SOME ASPECTS OF SCHEDULING IN A GROUP TECHNOLOGY MANUFACTURING SYSTEM

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SUMMARY

Since the late 1940's, the concept of group technology manufacturing has become more commonly used. One of the essential requirements for full utilisation of the benefits of Group Technology is to adopt appropriate operation scheduling methods. This work proposes a manual scheduling rule (Rule Y) to tackle the group scheduling problems in a group layout system. The procedures for short-term programme formation and loading of operators are also suggested. The main criteria for assessment of the effectiveness of this scheduling work are throughput time, operator utilisation and work-in-progress. The Gantt chart technique is used to represent the schedule for both machines and operators.

An outline of Petrov's heuristic rules for scheduling is described in the thesis and comparisons of the performance of the proposed rule with Petrov's rules III and IV were made in order to indicate the justification of the proposed rule.

A large simulation was used to show how the rule can be applied to compare its effectiveness with Petrov. Comparisons are also shown with a Branch and Bound algorithm. Data used in the simulation was obtained from a large company fully committed to Group Technology.

The conclusions drawn are that Rule Y is an improvement over existing heuristics for Group Technology scheduling and that the inclusion of the operator schedule is a new contribution to work in this field.

* * * * * *

KEY WORDS: Groups - Cells - Scheduling - Rules - Throughput Time.

DECLARATION

None of the work presented in this thesis has been submitted in support of an application for another qualification of this or any other institution.

J. S. Yin.

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CHAPTER ONE

INTRODUCTION

Production control is defined in the British Standard (BS3138) as "the procedures and means by which manufacturing programmes and plans are determined, information issued for their execution and data collected and recorded to control manufacture in accordance with plans". It means controlling the flow of work to meet delivery dates, keeping down investment in stock and work-in-progress, and maintaining the utilisation of plant and manpower to the maximum.

In the last few decades, the production control and factory layout have changed little. Batch production is the largest part of the engineering industry in this country. In the majority of British engineering companies the machines in the workshops are still arranged in functional layout (figure 1-1) where similar machines are grouped together according to type. The material flow system in this type of layout is very complicated. The component itself must travel a considerable distance around the factory before all the operations are performed upon it. On visiting each machine a component has to wait in the queue and the necessary planning which is required to route a component around the factory becomes an extremely difficult task. The consequences of the above problems are high levels of work-in-progress, poor machine and manpower utilisation, uncertainty of throughput time and bad deliveries.

One modern approach to tackle the above problems of planning, control and manufacture is to adopt the principles of Group Technology (GT) which changes both plant layout and production control of a company (1). Thornley (2) states that:

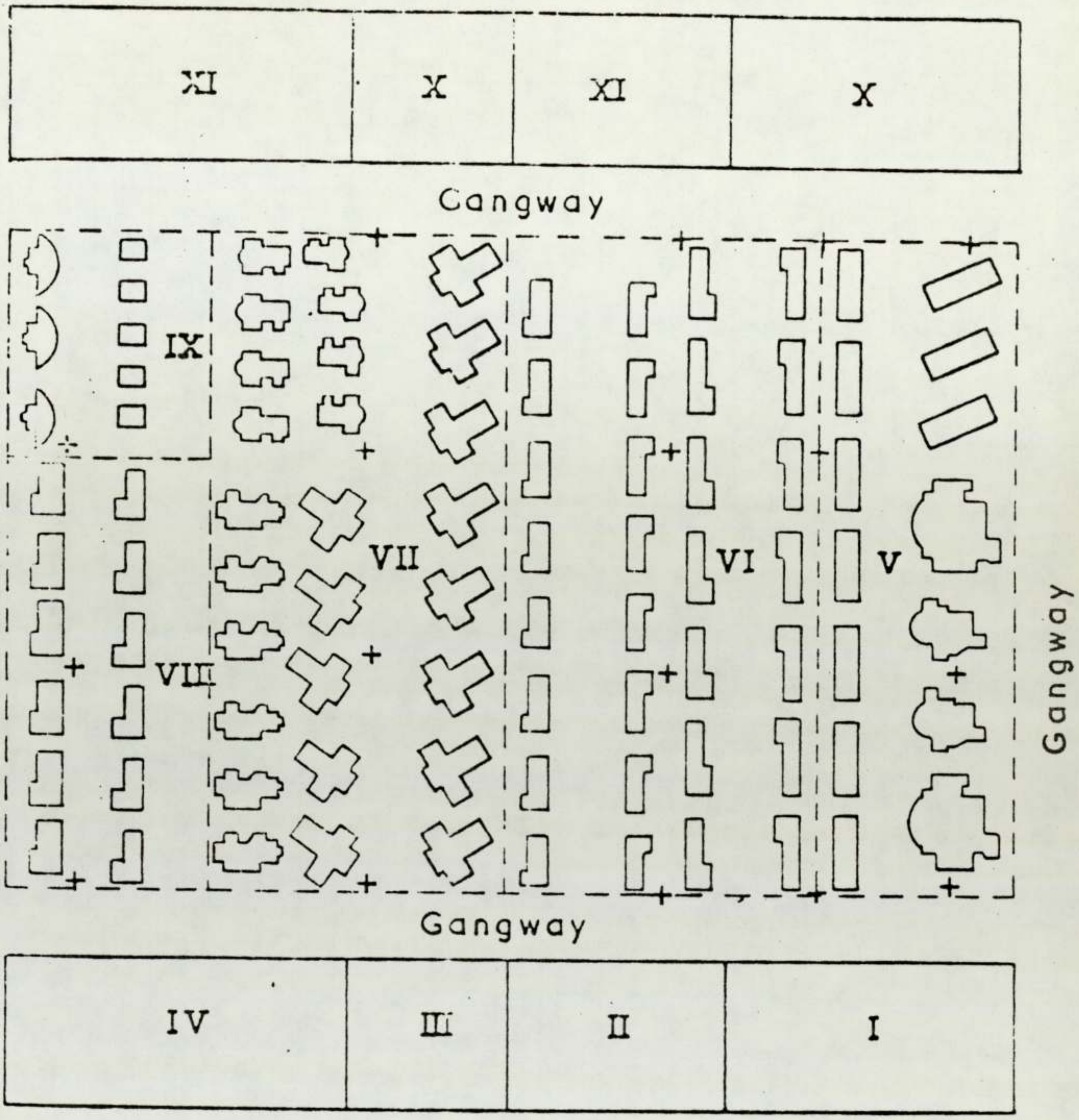


Fig 1-1 FUNCTIONAL LAYOUT (AFTER THORNLEY)

I — stock of rough castings; II-grinding section; III — tool distributing stores; IV — office; V — heavy turret and vertical lathes; VI —universal lathes; VII —milling; planing and slotting machines; VII —turret lathes; IX —boring machines; X technical inspection; XI - inter-operational stores

> "Group Technology or Parts Family Manufacture is a method of achieving some degree of mass production in batch production industries. Large batches are formed from small batches of identical components by grouping them in accordance with those features which determine their manufacturing methods, with a reduction in setting time and increased productivity."

The effects and achievements of GT on the various factors of the company are shown in Figure 1-2. A complete concept must be considered from several aspects such as design, sales, planning, control, servicing, manufacture, stock etc. and in fact every part of the company.

As mentioned above, GT must be implemented in total concept, but operation scheduling methods play an important role in production control in order to fully benefit from GT systems. There is relatively little information available in the specific area of scheduling related to GT and the first comprehensive book dealing with these problems is by Petrov (3). In this book he dealt with a systematic account of group production organisation and planning and showed a way to obtain a "good" schedule via several heuristic rules. Later, Burbidge (4) introduced Production Flow Analysis (PFA) for analysing the operation sequence and the process route for components by using the data from operation route cards. PERA (5) dealt with the loading and scheduling of work in GT cells considering batch overlapping and machine breakdowns and delays, together with several priority rules. Hitomi and Ham (5,6) introduced Group Scheduling (GS) in which a two-phase approach using

