         6  39 310 138 333 327 140   0   0   0
183          4         4        1         2  39 111 138 333 141 327 118   0   0
185          4         4        1         2  39 310 138 333 141 327 118   0   0
188          3         3        1         2  39 138  35 141 327   0   0   0   0
189          8         8        1         2  39 138  35 141 327   0   0   0   0
190          2         2        1         2  39  23   0   0   0   0   0   0   0
191          2         2        1         2  35  29 141   0   0   0   0   0   0
192          2         2        1         2  35  29 141   0   0   0   0   0   0
193          6         6        1         2  35  29 138 310 141   0   0   0   0
195          3         3        1         2  35 138 310 141   0   0   0   0   0
197         32        32        1         9 310 241  39 226   0   0   0   0   0
198         16        16        1         9 310 241  39 226   0   0   0   0   0
199          2         2        1        64 144 327 131 310 140 141 118   0   0
200         12        12        1         8  39 128 140   0   0   0   0   0   0
203          6         6        1         4 310 138  39 141 118   0   0   0   0
205          6         6        1         2 138 111 333 141   0   0   0   0   0
207          1         1        1         8  39 138 144 333 141 140 128   0   0
208          1         1        1       103  39 138 310 333 141 327   0   0   0
209          1         1        1       103  39 310 141   0   0   0   0   0   0
212          1         1        1         6 138 310 327 140   0   0   0   0   0
217         50        50        1         6 310  39 327 118 140   0   0   0   0
220          8         8        1         6  39 138 310 141 131 333   0   0   0
223          1         1        1         1 241  19   0   0   0   0   0   0   0
226          1         1        1         2 338 310 341   0   0   0   0   0   0
228         18        18        1         8 144 310 141   0   0   0   0   0   0
230          8         8        1         8 140  39 138 310 141 333   0   0   0
231          8         8        1         2  39 310 141  43   0   0   0   0   0
232          4         4        1         8  39 333   2   0   0   0   0   0   0
233          4         4        1         8  39 333   2   0   0   0   0   0   0
237          2         2        1         2   0   0   0   0   0   0   0   0   0
238          1         1        1         2 140   0   0   0   0   0   0   0   0
239          1         1        1         8 140  39 111 327   0   0   0   0   0
242          1         1        1         9  39  25 226 140   0   0   0   0   0
248          1         1        1         8 128 140   0   0   0   0   0   0   0
251          1         1        1       103 138 113 310 333 141   0   0   0   0
257          1         1        1         4 310 141  39 138   0   0   0   0   0
258          2         2        1         4 310  39   0   0   0   0   0   0   0
270         24        24        1         8   0   0   0   0   0   0   0   0   0
271         24        24        1       103 310 333 141   0   0   0   0   0   0
272         24        24        1         8 111 141   0   0   0   0   0   0   0
274          2         2        1         8 111 141   0   0   0   0   0   0   0
277          2         2        1         2 341   0   0   0   0   0   0   0   0
278          2         2        1       103 310 141  35   0   0   0   0   0   0
281          1         1        1        64 138 310 333 141 327 131   0   0   0
282          1         1        1       144 310 141  39 327   0   0   0   0   0
283          1         1        1       103 144 310 141  39 327   0   0   0   0
290          8         8        1         2   0   0   0   0   0   0   0   0   0
295          1         1        1         2   0   0   0   0   0   0   0   0   0
296          1         1        1         2   0   0   0   0   0   0   0   0   0
299          1         1        1         2  39 327   0   0   0   0   0   0   0
301          1         1        1         2  23   0   0   0   0   0   0   0   0
303          1         1        1         2   0   0   0   0   0   0   0   0   0
305          1         1        1       205 310  39 226   0   0   0   0   0   0
311          1         1        1         2 111 140   0   0   0   0   0   0   0
315          1         1        1         4  39 327   0   0   0   0   0   0   0
316          1         1        1         4  39 138 333 111 141 327   0   0   0
319          1         1        1         2 111   0   0   0   0   0   0   0   0
```

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 322 | 2 | 2 | 1 | 64 | 113 | 141 | 35 | 0 | 0 | 0 | 0 | 0 | 0 |
| 325 | 1 | 1 | 1 | 2 | 140 | 138 | 333 | 39 | 327 | 0 | 0 | 0 | 0 |
| 326 | 1 | 1 | 1 | 2 | 39 | 111 | 141 | 327 | 0 | 0 | 0 | 0 | 0 |
| 327 | 1 | 1 | 1 | 2 | 39 | 138 | 333 | 111 | 36 | 327 | 0 | 0 | 0 |
| 339 | 1 | 1 | 1 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 347 | 1 | 1 | 1 | 8 | 39 | 111 | 141 | 327 | 0 | 0 | 0 | 0 | 0 |
| 355 | 3 | 3 | 1 | 4 | 35 | 140 | 118 | 0 | 0 | 0 | 0 | 0 | 0 |
| 359 | 1 | 1 | 1 | 8 | 39 | 111 | 138 | 333 | 141 | 25 | 0 | 0 | 0 |
| 360 | 10 | 10 | 1 | 2 | 341 | 327 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 402 | 7 | 7 | 1 | 8 | 39 | 138 | 45 | 141 | 327 | 0 | 0 | 0 | 0 |
| 404 | 1 | 1 | 1 | 103 | 310 | 141 | 39 | 327 | 0 | 0 | 0 | 0 | 0 |
| 406 | 10 | 10 | 1 | 2 | 111 | 141 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 407 | 10 | 10 | 1 | 2 | 341 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 409 | 1 | 1 | 1 | 2 | 341 | 39 | 327 | 0 | 0 | 0 | 0 | 0 | 0 |
| 410 | 1 | 1 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 411 | 1 | 1 | 1 | 205 | 39 | 226 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 412 | 1 | 1 | 1 | 2 | 39 | 111 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 413 | 8 | 8 | 1 | 2 | 39 | 327 | 140 | 0 | 0 | 0 | 0 | 0 | 0 |
| 415 | 24 | 24 | 1 | 103 | 310 | 141 | 39 | 327 | 0 | 0 | 0 | 0 | 0 |
| 416 | 24 | 24 | 1 | 103 | 310 | 144 | 138 | 141 | 39 | 327 | 0 | 0 | 0 |
| 418 | 24 | 24 | 1 | 103 | 333 | 39 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 419 | 24 | 24 | 1 | 103 | 138 | 111 | 333 | 141 | 0 | 0 | 0 | 0 | 0 |
| 420 | 24 | 24 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 421 | 24 | 24 | 1 | 8 | 310 | 141 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 423 | 2 | 2 | 1 | 2 | 111 | 141 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 426 | 2 | 2 | 1 | 2 | 341 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 427 | 2 | 2 | 1 | 2 | 111 | 141 | 35 | 0 | 0 | 0 | 0 | 0 | 0 |
| 429 | 1 | 1 | 1 | 6 | 138 | 310 | 333 | 141 | 327 | 131 | 0 | 0 | 0 |
| 430 | 1 | 1 | 1 | 103 | 144 | 310 | 141 | 39 | 327 | 118 | 0 | 0 | 0 |
| 431 | 1 | 1 | 1 | 103 | 144 | 310 | 141 | 39 | 327 | 118 | 0 | 0 | 0 |
| 433 | 1 | 1 | 1 | 2 | 138 | 39 | 111 | 141 | 327 | 0 | 0 | 0 | 0 |
| 434 | 1 | 1 | 1 | 2 | 39 | 111 | 241 | 327 | 220 | 0 | 0 | 0 | 0 |
| 435 | 2 | 2 | 1 | 103 | 144 | 310 | 39 | 327 | 0 | 0 | 0 | 0 | 0 |
| 436 | 1 | 1 | 1 | 2 | 338 | 333 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 437 | 1 | 1 | 1 | 2 | 238 | 333 | 23 | 0 | 0 | 0 | 0 | 0 | 0 |
| 438 | 1 | 1 | 1 | 2 | 338 | 333 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 439 | 1 | 1 | 1 | 6 | 140 | 39 | 118 | 128 | 138 | 333 | 0 | 0 | 0 |
| 440 | 1 | 1 | 1 | 64 | 138 | 141 | 310 | 140 | 39 | 22 | 0 | 0 | 0 |
| 441 | 1 | 1 | 1 | 8 | 39 | 140 | 25 | 21 | 0 | 0 | 0 | 0 | 0 |
| 442 | 2 | 2 | 1 | 103 | 144 | 310 | 141 | 39 | 327 | 0 | 0 | 0 | 0 |
| 443 | 1 | 1 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 444 | 1 | 1 | 1 | 4 | 39 | 310 | 140 | 0 | 0 | 0 | 0 | 0 | 0 |
| 445 | 1 | 1 | 1 | 2 | 39 | 138 | 333 | 141 | 327 | 140 | 0 | 0 | 0 |
| 446 | 1 | 1 | 1 | 2 | 39 | 138 | 333 | 141 | 327 | 140 | 0 | 0 | 0 |
| 447 | 1 | 1 | 1 | 103 | 113 | 138 | 118 | 131 | 144 | 310 | 141 | 0 | 0 |
| 450 | 1 | 1 | 1 | 103 | 39 | 327 | 140 | 0 | 0 | 0 | 0 | 0 | 0 |