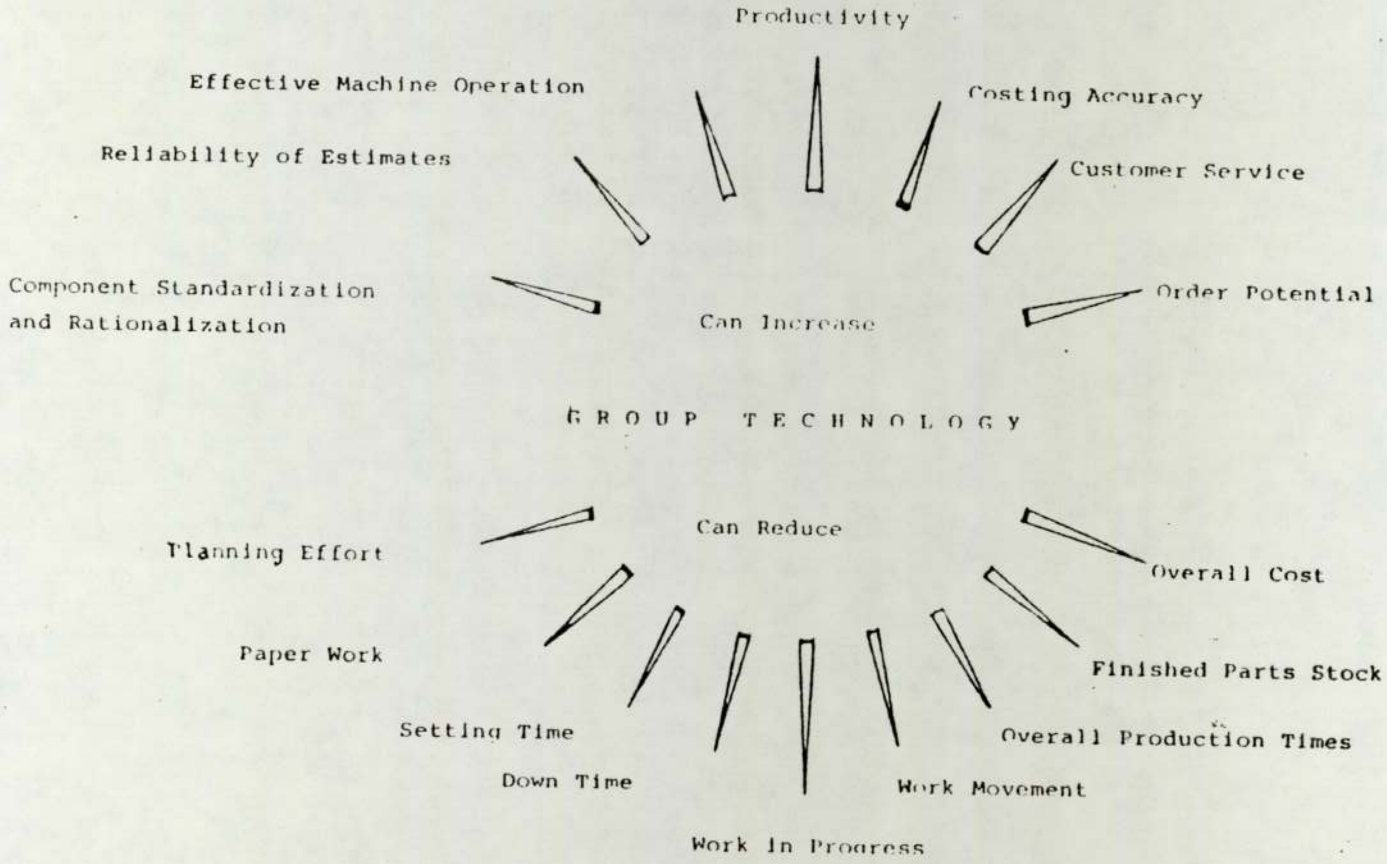


FIGURE 1-2 GENERAL ACHIEVEMENTS OF GROUP TECHNOLOGY (AFTER THORNLEY)

optimising algorithm. But none of the above methods has taken the factor of operator into consideration. In GT systems a certain degree of flexibility of operator is required due to under utilisation of certain machines. This requires a formal method for drawing a plan not only for the work but also for the even movement of the operators. Connolly et al (7) have suggested the Gantt chart method to schedule both work and operator in GT systems, but no proper procedures have been given. English (8) has proposed a technique of machine loading and scheduling together with the consideration of operators for Group Flow-line Layout system.

Unfortunately, the above methods, except Petrov's heuristic rules, are only concerned with Single Machine or Group Flow-line Layout systems. But the report (9) states that most of the component processing industries are in Group Layout systems or Cells i.e. different components in the "families" produced in a given group use different combinations of machine in different sequences. The basic aim of this thesis is to develop a heuristic method for Cell loading, and machine and operator scheduling in a Group Layout system. The project consists of two parts; ie.

1) to develop a heuristic rule for component sequencing
2) to develop a method for operator loading

The data is obtained from a component processing company which is totally committed to GT systems. The proposed method is compared with Petrov's heuristic rules which claimed to be within 10% of the theoretical optimal solution in terms of

throughput time. The project also shows how short-term periodic production programmes are formed and investigates the utilisation and flexibility of operators within a cell. Methodology for designing and implementation of GT systems is also discussed in the early part of the thesis.

CHAPTER TWO

A SURVEY OF MANUFACTURING SYSTEMS AND GROUP TECHNOLOGY PRINCIPLES

2.1 The Manufacturing System

A manufacturing or production system is concerned with the conversion of materials and parts to goods or products. Such a process comprises three basic physical resources, or 3 M's - Men, Material and Machines - which are coordinated by means of plans and control exercised by management.

There are four main classificationsof manufacturing systems (10) which are as follows:

1) Continuous production - which involves the production of a single type of product by using facilities for 24 hours per day and 365 days per year; eg. petroleum refinery, chemical industries, steel making industries etc.
2) Mass/Flow production - which has small variety of products with a large demand. Facilities do not normally run continuously; eg. automobile industries.
3) Batch production - which is concerned with a large variety of products with relatively small quantities of each product manufactured at each time. The manufacture of the same products are repeated from time to time. This type of system accounts for about 70% of the total engineering industry (11).
4) Jobbing production - which has a large variety of products but the quantities of each product are much smaller than with batch production. It may be 'one-off' and the manufacture of the same product is rarely repeated.

There are three basic facility layout associated with the different types of manufacturing systems which are as follows:

Layout By Product

The facilities are arranged according to the sequence of operations demanded by the products. Continuous and mass/flow production systems generally fall into this category.

Layout By Process (Functional Layout)

The facilities of similar types or purposes are located together; eg. capstan shop, milling shop, drilling shop, assembly shop etc. Batch and jobbing production systems generally fall into this category.

Layout By Fixed Position

The product remains stationary and the facilities required during its manufacture are brought to the job. This layout is associated with jobbing production; eg. civil engineering works, ship building etc.

The inter-relationship of each type of layout for each type of production is illustrated in Figure 2-1.

It has been realised for a long time that the most economic method of manufacturing is continuous or mass/flow production system. Unfortunately, owing to the nature of products and the fluctuation in market demand, the quantities of most products are normally less than those economically justified to set up production lines for continuous or mass/flow production. So, less than 25% of the total engineering industry in this country and the rest of the world is concerned with continuous or mass/flow production. The greatest share of production

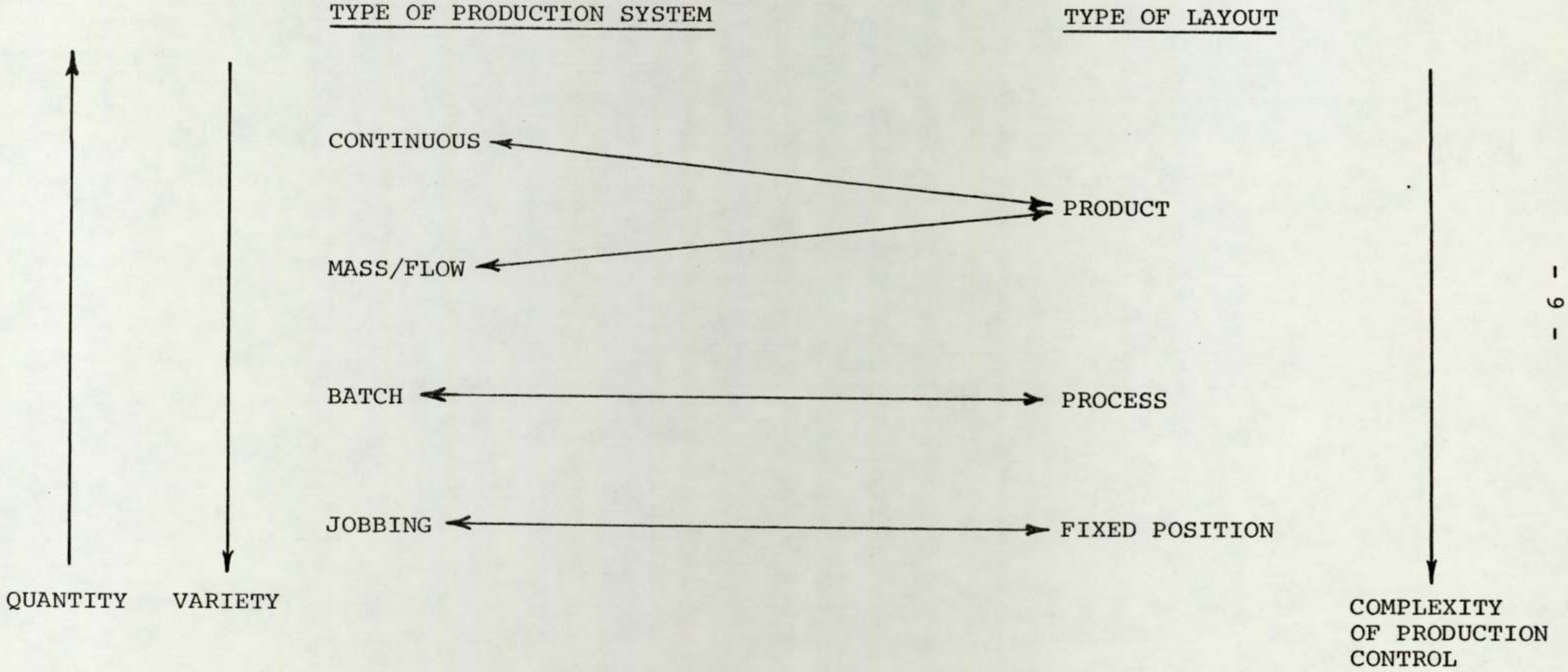


FIG 2-1 INTERACTION BETWEEN PRODUCTION SYSTEM, LAYOUT AND CONTROL (AFTER SAWYER)

systems in the engineering industry is based on batch production/functional layout.

In batch production systems, in order to maintain maximum utilisation of both machines and labour, the sizes of component batches are usually increased above the required order quantity ie. the economic batch quantity (EBQ). Such batch sizes will generate work-in-progress which in turn results in large stocks of finished components and increases the inventory costs. In addition, components not immediately required for sale tend to occupy manufacturing facilities and delay more urgent orders required to meet the demands of the market. The main reason for this is the traditional functional layout of batch production system which create complicated material flow systems and unnecessary long throughput times. Batch production is the largest single type of manufacture currently used and because it has so many defects, it has brought to the attention of engineers and researchers the need to try to improve the system. As mentioned above, mass production is one of the most economic methods of manufacture and in the middle of this century a technique called 'Group Technology' was developed which is a method of achieving some degree of mass production efficiency in batch production systems.

2.2 The Definition and Concept of Group Technology

Group Technology (GT) is a new concept of manufacturing systems which is coming into more common use. There is no one accepted universal definition of group technology. Most of the definitions of group technology have been associated with its implementation into industry. But the basic concept is the same and all aim towards a common goal, ie. the achievement of production targets in the shortest possible, reliable time by the most efficient and psychologically satisfying means. A few of these will suffice to explain the meaning of the term.

Thornley (12) defines GT as:-

> "Group Technology or Part Family Manufacturing is a method of achieving some degree of mass production technology in the batch production industry."

Burbidge (13) defines GT as:-

> "A new approach to batch production based on group layout and the simplification of material flow. It seeks for batch production, the same advantages of those obtained with line layout in mass production."

Ranson in his book (11) defines GT as:-

> "The logical arrangement and sequence of all facets of company operation in order to bring the benefits of mass production to high variety, mixed quantity production."

Ivanov (14) states the concept of GT as:-

> "The basic concept of component group machining is that instead of the production sequence, tooling and machine set-ups being based on single components, the planning units become an entire group of similar components or operations calling for the use of similar equipment and tooling."

Generally, the basic principle of group technology is based on the systematic grouping of identical or similar components together. All components combined into a family are subjected to common planning and machining, thus achieving a high rationalisation effect.

How group technology is implemented, varies in many ways. Some successful applications can be found using all the published and otherwise available methods (7, 9, 11).

2.3 The Basic Forms of Group Technology (GT)

The essential step to apply GT is to collect parts with similar shape and machining characteristics together to form families and routeing them through a machine or a group of machines with the assistance of production control. There are three basic forms of these machines layout (17):

1) the Single Machine System (Machining Centre), often using the Composite or Complex Component Technique;
2) the Group Layout System (the GT-Cell);
3) the Group Flow-Line System.

The three layout forms lie between the functional machine layout and the flow line layout of mass production systems. The inter-relationship of these layout is illustrated in Fig 2-2.

2.3.1 The Single Machine System

Statistical studies conducted upon the machine itself have shown that a fairly high percentage of non-cutting time has been found to be allocated to setting up the machines (18).

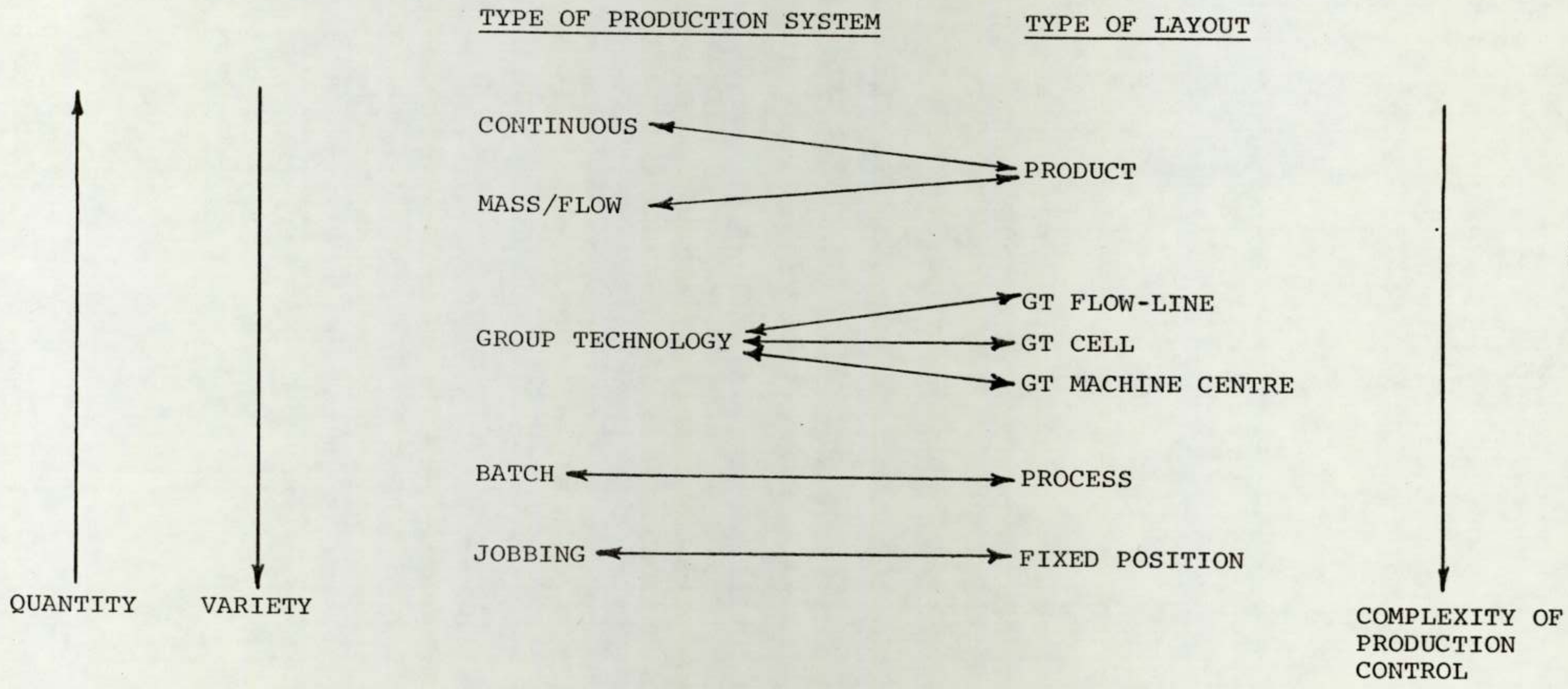
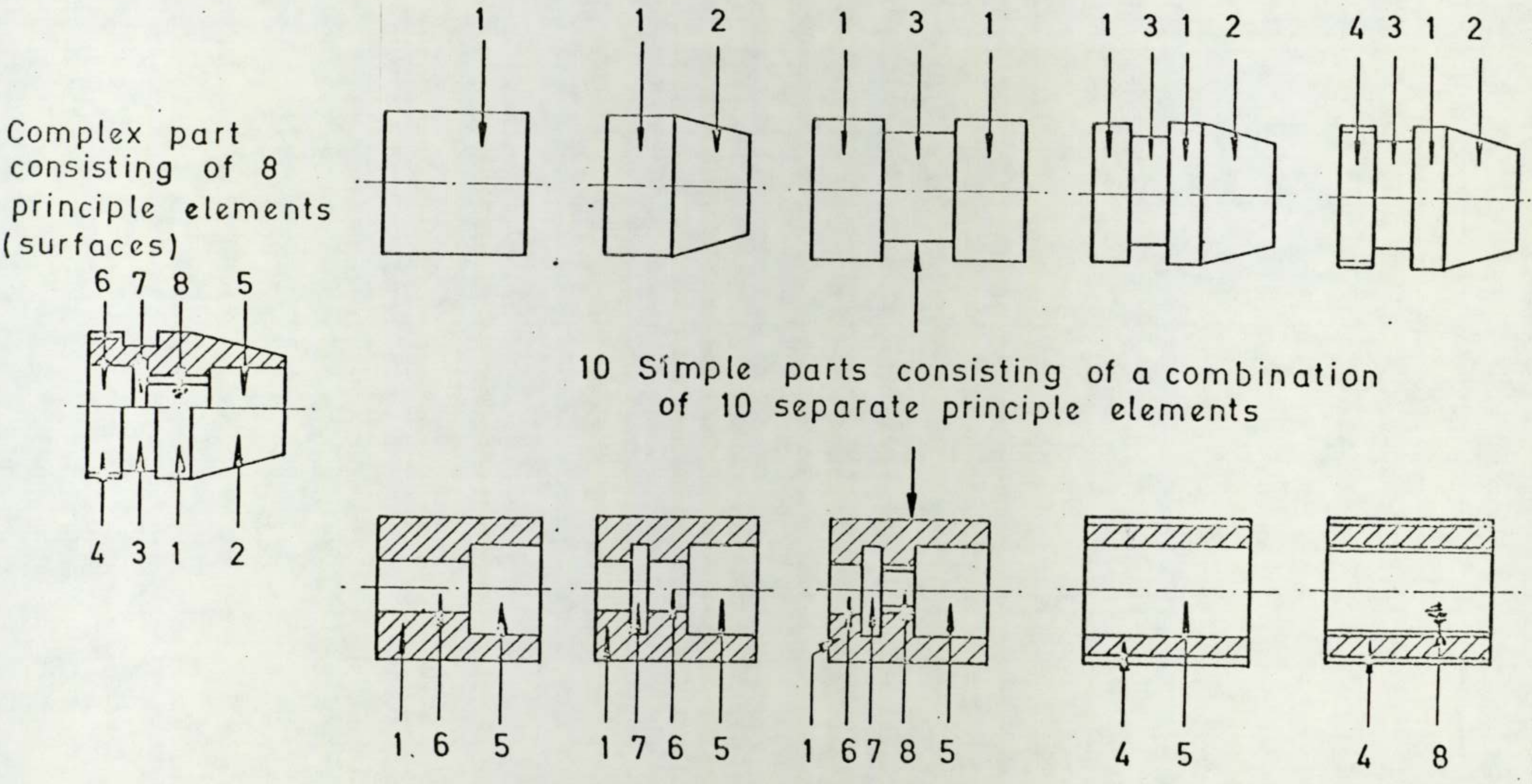