| 453 | 1 | 1 | 1 | 2 | 140 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 455 | 1 | 1 | 1 | 2 | 333 | 111 | 141 | 0 | 0 | 0 | 0 | 0 | 0 |
| 456 | 1 | 1 | 1 | 2 | 140 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 457 | 1 | 1 | 1 | 6 | 138 | 333 | 140 | 0 | 0 | 0 | 0 | 0 | 0 |
| 458 | 1 | 1 | 1 | 2 | 140 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 459 | 1 | 1 | 1 | 4 | 310 | 141 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 460 | 1 | 1 | 1 | 2 | 333 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 461 | 2 | 2 | 1 | 2 | 310 | 341 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 462 | 1 | 1 | 1 | 2 | 140 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 463 | 2 | 2 | 1 | 6 | 39 | 131 | 333 | 327 | 140 | 0 | 0 | 0 | 0 |
| 466 | 2 | 2 | 1 | 103 | 310 | 141 | 327 | 0 | 0 | 0 | 0 | 0 | 0 |
| 467 | 2 | 2 | 1 | 8 | 111 | 141 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 468 | 1 | 1 | 1 | 103 | 310 | 141 | 327 | 0 | 0 | 0 | 0 | 0 | 0 |
| 469 | 4 | 4 | 1 | 2 | 310 | 341 | 327 | 0 | 0 | 0 | 0 | 0 | 0 |
| 470 | 4 | 4 | 1 | 2 | 144 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 471 | 1 | 1 | 1 | 2 | 333 | 341 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 472 | 1 | 1 | 1 | 103 | 310 | 141 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 473 | 1 | 1 | 1 | 103 | 310 | 141 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 474 | 1 | 1 | 1 | 8 | 138 | 333 | 141 | 0 | 0 | 0 | 0 | 0 | 0 |
| 475 | 12 | 12 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 478 | 6 | 6 | 1 | 103 | 144 | 310 | 141 | 0 | 0 | 0 | 0 | 0 | 0 |
| 480 | 16 | 16 | 1 | 64 | 141 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 481 | 42 | 42 | 1 | 8 | 39 | 25 | 140 | 0 | 0 | 0 | 0 | 0 | 0 |
| 482 | 65 | 65 | 1 | 103 | 144 | 333 | 141 | 0 | 0 | 0 | 0 | 0 | 0 |
| 483 | 1 | 1 | 1 | 2 | 39 | 310 | 45 | 141 | 43 | 0 | 0 | 0 | 0 |

```
484          1          1         1           8 141   0   0   0   0   0   0   0   0
485          1          1         1           8 310 141   0   0   0   0   0   0   0
486          1          1         1           8 310 141   0   0   0   0   0   0   0
487          1          1         1          39   2   0   0   0   0   0   0   0   0
491          4          4         1         113  39 138   6 310 333 141 220  22 131
492          1          1         1           8   0   0   0   0   0   0   0   0   0
493          1          1         1           2 310 341   0   0   0   0   0   0   0
495          1          1         1         103  35 141   0   0   0   0   0   0   0
496          1          1         1          64 141  39 327   0   0   0   0   0   0
497          4          4         1         103 144 310 141  39 327   0   0   0   0
498          1          1         1         205  39 226   0   0   0   0   0   0   0
499          2          2         1           8 140 111 141 327   0   0   0   0   0
500         12         12         1           4  39 138 333  23   0   0   0   0   0
  7          2          2         1         613 438 633  39 418   0   0   0   0   0
 21          2          2         1         613 541 538 633  36 520 540   0   0   0
 31          2          2         1         613 638 633 641   0   0   0   0   0   0
 32          2          2         1         613 638 633 641   0   0   0   0   0   0
633          1          1         1         613 638 633 641   0   0   0   0   0   0
 35          4          4         1          12 538 511 541   0   0   0   0   0   0
 40          1          1         1         613 641   0   0   0   0   0   0   0   0
641          1          1         1          14  39 438 431 410 441 418   0   0   0
 42          2          2         1         418   0   0   0   0   0   0   0   0   0
 47          1          1         1         438 410  35 633 431   0   0   0   0   0
 49          1          1         1         613 438 633 441 418   0   0   0   0   0
 50          1          1         1          12 541 520   0   0   0   0   0   0   0
 53          1          1         1         641   0   0   0   0   0   0   0   0   0
 55          1          1         1         613 441  39 438 410   0   0   0   0   0
 58          1          1         1         613 441  39 438 633 418   0   0   0   0
 59          1          1         1         613  39  14 444 438 633 441 418   0   0
 60          1          1         1          12 538  42 511 633   0   0   0   0   0
 61          2          2         1         613 641 633   0   0   0   0   0   0   0
 62          1          1         1         613 438 410 633 441   0   0   0   0   0
 65          1          1         1          12  39 538 633 541 520   0   0   0   0
 66          2          2         1          12  39 538 633 541 520   0   0   0   0
 72          1          1         1         418  14  37 613 441 438 633   0   0   0
 78          1          1         1         641   0   0   0   0   0   0   0   0   0
 98          2          2         1         613 438 633 441 418 431   0   0   0   0
103          1          1         1          14 441 431 633   0   0   0   0   0   0
104          1          1         1          14 441 633 431   0   0   0   0   0   0
112          1          1         1         613 405 410 441  39   0   0   0   0   0
113          6          6         1          39  22 520 541   0   0   0   0   0   0
114          6          6         1         613 438  37 410 441  39 633   0   0   0
117          3          3         1         613 538 633 511 541  39 520 540   0   0
118          3          3         1         613 538 633 511 541  39 520 540   0   0
121          3          3         1         641   0   0   0   0   0   0   0   0   0
122          3          3         1         613 538 633 541   4 511  39   0   0   0
125         12         12         1         613  39  15 638 633 641   0   0   0   0
127         12         12         1         613 638  15 633 641  39   0   0   0   0
129          3          3         1         540  39 528   0   0   0   0   0   0   0
132          1          1         1         538  12 541  39   0   0   0   0   0   0
133          1          1         1         633 438  34  35 410 441  39   0   0   0
134          1          1         1         541 538 520   0   0   0   0   0   0   0
140          6          6         1         613  39 538 633 541 520   0   0   0   0
141          6          6         1         613  39 538 633 541 520   0   0   0   0
142          6          6         1         613 638 633 641   0   0   0   0   0   0
144         12         12         1         613  38 403  35 633 641   0   0   0   0
145          1          1         1         613  39  22  36 538 633 541 520   0   0
146          1          1         1         613  39  22 511  21 538 633 541 520   0
147          1          1         1          14 438  32 431 633 441   0   0   0   0
149         18         18         1         641   7  39 627   0   0   0   0   0   0
154          4          4         1         441  39 627 418   0   0   0   0   0   0
167          2          2         1         613 638 633 641   0   0   0   0   0   0
172         12         12         1         613  39 438 633 441 418   0   0   0   0
175          6          6         1         613 438  39 633 441 418   0   0   0   0
176          4          4         1         613 438  39 410 633 441 418   0   0   0
177          6          6         1         613 438 410   3 633 441   0   0   0   0
181          4          4         1         405 613 438 410 633 441   0   0   0   0
182          4          4         1         613 438  39 441 418 431   0   0   0   0
184          4          4         1         613 438  39 441 418 431   0   0   0   0
186         48         48         1          39  12 511 520  35   0   0   0   0   0
187          8          8         1          39   7 613 627 641   0   0   0   0   0
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194           9           9         1      613  39 541 633 511   4   0   0   0   0