FIG 2-2 INTERACTION BETWEEN SYSTEM, LAYOUT AND CONTROL (INCLUDING FAMILY PRODUCTION) (AFTER SAWYER)

The saving of set-up time by sequencing the flow of work to a machine so as to minimize the changes of the set-up is a complex task, particularly in a multi-product environment. It is difficult to develop a fully optimised solution because of the interaction and conflict of the various sequencing criteria. This problem can be eased by using classification and coding systems to collect parts with similar shape and machining characteristics together to form a family and a real or imaginary part, embodying all features of every part in the family is drawn up which is known as the Composite or Complex Component. Fig 2-3 shows a typical example as proposed by Mitrofanov (15). Individual machines may then be tooled-up to produce this Composite component and therefore with only minor adjustments the machine can produce any combination of the component features in the family. Moreover, it is possible to create for production control a better sequence of information and data sheets in the form of sequence families through the technological similarities of the components.

2.3.2 The Group Layout System

The basic idea of the group layout system is to divide the plant into sections known as groups or cells. Each group of machines is capable of carrying out the processes required to make a family of components. Usually an estimated amount of work is loaded onto the cell which is then progressed in any order through each operation in the cell. Only small batches of components in a family are issued at any one time to the production cell which are then processed on the machines. Due to under-utilisation of certain machine tools in the system



EXAMPLE OF COMPLEX COMPONENT
(AFTER MITROFANOV)

FIG 2-3

a certain amount of flexibility of operator is required to balance this load. So, a cell will normally have more machines than men.

Each machine in the cell may be visited by a component more than once in the cycle. This system simplifies the production control via the simplification of material flow system and shorter distance travelled by the components (Fig 2-4). But the system must be operated in a tight control system in order to prevent loading the cell with "foreign" work from another family which will tend to a breaking up of the system (17).

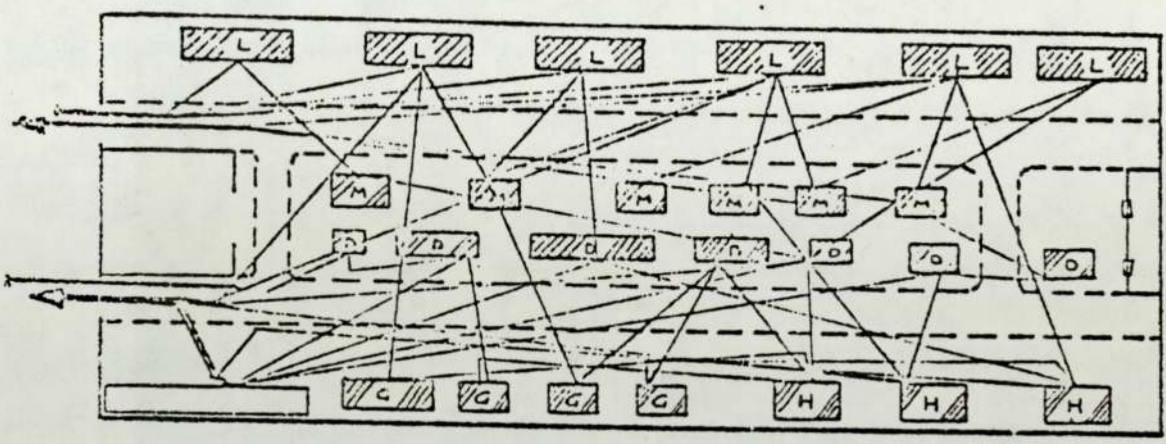
2.3.3 The Group Flow-Line System

The system is similar to the group layout system, that is, the plant is divided into groups on components basis. The main difference in the two systems lies in the actual physical placing of the machines and in the sequencing of operations.

For the flow line system the machines are laid out in the sequence of operations (Fig 2-5) and are usually linked to each other by a conveyor arrangement. A component only visits any machine once in the line and then only in the line sequence order. But it is not necessary that every component in the family visits every machine in the line. As in group layout, certain flexibility of operator is required to balance the load.

The loading of the group flow line system is much easier because the operation sequence of components in the family is the same and it can be done by loading the key machines in the line.

COMPLICATED MATERIAL FLOW SYSTEM (Functional layout)



SIMPLE MATERIAL FLOW SYSTEM (Group layout)

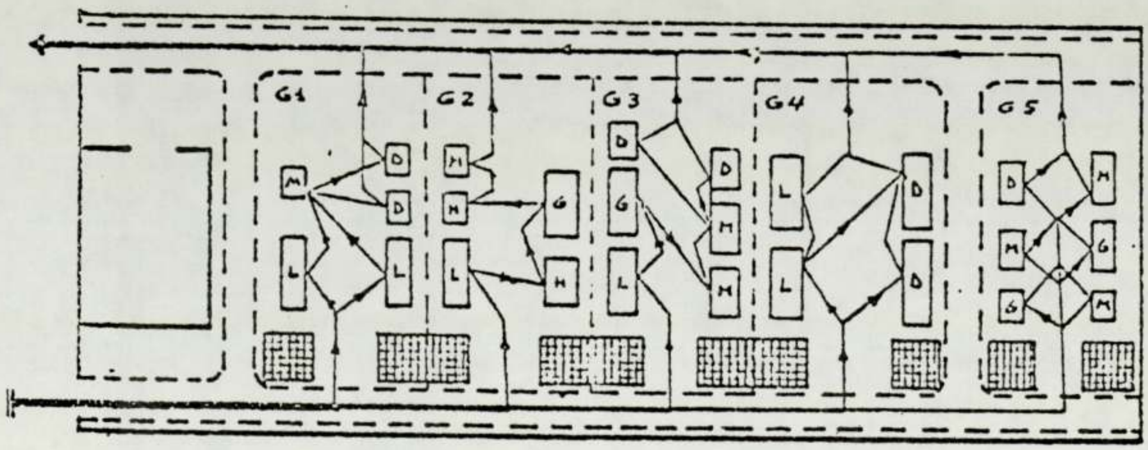
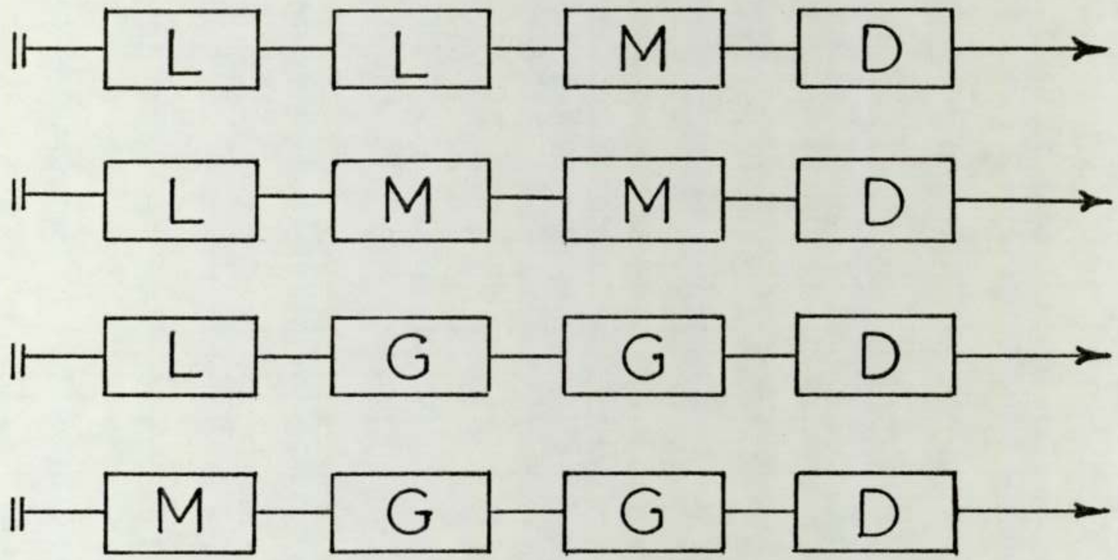


FIG. 2-4 SIMPLIFICATION OF MATERIAL FLOW WITH GROUP LAYOUT
(after Burbidge)

Machines in each line always used in the same sequence.



KEY: L = Lathe M = Miller G = Grinder D = Driller

FIG 2-5 GROUP FLOW-LINE SYSTEM

2.4 A Historical Review of Group Technology

Group Technology (GT) is not a new technique. The beginning of GT is generally attributed to the Russians. The early development and application of this technique has been traced back to 1920's (19). In the period from 1945-53 a number of important proposals of S P Mitrofanov were adopted and applied in Soviet factories. In 1965 not less than 800 factories in USSR were claimed to be actively using the principles of group technology.

In 1959 Mitrofanov published the first book written of group technology which was subsequently translated into English and published in 1966 as "Scientific Principles of Group Technology" (15). This book gave a considerable amount of information on subjects such as classification, the 'Complex Component' and group tooling. The book clarified the early approach used by the USSR to GT which was concentrated on the single machine concept using the complex component principles. Since Mitrofanov's book, a number of other important books by Soviet scientists and researchers have been published which deal with subjects such as techniques of and parameters for grouping machines (14), flow-line planning, production control and scheduling (3).

The first reported work on GT outside USSR was done by a French company - Forges et Ateliers de Constraction Electriques de Jearmant (20). Some neighbouring countries of USSR have also used GT for many years and they were influenced by USSR. These East European Countries are Czechoslovakia, East Germany, Yugoslavia, Bulgaria and Italy (19, 4).

West European efforts were probably most strongly developed in West Germany and United Kingdom. In the early 1960's Professor Opitz and his research team at Aachen University carried out research work leading to his publication of a classification and coding system (2) which is widely used today as one of the initial steps taken towards GT implementation. The growth of GT in UK was greatly influenced by the works of Mitrofanov and Opitz (21, 22). The project carried out by Ranson in Serk Audco is probably the first GT scheme undertaken in this country. The company received the Queen's Award in 1970 for the technical innovation of GT. The project based on the Brisch classification system, and eliminated the traditional ordering system (EBQ). The transformation and benefits obtained by the company are given in a book by Ranson (11) and several articles and papers (23, 24). Some other well known firms which have successfully implemented GT are Ferodo, Ferrantti Ltd, Rolls Royce, GEC-Elliot Control Valves Ltd, Mather and Platt Ltd, Baker Perkins etc. Many other firms have partly introduced GT or are still in the stage of planning to introduce (9, 21, 25).

Other than the works carried out by the above firms in this country, the contribution of the works in other fields must not be overlooked, especially the Universities. Grayson (19) states that:

> 'The Universities have had a dual role: Research (and development) and consultancy (including formal and ad-hoc education programmes).'

Various papers have been presented at the conferences for GT in Turin (9, 26), at the University of Manchester and Birmingham (MTDR), at the University of Aston in Birmingham, in the Group Technology Centre in Blacknest and at the annual conference held by the Institution of Production Engineers.

There seems little awareness of the GT concept in many countries outside Europe, particularly in the developing and underdeveloped countries. Recently, Japan has introduced GT in a number of factories using classification and coding system, and a 'Group Technology Studying Committee' was established in Japan in 1967 (27). America also has shown some interest in classification and coding systems and GT is just emerging. Professor Colwell expects that there will be a tremendous expansion of GT in United States during the next five years (28).

CHAPTER THREE

GROUP TECHNOLOGY SYSTEMS DESIGN AND IMPLEMENTATION

3.1 Some Characteristics and Factors of Group Technology Systems

Before moving on to analyse the method of approach to group technology systems, it will be beneficial to study some characteristics and factors that will affect the group formation; as there is no standard method of analysis which suits all requirements for a 'perfect' group. Some of the main factors that will affect the group formation are as follows:

a) types of product;
b) product mix;
c) product information;
d) size of company;
e) manufacturing processes used;
f) availability of machines and machine tools;
g) systems of production control applied;
h) customers service requirement;
i) class of labour available and relations.

Pullen (33) based on his research, formed a list of essential and desirable characteristics of group technology. The essential characteristics are as follows:

a) Number of men must be greater than three and less than fifteen.
b) Number of men must be less than the number of machines.
c) Operators must be allowed some degree of self-management.
d) Operators must move from machine to machine to some extent.
e) The group should manufacture components or products identifiable in a factory wide context.

f) The group should have single physical location.

Recently, Burbidge (39) also states that there are seven main desirable characteristics of group technology. These are as follows:-

a) The team - groups contain a specific team of workers who work solely or generally in the group.
b) Products - groups produce a specific family or set of products.
c) Facilities - groups are equipped with a specified set of machines and/or other production equipment, which are used solely or generally in the group.
d) Group layout - the facilities are laid out together in one area reserved for the group.
e) Target - the workers in the group share a common product output target.
f) Independence - the groups should be independent of one another.
g) Size - the group should be limited to restrict the number of workers per group. A desirable group would be one consisting of 6 to 15 workers.

From the above information, both Pullen and Burbidge show some common and essential group characteristics. In addition to these characteristics, there are other desirable characteristics such as payment systems, suitable paperwork etc. Knowing the characteristics and factors to be considered in machine groups formation, the next stage is to analyse the method of approach to design group technology systems. This will be discussed in the following sections.

3.2 Methods of Approach

During a group technology system analysis, it is most important to bear in mind that one is dealing with a complex manufacturing system. There is no point in attacking only one small part of a particular troublesome area and neglecting the impact on the company as a whole. To implement a system, it is necessary to introduce a little at a time, but it must have an overall plan for the whole company from the start (2).

There is no doubt that a prerequisite for implementation of a group technology system is the grouping of parts or components into families which are similar with respect to manufacturing. There are three main methods of family formation.

i) Rule of thumb, based on local product knowledge;
ii) Classification and coding system;
iii) Production Flow Analysis (PFA).

3.2.1 Rule of Thumb

Most companies have certain 'obvious' families of components which can be selected by eye, that is, by direct observation of the parts and machines by a skilled production engineer. Most of the earlier applications of group technology were planned in this method (13). But, this is not a systematic approach and it makes little or no impact on the total company operation, and it might even have prevented the company from moving towards an overall approach (18). From the experience of researchers it has been shown that rule of thumb has limited possibilities to find the best division of parts into families.

3.2.2 Classification and Coding System

Classification and coding is probably the most widely used and most successful method of implementing group technology. In this system, each component is examined and is then given a code number which indicates values for such features as, dimensions, materials, special features, and machines to be used. There are two general approaches to classification systems. One approach results in a universal classification system generally applicable in different types of metal engineering industries. Another approach is a tailor-made classification system which offers only general principles while the final classification would depend on each special case.

(i) The Universal Classification System

Family formation by using a universal classification system has been used most frequently because it can be used for any firm and it is generally considered cheaper to install, since it does not require the services of specialist consultants.

Parts selected by this type of system are based on certain pre-determined geometric features such as overall shape, size and possible material. The system can usually facilitate design retrieval, provide a foundation for simplification and standardisation, promote better utilisation of existing resources and can facilitate production planning to some extent - for example where components of similar shape require similar manufacturing processing. The typical examples of the universal classification system are the Opitz and Vuoso classification systems.

(ii) The Tailor-made Classification System

The philosophy of this type of classification system is that the components and products of any engineering company are often quite different. This implies that a classification system should be designed to cater specifically for each company.

The implementation of the tailor-made classification system is usually carried out by the consultant who teaches representatives of the client the rules of the classification so that when the consultant leaves, the system of classification can still continue progressively to embrace all necessary components. The Brisch classification system is one of the typical examples of the tailor-made classification system.

3.2.3 Production Flow Analysis (PFA)

Production Flow Analysis (PFA) is a technique developed by Burbidge (36) in the early 1960's as an alternative to classification and coding system for family formation. This technique has a dual function. It is used for finding families of components and associated groups of machines for cellular layout, that is, PFA normally forms component families and machine groups in one goal.

The aim of PFA is to find the simplest possible material flow system by eliminating all unnecessary routes or material flow paths. The main information needed is an accurate route card for every component produced. The technique is concerned only with production methods, and does not consider the design features or geometric characteristics of components.

Burbidge (36) suggests four main stages in which the technique may be applied and these are:-

1) Factory Flow Analysis
2) Group Analysis
3) Line Analysis
4) Tooling Analysis

The first stage, 'Factory Flow Analysis', identifies the best flow lines for material between the different processing departments in a factory. A complete route card is required for every component to analyse components utilising similar routes. The procedure is such that all components are coded according to their operations routings, to indicate the departments visited by each component and then sorted by this code to produce families of components with the same inter-department routings.

The second stage, 'Group Analysis', is concerned with two parts, firstly, the division of the plant into groups and the assignment of them to each processing department; and secondly, the division of the components into associated families. It is postulated that in any processing department engaged in batch production, there is a natural division into groups and families already in existence and that the task is to find these natural families and groups rather than to create new ones (26).

The third stage, 'Line Analysis', is concerned with the flow of materials between machines inside the groups and with planning the best plant layout of the machines. A network analysis approach is suggested by Burbidge (4) in the form of a flow process chart which is rationalised to find the best flow condition.

The final stage is 'Tooling Analysis'. In each processing department, routes are sorted out to find composite parts and other tooling families which can be machined with the same tooling. This approach will reduce investment in tooling and setting times.

It is evident from the preceding sections that either classification and coding systems or production flow analysis can be chosen for family formation of components for the introduction of group technology. But it is not the object here to discuss individual merits of different methods and it is up to the individual companies to decide which system will serve them best under different circumstances.

3.3 Machine Group Formation

After the components are formed into families according to their similarities, the machine types are determined and the average annual loading on each machine is calculated. This technique is basically a quantitative approach and therefore the specific machine allocation to the group will require a good knowledge of production within a factory. Further information such as the production rate and the total quantity required is also important when considering a machine group formation. The formation of groups can be divided into three stages:-

1) Capacity calculation for each family
2) Capacity balancing by modifying families
3) The integration or elimination of minority groups and machine loads.