196           3           3         1       12 538 541 633 511   4   0   0   0   0
201           6           6         1      613 438  39 410 633 441   0   0   0   0
202           6           6         1       39 438 613 441 431   0   0   0   0   0
204           6           6         1      418 613 438  39 633 410 441   0   0   0
216           2           2         1      613 638 641  39 633 626   0   0   0   0
221           1           1         1      613 511 538 633  39 541 520 540   0   0
222           6           6         1      613 438 633  39 418   0   0   0   0   0
227           1           1         1       39 613 511 541 540   0   0   0   0   0
229           8           8         1      538 540  39  21 541   0   0   0   0   0
234          10          10         1      613 638 641  39 626   0   0   0   0   0
235           4           4         1      613 638 641  39 633 626   0   0   0   0
236           4           4         1      613 441  39 438 633 418   0   0   0   0
240           6           6         1      613 441  39 438 410 633 418   0   0   0
241           1           1         1      613 441  39 438 633 418   0   0   0   0
243           1           1         1      613 438  39 633 410 441 418   0   0   0
244           1           1         1      613 431  39 418 627 540   0   0   0   0
245           4           4         1      613 431  39 418 627 540   0   0   0   0
246           1           1         1      613  39 444 438 633 441   0   0   0   0
247           1           1         1      613 431 410  39 438 633 441 418   0   0
249           1           1         1       14 438 633 441   0   0   0   0   0   0
250           1           1         1       12 511 538 633 541   0   0   0   0   0
252           1           1         1      613 638 633   0   0   0   0   0   0   0
253           1           1         1      613 638 633   0   0   0   0   0   0   0
254           2           2         1      638  15 641 627  39 633 626   0   0   0
255           1           1         1      613 641 638 633   0   0   0   0   0   0
256           2           2         1      638 633   0   0   0   0   0   0   0   0
259           8           8         1      613 638 633 641   0   0   0   0   0   0
260           1           1         1      613 638 633 641   0   0   0   0   0   0
261           1           1         1      613 641   0   0   0   0   0   0   0   0
262           1           1         1      613 638 633 641   0   0   0   0   0   0
263           1           1         1      641   0   0   0   0   0   0   0   0   0
264           4           4         1      613   0   0   0   0   0   0   0   0   0
265          24          24         1       12 538 541 511 633   0   0   0   0   0
266          24          24         1       30  35 441   0   0   0   0   0   0   0
267          24          24         1      613  39 438 444 633 441 418   0   0   0
268          24          24         1      613  39 438 444 633 441 418   0   0   0
269          24          24         1       12 533 633 541  21   0   0   0   0   0
273           2           2         1      613 438 410 633 441   0   0   0   0   0
275           2           2         1      418 613 431 438 410 633 441   0   0   0
276           2           2         1      613 438 431 410 444 441   0   0   0   0
279           2           2         1       14 438 431 405 441 410 633   0   0   0
280           1           1         1       14 438 431 405 441  32 633   0   0   0
284           1           1         1      538 540  39 541  21   0   0   0   0   0
285           1           1         1      538 540  39 541  21 541   0   0   0   0
286           1           1         1      641   0   0   0   0   0   0   0   0   0
287           2           2         1       12 538 633 541   0   0   0   0   0   0
288          22          22         1       12 520 541   0   0   0   0   0   0   0