The information required by the first stage are as follows:

a) Operation and set-up times for each component;
b) Machine description for each operation;
c) Annual demand of components.

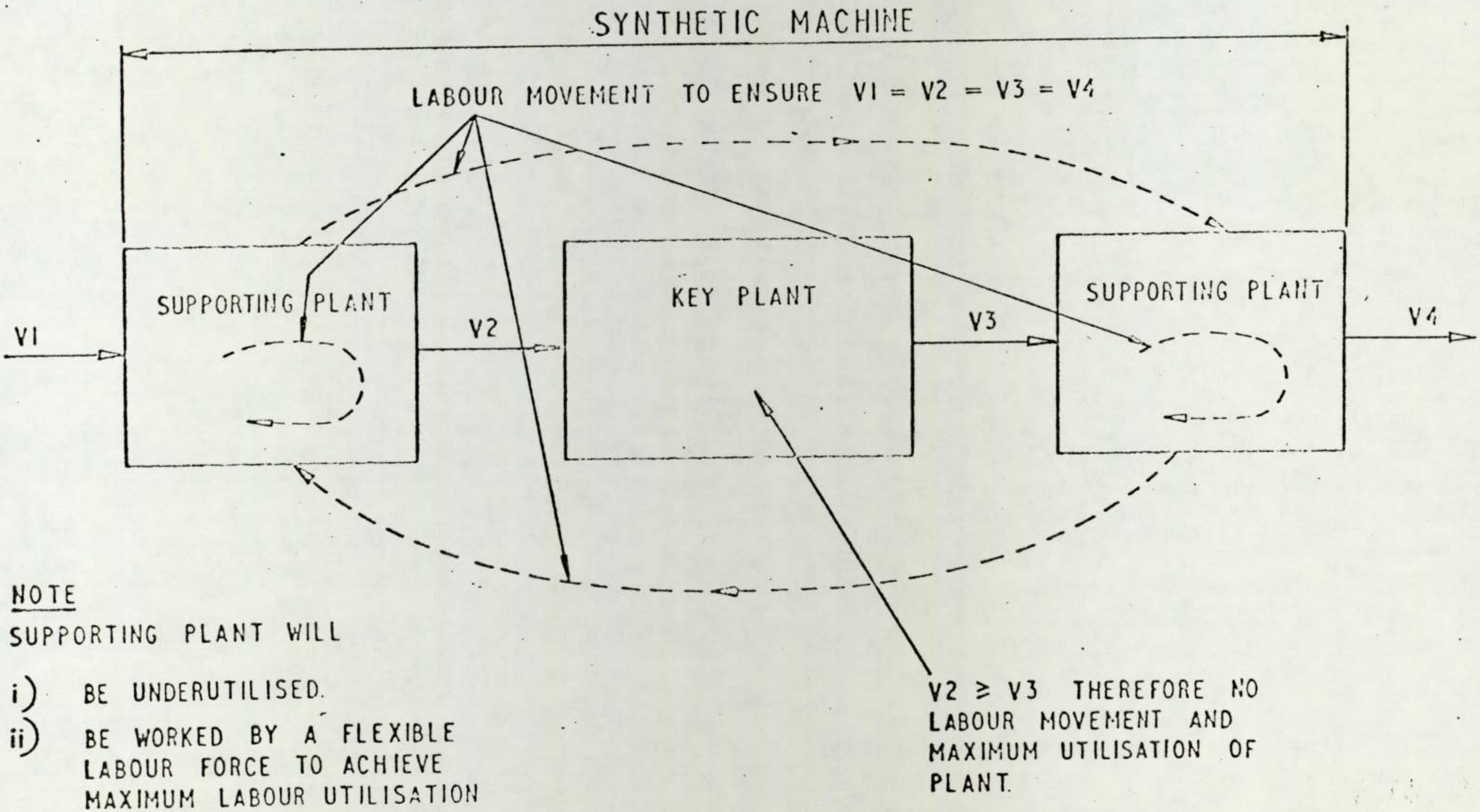
With the above information, the annual operation time on each machine type for all different machine types can be calculated for each family.

As mentioned in the beginning of this chapter, the desirable group size is from 6 to 15 operators. Williamson (40) also claims that 10 people make a good group. Hence, it would seem that the number of operators is one of the appropriate parameters for group size. The parameter can be used to determine the annual capacity of each group. But in this aspect, the skills of the operators must also be taken into account to determine the annual capacity of the group. For convenience purposes, let it be that 10 operators is an ideal group; then the annual capacity of each group can be determined by adding yearly machining hours for each family and combining families using similar machines until enough yearly hours to utilise 10 operators have been accumulated. If a family has more annual hours per year than can be handled by ten operators, the group should be multiplied to cope with the total manufacturing load or to form a sub-group within the main group. Advantage can be taken of such duplication to specialise further; for instance by having basically similar groups each dealing with different size ranges, or perhaps quality.

Another parameter that governs the capacity of the group is the key machine principle. When loading a group, the workloads in each group add up to a sensible figure of which at least one machine is to be fully loaded and this will be the limiting or key machine as far as output from the manufacturing unit is concerned. The remaining supporting machines may be under-utilised. The functions of the supporting machines are concerned with the supplying and despatching of work to and from the key machines. Consequently, the key plant is very highly utilised owing to the grouping of batches. A flexible labour force is therefore used which can alternate among the various supporting machines. Figure 3-1 shows how this can be achieved.

Undoubtedly, the previous stages of analysis will lead to a number of poorly utilised supporting machines. In general, this is accepted on the ground that the supporting plant are generally cheap equipment and the group technology philosophy is more concerned with ensuring maximum utilisation of labour rather than equipment. Kruse (25) suggests a number of ways to deal with this deficiency:

a) replanning of the work on the different machines;
b) using group tooling to reduce operation and setting times on overloaded machines;



NOTE

SUPPORTING PLANT WILL

i) BE UNDERUTILISED.

ii) BE WORKED BY A FLEXIBLE LABOUR FORCE TO ACHIEVE MAXIMUM LABOUR UTILISATION WHILST ENSURING $V1 \geq V2$.

FIG 3-1 KEY MACHINE CONSIDERATIONS (AFTER THORNLEY)

c) the use of special attachments or unit heads for a limited amount of special work on certain components in the group;

d) accepting poor utilisation on low cost machines;

e) considering the sharing of one machine by more than one group (in extreme cases only!);

f) producing parts to a semi-finished state in one group and transferring to another group for finishing.

3.4 Plant Layout

Once groups have been formed, the next step is to analyse the flow patterns within the group to determine its plant layout. Machines in a group can be arranged in a flow line or a group layout. The layout of the machines will depend on the nature of the components involved. It is desirable to have a flow line layout if the majority of components have a similar flow pattern. Burbidge and El-Essawy recommended line analysis and component flow analysis respectively for this process which have been mentioned earlier in this chapter.

'FROM-TO' charts are another useful aid to determine the primary flow patterns in a group which forms an excellent basis for layout. If the majority of parts give a similar flow pattern, then those parts not conforming can be possibly catered for by re-planning, or by duplication of similar machines at the different places in the line, or two (or more) patterns of flow may be combined in one line. It should be noted that by-pass movements from a machine to one several places down the line in the main direction of flow are accepted. If flow line layout was possible, material handling could be by conveyor and even if by-pass movements are present, a conveyor is still feasible. Machines are normally arranged on both sides of a conveyor to shorten the line.

Although the flow line is an ideal case of plant layout for group technology systems, owing to variations in the number of operations on the components and their operation sequences, a sequence of machines to satisfy any one component is unlikely to satisfy all of them without backtrack. In this case group, or cell layout is more suitable. Having analysed the primary flow pattern of the components, machines in the group can be arranged in a circular, square or rectangular area with a clearly marked boundary. Either type of layout will reduce the distance travel in cross-flow or back tracking flow and will provide face-to-face contact of group members with subsequent better communication. But, as cross-flow or backtracking will occur in group layout, some delays in machine loading will result.

Having laid out the individual groups, then the overall plant layout in the factory must be arranged in such a way that their relationships to services, stores and assembly provide for efficient material flow. However, an important consideration in the formation of groups is the overall physical restrictions imposed by the specialist technology of the industry concerned, such as heat-treatment and plating. These types of work must often be retained in a centralised facility for technical reasons, and it is therefore useful to construct groups which lead from or to these natural breaks. Detailed overall plant layout techniques for efficient material flow can be obtained from the books by Muther (41,42).

3.5 Management and Organisation Structure

The implementation of group technology does not just mean the changes of technical factors such as classification, analysis of component data and re-organisation of plant layout, but may also involve some changes in management and organisation structure. Some of the difficulties in the use of group technology mentioned in Koenigsberger (28) may be due to failure to change the organisational structure to meet the needs of a new social-technical situation.

For a successful changeover from existing to new system structure, it is essential to have good communications at the planning stage. It is the belief that the implementation of group technology is most likely to be successful if it is led by the chief executive of the company (9). It is also essential to maintain a regular discussion between departments at various stages of implementation to avoid conflicting interests. Moreover, it is advisable to make certain that the cooperation of everyone concerned is obtained.

Inherent in the group technology philosophy is the concept that there should be more machines than men in a group. Hence, operator flexibility will occur. There are two types of flexibility of operators:

1) flexibility within a cellular group
2) flexibility between cellular groups

The consequence of the flexibility of operator is that an operator no longer works continuously at one particular machine, but he is required to move between machines or groups to ensure continuity of work flow. Incentive schemes must take account of this new requirement as operators may resist changes owing to the fact that they have to be paid for the skills they possess rather than for the skills they are utilising. Useful information on wages and payments systems can be obtained from Arn (43, 44). Retraining of operators is required as they are expected to operate more than one type of machine. But, restriction on this type of flexibility may be imposed by trade unions. The trade unions concern for the preservation of the status of the skilled men and for maximum job security for all members make them highly resistent to this kind of change without adequate safeguards. So, having decided to implement group technology the cooperation of the unions and workers cannot be overstressed and top trade union leaders must be informed beforehand of the change and the company's intentions.

The main change in the organisation is the broader structure with fewer hierarchical levels (9). This is because managers can control the work of far more people in groups than is possible with traditional forms of organisation. Consequently, it shortens the communication channel between workers and managers or directors. It is possible that this can lead to better management-worker relations.

The change of production control plays an important role in a successful implementation of group technology. Details of production control methods used with group technology will be discussed in the next chapter. Sequencing and scheduling for group manufacturing systems also have to be changed in order to achieve short and reliable manufacturing time. More details will be discussed in chapter five.

Costing procedures can also be simplified by considering each cell or flow line as an independent cost centre. So, cost per component can be computed more accurately.

CHAPTER FOUR

PRODUCTION CONTROL

4.1 Introduction

The term 'Production Control' embraces activities which strictly speaking are both planning and controlling activities. Production control is also the function of management which plans and directs the materials supply and processing activities of an enterprise. In order for production to be efficient, and for the desired output to be achieved on time, it is necessary to ensure that the right number of parts or products are in the right place at the right time for the minimum cost. In brief; production control is concerned with material flow. Careful planning and control are necessary to achieve the production objectives stated above. Therefore, the production control department is the nerve-centre of the manufacturing body. Although it is a vital department, it cannot exist in isolation and must have close liaison with other departments besides the production shops.

4.2 The Historical Development of Production Control

There was little awareness of the functions of production planning and control before the 19th Century. But after that date the producers required greater security for their materials, work-in-progress and finished stocks and the customers demanded better services, the need for the developments of production planning and control were realised and accepted. In the late 1860's, the techniques of planning and control were very limited. Planning was still verbal and production control was conducted by observation. By 1905 definite planning systems had emerged which were based on established times for each operation, planning the best sequence of work for all the throughput and dispatching according to pre-determined routes and at prescheduled times. By 1918, it was realised that these systems must have close liaison with other departments such as marketing and design departments. After the First World War, owing to the greater need to produce profitably, this factor demanded better control over the usage of all resources and paperwork for planning and control were introduced as a substitute for the verbal means, hence, organisation structures emerged to facilitate this. From 1925 it was accepted that production control could assist a firm to economise in production and to achieve delivery of goods when planned.

The planning function was seen to comprise of three successive levels, namely, programming, ordering and dispatching (these will be discussed in more detail in the latter part of the chapter). There was little further development until the advent of the Second World War when changes were made largely because of the complexity of and the urgency associated with aircraft production. A series of booklets and reports which were concerned with production control were published from 1943 to 1965 by the British Standard Institution and the Anglo-American Council on Productivity (29). In the present decade production control has changed more radically, perhaps because of the increasing use of computers, and/or perhaps because of the operation research techniques, and to some extent because of group technology (30). Nevertheless, no matter how advanced the modern computers and techniques, therein lies the contribution of man to the modern man-machine partnership. Man must collect the necessary data, recognise the types of problem and its potential solution format, develop or select an appropriate programme, and interpret or modify the machine output.

4.3 Levels of Production Control

There are three main levels of production control, known as (i) programming, (ii) ordering and (iii) dispatching. The types of plan made at each of these levels are illustrated in Figure 4-1 (4).

4.3.1 Programming

Programming is the level of planning at which plans are made of the production output of products from the factory. The plans or schedules at this level are called production programmes.

The basic information required for programming is from the 'Sales Programmes' or 'Sales Forecasts' which are generally produced by the Marketing Department. Such forecasts will predict which products customers are most likely to buy, in what quantity and at what rate.

The marketing department will produce two types of programmes, namely, (i) long-term programmes and (ii) short-term programmes. Long-term programmes will affect allocation of capital and planning, plant development, product development and training. Such programmes should be regularly reviewed in the light of market trends and adjusted to give more accurate short-term programmes. Short-term programmes form the basis of production control activities because they will influence the use of plant and labour as well as the usage of materials. So, close liaison must exist between the marketing department and the production control department to ensure that sales are keeping up with what the factory can produce in terms of quantity and delivery date.

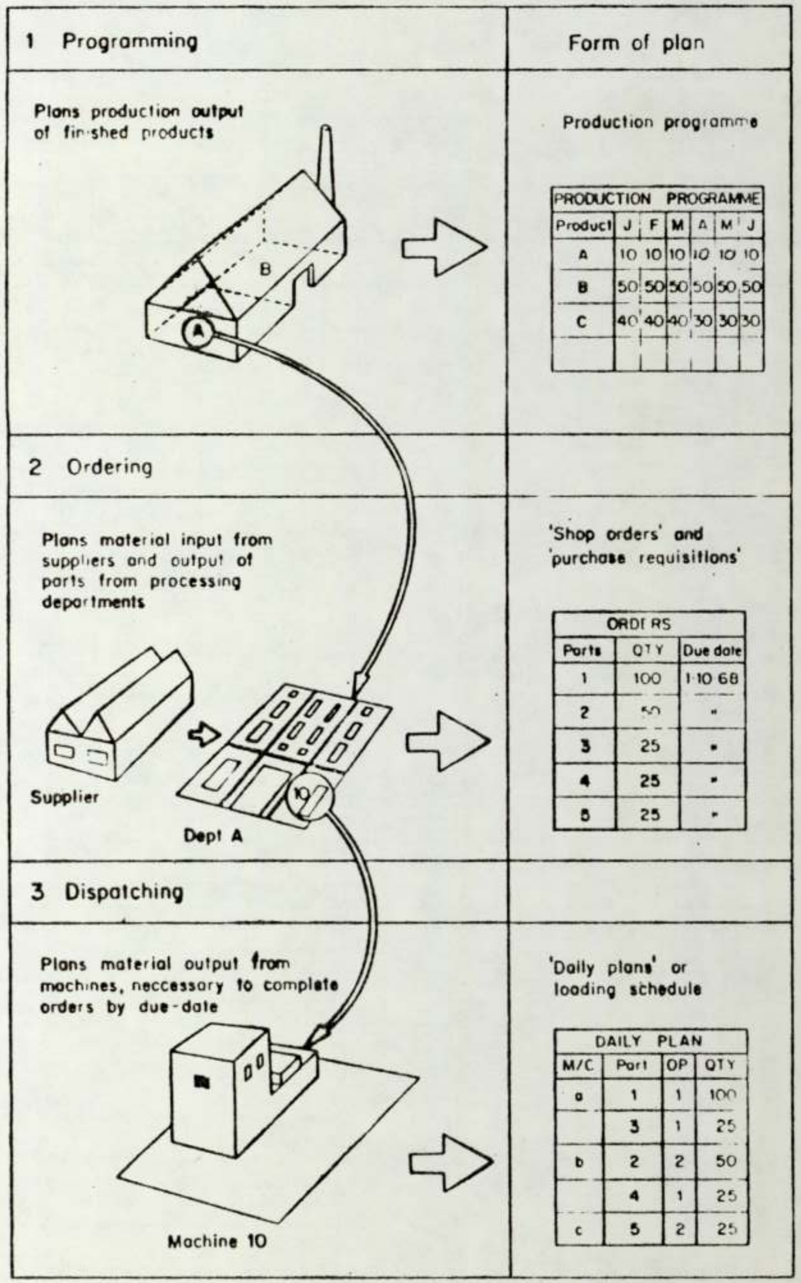


Fig 4-1. Levels of Production Control (After Burbidge)