289          20          20         1       12  42 520   0   0   0   0   0   0   0
291           2           2         1       12  39 538 541 633 520   0   0   0   0
292           1           1         1      613 438 410 633 405  35 441   0   0   0
293           1           1         1       12 538 511  35  21   0   0   0   0   0
294           1           1         1       35 528 541 540   0   0   0   0   0   0
297           1           1         1      613 641 638 633   0   0   0   0   0   0
298           1           1         1      613 438 441  39 418   0   0   0   0   0
300           1           1         1      613 641 638 633   0   0   0   0   0   0
302           1           1         1      613  39 538 528 633 540   0   0   0   0
304           1           1         1       14 438 431  32 633 441   0   0   0   0
306           1           1         1      613 438  37 633 418   0   0   0   0   0
307           1           1         1      613 441  39 438  37 633 418   0   0   0
308           2           2         1      613 441  34 438 410   0   0   0   0   0
309           1           1         1      613 441  34 438 410   0   0   0   0   0
310           2           2         1      613 410 441 438 633   0   0   0   0   0
312           1           1         1      613 638 633 641   0   0   0   0   0   0
313           1           1         1      613  39 438 633 418   0   0   0   0   0
314           1           1         1      613 438 633 410 441 418   0   0   0   0
317           1           1         1       14 438 431 633  32 441   0   0   0   0
318           1           1         1       32 431 438 633   0   0   0   0   0   0
320           1           1         1      613 438 444 441  39 633 418   0   0   0
321           1           1         1       14   3  35   0   0   0   0   0   0   0
323           1           1         1      613 638 641 633   0   0   0   0   0   0
```

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 324 | 1 | 1 | 1 | 613 | 441 | 633 | 418 | 431 | 0 | 0 | 0 | 0 | 0 |
| 328 | 1 | 1 | 1 | 613 | 438 | 441 | 39 | 633 | 418 | 0 | 0 | 0 | 0 |
| 329 | 1 | 1 | 1 | 613 | 438 | 441 | 39 | 633 | 418 | 0 | 0 | 0 | 0 |
| 330 | 4 | 4 | 1 | 613 | 438 | 410 | 441 | 633 | 418 | 431 | 0 | 0 | 0 |
| 331 | 4 | 4 | 1 | 410 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 332 | 1 | 1 | 1 | 30 | 438 | 32 | 633 | 441 | 0 | 0 | 0 | 0 | 0 |
| 333 | 48 | 48 | 1 | 438 | 30 | 441 | 431 | 35 | 0 | 0 | 0 | 0 | 0 |
| 334 | 1 | 1 | 1 | 32 | 441 | 35 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 335 | 1 | 1 | 1 | 32 | 441 | 35 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 336 | 3 | 3 | 1 | 32 | 441 | 431 | 35 | 0 | 0 | 0 | 0 | 0 | 0 |
| 337 | 2 | 2 | 1 | 12 | 538 | 633 | 541 | 0 | 0 | 0 | 0 | 0 | 0 |
| 338 | 2 | 2 | 1 | 32 | 441 | 431 | 438 | 633 | 0 | 0 | 0 | 0 | 0 |
| 340 | 1 | 1 | 1 | 32 | 438 | 633 | 441 | 0 | 0 | 0 | 0 | 0 | 0 |
| 341 | 1 | 1 | 1 | 30 | 431 | 438 | 32 | 633 | 441 | 0 | 0 | 0 | 0 |
| 342 | 1 | 1 | 1 | 438 | 32 | 441 | 431 | 0 | 0 | 0 | 0 | 0 | 0 |
| 343 | 2 | 2 | 1 | 12 | 541 | 538 | 633 | 21 | 0 | 0 | 0 | 0 | 0 |
| 344 | 21 | 21 | 1 | 30 | 441 | 35 | 431 | 0 | 0 | 0 | 0 | 0 | 0 |
| 345 | 1 | 1 | 1 | 30 | 441 | 431 | 35 | 438 | 633 | 0 | 0 | 0 | 0 |
| 346 | 1 | 1 | 1 | 30 | 438 | 633 | 441 | 35 | 431 | 0 | 0 | 0 | 0 |
| 348 | 1 | 1 | 1 | 14 | 438 | 39 | 418 | 431 | 410 | 441 | 633 | 0 | 0 |
| 349 | 1 | 1 | 1 | 30 | 431 | 441 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 350 | 4 | 4 | 1 | 438 | 30 | 441 | 431 | 35 | 0 | 0 | 0 | 0 | 0 |
| 351 | 1 | 1 | 1 | 438 | 30 | 441 | 35 | 0 | 0 | 0 | 0 | 0 | 0 |
| 352 | 1 | 1 | 1 | 438 | 30 | 32 | 633 | 441 | 431 | 35 | 0 | 0 | 0 |
| 353 | 1 | 1 | 1 | 37 | 410 | 441 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 354 | 1 | 1 | 1 | 37 | 410 | 441 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 356 | 1 | 1 | 1 | 34 | 441 | 431 | 35 | 0 | 0 | 0 | 0 | 0 | 0 |
| 357 | 2 | 2 | 1 | 438 | 34 | 441 | 30 | 35 | 0 | 0 | 0 | 0 | 0 |
| 358 | 24 | 24 | 1 | 37 | 431 | 438 | 32 | 441 | 0 | 0 | 0 | 0 | 0 |
| 361 | 10 | 10 | 1 | 37 | 21 | 22 | 538 | 511 | 633 | 541 | 0 | 0 | 0 |
| 362 | 10 | 10 | 1 | 37 | 441 | 34 | 431 | 35 | 0 | 0 | 0 | 0 | 0 |
| 363 | 20 | 20 | 1 | 32 | 441 | 431 | 35 | 0 | 0 | 0 | 0 | 0 | 0 |
| 364 | 24 | 24 | 1 | 34 | 30 | 441 | 633 | 0 | 0 | 0 | 0 | 0 | 0 |
| 403 | 1 | 1 | 1 | 613 | 541 | 538 | 633 | 36 | 520 | 540 | 0 | 0 | 0 |
| 405 | 10 | 10 | 1 | 613 | 638 | 633 | 641 | 0 | 0 | 0 | 0 | 0 | 0 |
| 408 | 1 | 1 | 1 | 37 | 441 | 32 | 438 | 633 | 0 | 0 | 0 | 0 | 0 |
| 414 | 24 | 24 | 1 | 613 | 15 | 39 | 638 | 633 | 641 | 0 | 0 | 0 | 0 |
| 417 | 24 | 24 | 1 | 12 | 538 | 633 | 541 | 520 | 0 | 0 | 0 | 0 | 0 |
| 422 | 2 | 2 | 1 | 613 | 438 | 410 | 633 | 441 | 0 | 0 | 0 | 0 | 0 |
| 424 | 2 | 2 | 1 | 418 | 613 | 431 | 438 | 410 | 633 | 441 | 0 | 0 | 0 |
| 425 | 2 | 2 | 1 | 613 | 438 | 431 | 410 | 444 | 441 | 0 | 0 | 0 | 0 |
| 428 | 2 | 2 | 1 | 14 | 438 | 431 | 3 | 441 | 32 | 633 | 0 | 0 | 0 |
| 432 | 1 | 1 | 1 | 538 | 540 | 39 | 541 | 520 | 0 | 0 | 0 | 0 | 0 |
| 448 | 1 | 1 | 1 | 613 | 438 | 633 | 444 | 410 | 441 | 0 | 0 | 0 | 0 |
| 449 | 2 | 2 | 1 | 613 | 438 | 431 | 633 | 444 | 410 | 441 | 0 | 0 | 0 |
| 451 | 2 | 2 | 1 | 613 | 638 | 633 | 641 | 0 | 0 | 0 | 0 | 0 | 0 |
| 452 | 1 | 1 | 1 | 613 | 638 | 633 | 641 | 0 | 0 | 0 | 0 | 0 | 0 |
| 454 | 1 | 1 | 1 | 613 | 638 | 633 | 641 | 0 | 0 | 0 | 0 | 0 | 0 |
| 464 | 2 | 2 | 1 | 613 | 418 | 431 | 438 | 410 | 633 | 441 | 0 | 0 | 0 |
| 465 | 2 | 2 | 1 | 14 | 39 | 418 | 431 | 438 | 410 | 633 | 441 | 540 | 0 |
| 476 | 3 | 3 | 1 | 613 | 438 | 633 | 410 | 441 | 0 | 0 | 0 | 0 | 0 |
| 477 | 3 | 3 | 1 | 538 | 511 | 633 | 541 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 479 | 3 | 3 | 1 | 613 | 638 | 633 | 641 | 0 | 0 | 0 | 0 | 0 | 0 |
| 488 | 1 | 1 | 1 | 613 | 638 | 633 | 641 | 0 | 0 | 0 | 0 | 0 | 0 |
| 489 | 2 | 2 | 1 | 613 | 438 | 441 | 410 | 633 | 0 | 0 | 0 | 0 | 0 |
| 490 | 1 | 1 | 1 | 30 | 35 | 441 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 494 | 1 | 1 | 1 | 613 | 39 | 441 | 418 | 438 | 633 | 0 | 0 | 0 | 0 |
| 206 | 6 | 6 | 1 | 37 | 39 | 540 | 538 | 633 | 627 | 17 | 0 | 0 | 0 |
| 210 | 6 | 6 | 1 | 403 | 37 | 540 | 39 | 17 | 0 | 0 | 0 | 0 | 0 |
| 211 | 6 | 6 | 1 | 403 | 39 | 540 | 17 | 0 | 0 | 0 | 0 | 0 | 0 |
| 213 | 1 | 1 | 1 | 403 | 4 | 410 | 638 | 633 | 641 | 39 | 626 | 17 | 0 |
| 214 | 10 | 10 | 1 | 613 | 410 | 638 | 633 | 39 | 17 | 540 | 0 | 0 | 0 |
| 215 | 6 | 6 | 1 | 613 | 641 | 36 | 39 | 638 | 633 | 17 | 0 | 0 | 0 |
| 218 | 6 | 6 | 1 | 613 | 638 | 17 | 410 | 641 | 36 | 39 | 0 | 0 | 0 |
| 219 | 6 | 6 | 1 | 17 | 540 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 224 | 18 | 18 | 1 | 613 | 638 | 633 | 540 | 36 | 39 | 17 | 0 | 0 | 0 |
| 225 | 6 | 6 | 1 | 613 | 540 | 36 | 39 | 17 | 638 | 633 | 0 | 0 | 0 |
| 365 | 10 | 10 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 366 | 10 | 10 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 367 | 10 | 10 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 368 | 20 | 20 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 369 | 24 | 24 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 370 | 12 | 12 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 371 | 22 | 22 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 372 | 22 | 22 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 373 | 23 | 23 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 374 | 16 | 16 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 375 | 14 | 14 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 376 | 18 | 18 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 377 | 30 | 30 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 378 | 30 | 30 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 379 | 35 | 35 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 380 | 31 | 31 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 381 | 10 | 10 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 382 | 25 | 25 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 383 | 17 | 17 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 384 | 12 | 12 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 385 | 14 | 14 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 386 | 22 | 22 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 387 | 24 | 24 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 388 | 23 | 23 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 389 | 16 | 16 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 390 | 15 | 15 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 391 | 19 | 19 | 1 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 392 | 22 | 22 | 1 | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 393 | 12 | 12 | 1 | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 394 | 10 | 10 | 1 | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 395 | 8 | 8 | 1 | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 396 | 12 | 12 | 1 | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 397 | 10 | 10 | 1 | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 398 | 10 | 10 | 1 | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 399 | 15 | 15 | 1 | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 400 | 12 | 12 | 1 | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 401 | 17 | 17 | 1 | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

```
FLOW MATRIX BETWEEN CELLS

          1        2        3        4        5        6        7        8        9
  1       0        9      327        2       12        4        0       59      135
  2       9        0       16        0        0        0        0        1       29
  3     327       16        0        0        0        0        0       10      126
  4       2        0        0        0        1      164        1       73       55
  5      12        0        0        1        0       58        3       11       30
  6       4        0        0      164       58        0        5       13       45
  7       0        0        0        1        3        5        0        0        4
  8      59        1       10       73       11       13        0        0       24
  9     135       29      126       55       30       45        4       24        0

MODIFIED FLOW VALUE MATRIX

          1        2        3        4        5        6        7        8        9
  1       0        9      327        2       12        4        0       59        0
  2       9        0       16        0        0        0        0        1        0
  3     327       16        0        0        0        0        0       10        0
  4       2        0        0        0        1      164        1       73        0
  5      12        0        0        1        0       58        3       11        0
  6       4        0        0      164       58        0        5       13        0
  7       0        0        0        1        3        5        0        0        0
  8      59        1       10       73       11       13        0        0        0
  9       0        0        0        0        0        0        0        0        0


THE OPTIMAL TRIANGLE IN COLUMN          IS            WITH TOTAL FLOW VALUE
                              1      1   3   8               396
                              2      2   1   3               352
                              3      3   1   8               396
                              4      4   1   3               329
                              5      5   1   3               339
                              6      6   1   3               331
                              7      7   1   3               327
                              8      8   1   3               396
                              9      9   1   3               327


THE OPTIMUM TRIANGLE IS     8   1   3  WITH TOTAL FLOW VALUE OF       396
```

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