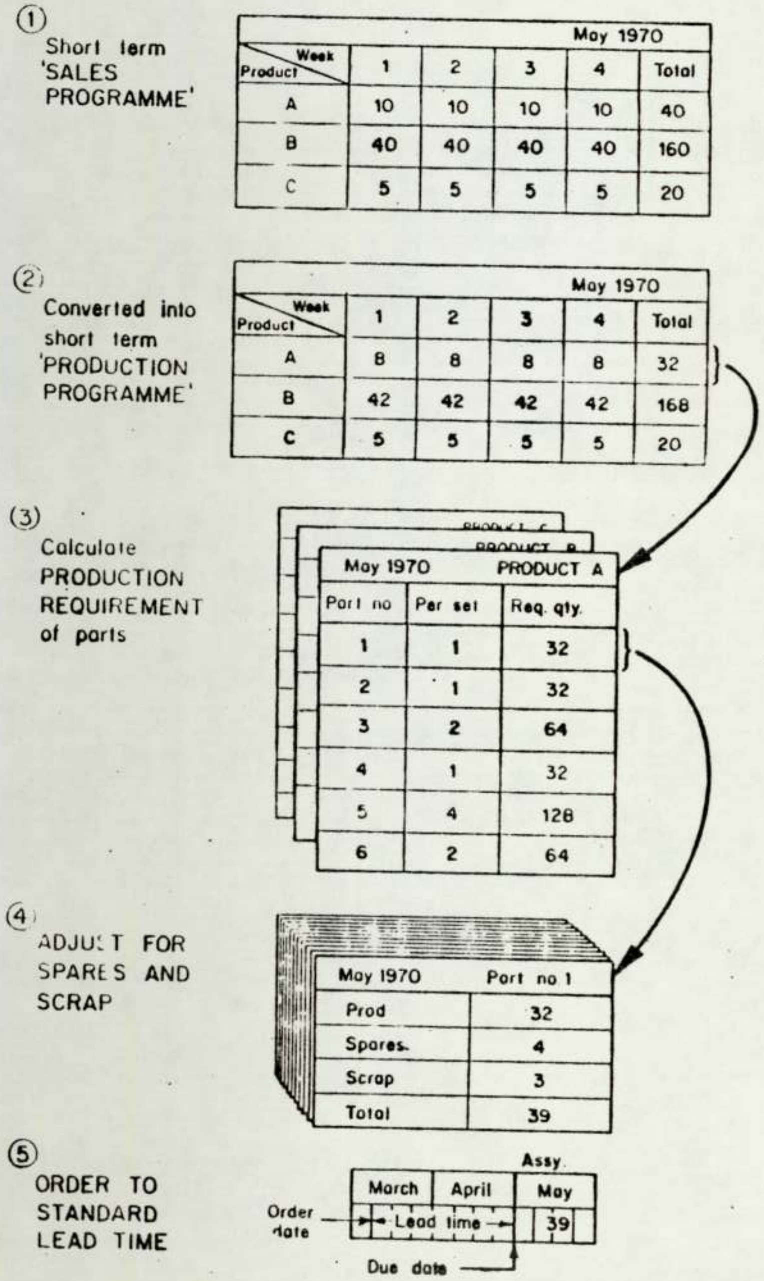


Fig 4-2. Period Batch Control Ordering System (After Burbidge)

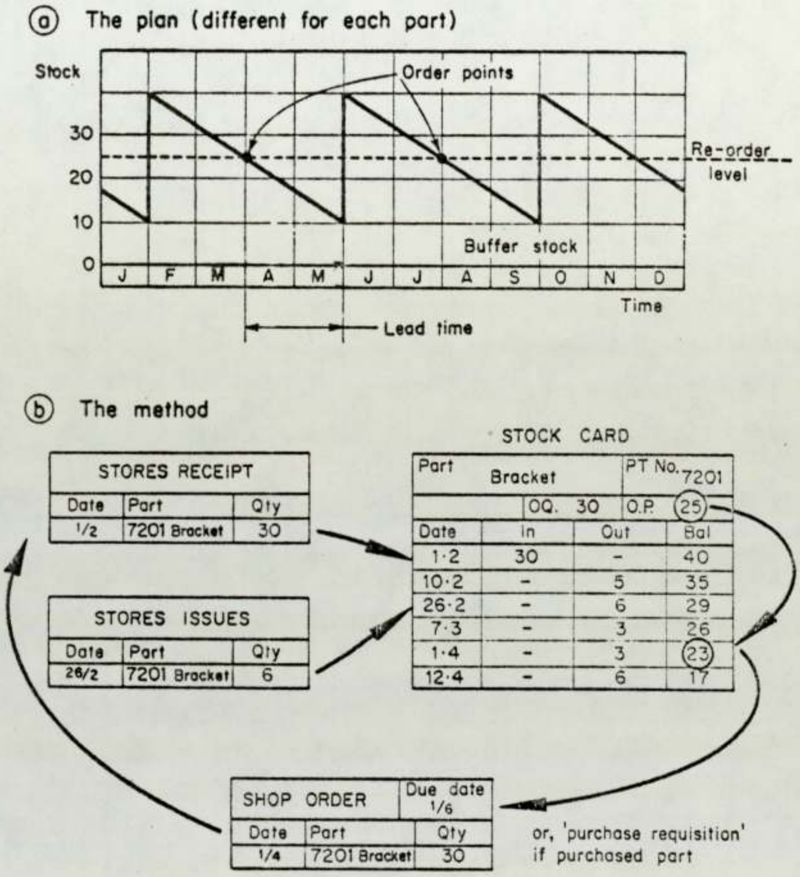
4.3.2 Ordering

Ordering is concerned with scheduling the output of components from processing departments and the input of materials and purchased parts from suppliers. The plans made and issued to the processing departments are known as 'Shop Orders' and if issued to the buying department they are known as 'Purchase Requisitions'.

There are two main systems of ordering, namely, 'Single-cycle-single-phase' or 'Flow Control' systems and 'Multi-cycle-multi-phase' or 'Stock Control' systems.

With the single-cycle ordering, the ordering interval is fixed and the quantities to be ordered are calculated from a series of short-term production programmes; a process known as 'Explosion'. In other words, for each production period (week, month or other suitable time units), the exact requirements for each component are worked out to fulfil production programmes or sales programmes. A typical flow control system called 'Period Batch Control' is illustrated diagrammatically in Figure 4-2.

With a multi-cycle system, there is no fixed order interval. The order quantity is generally fixed separately for each component and its interval between orders is varied to regulate output. The order quantity is generally based on some mathematical formula such as Economic Ordering Quantity (EOQ) which balances setting and ordering cost with stock holding cost to minimise overall production cost. For every component there is a re-order level which is fixed as illustrated in Figure 4-3. When the stock of any component drops to its re-order level, a new order is placed for the fixed order quantity.



STORES RECEIPT		
Date	Part	Qty
1/2	7201 Bracket	30

STORES ISSUES		
Date	Part	Qty
26/2	7201 Bracket	6

STOCK CARD

Part	Bracket		PT No. 7201
	OQ. 30		O.P. ㉕
Date	In	Out	Bal
1·2	30	-	40
10·2	-	5	35
26·2	-	6	29
7·3	-	3	26
1·4	-	3	㉓
12·4	-	6	17

SHOP ORDER		Due date 1/6
Date	Part	Qty
1/4	7201 Bracket	30

Fig 4-3 The Stock Control Ordering System (After Burbidge)

4.3.3 Dispatching

Dispatching is concerned with the plans for scheduling work to be done in each processing shop. It includes the task of scheduling and planning the sequence of operations to be performed on each component and the actual disposition of machines and other plant on the shop floor. This responsibility usually falls on the shoulders of the foreman. For instance, in a machine shop of an engineering factory, the foreman will receive hundreds of orders for batches of different components, each made by a series of operations on different machines.

Normally, some arbitrary decision rules or priority rules are used to help the foremàn to solve the problem in such a way that the optimum conditions are created in respect to due dates, loading and throughput.

4.4 Production Control and Group Technology

In a group technology manufacturing system, production control becomes one of the most critical areas of management control. In order to operate group technology manufacturing systems efficiently, it is necessary to change the production control from conventional stock control to flow control.

The conventional stock control systems are inefficient and unstable particularly in regulating the product sets in GT systems. Burbidge states that the deficiencies of the stock control systems are as follows (1):-

1) They can only operate successfully with a high investment of stock;
2) They are the major losses from material obsolescence;
3) They generate a widely fluctuating and upredictable variation in the stock level;
4) They generate an unbalance and upredictable variation in load of work on the factory;
5) If used to control a succession of process, they magnify the demand and stock variation at each following level;
6) They make it impossible to take advantages of the savings with family processing.

As mentioned previously, stock control is generally based on a batch size known as EOQ; batches are indirectly governed by the demand pattern and batches are called up not to suit assembly requirements but in response to specific stock levels. Moreover, the EOQ by its random nature produces capacity fluctuation. Although it can use buffer stores to overcome the problem of capactiy balancing, it will generate work-in-progress and will cause longer throughput times. From a GT point of view, stock control systems are not suitable for production control in a batch production plant.

In flow control systems, batch size and delivery dates are calculated directly from a series of short-term production programmes. Both of them are based on the requirements, hence product sets will be obtained to reduce unnecessary obsolescence. One of the common flow control systems is Period Batch Control (PBC) system.

The concept of PBC is very simple: in a fixed production period (week, month or any suitable time period), the exact requirements. for each component are worked out to fulfil assembly or sales requirements and batches are loaded covering these requirements only. For each production period a requirement list is drawn up and batches generated accordingly.

Period batch control is a single-cycle-single-phase ordering system; ie. the order quantities are varied as necessary to follow variations in output requirements. In order to reduce work-in-progress and finished parts stock, a short ordering cycle is preferable. But the ordering cycle is limited by the throughput time, as for any component the ordering cycle must not be less than the throughput time. Owing to the change of plant layout in GT systems, the throughput time will be greatly reduced. Therefore, period batch control seems to satisfy the requirements of GT systems.

Burbidge also states that the requirements for production control in a GT system are as follows (4):-

1) A single-cycle ordering system must be used for all made parts;
2) A high ordering frequency (short cycle) must be used;
3) With standard products, a standard machine loading sequence is preferable, the different parts being loaded on the machines in the same sequence in each successive cycle.

He further claims that (32) "it is accepted today that period batch control is an essential ingredient for successful group technology application".

It is by no means true that all the stocks must be controlled by period batch control in an enterprise. Generally, a composite system with several different types or ordering methods are used for different classes of stocks. The stocks can be classified by using a Pareto analysis. Usually, Pareto or ABC curves (See Fig 4-4) are used to divide stock items into three classes in accordance with their cost value; ie. Class A (high value items), Class B (medium value items) and Class C (low value items).

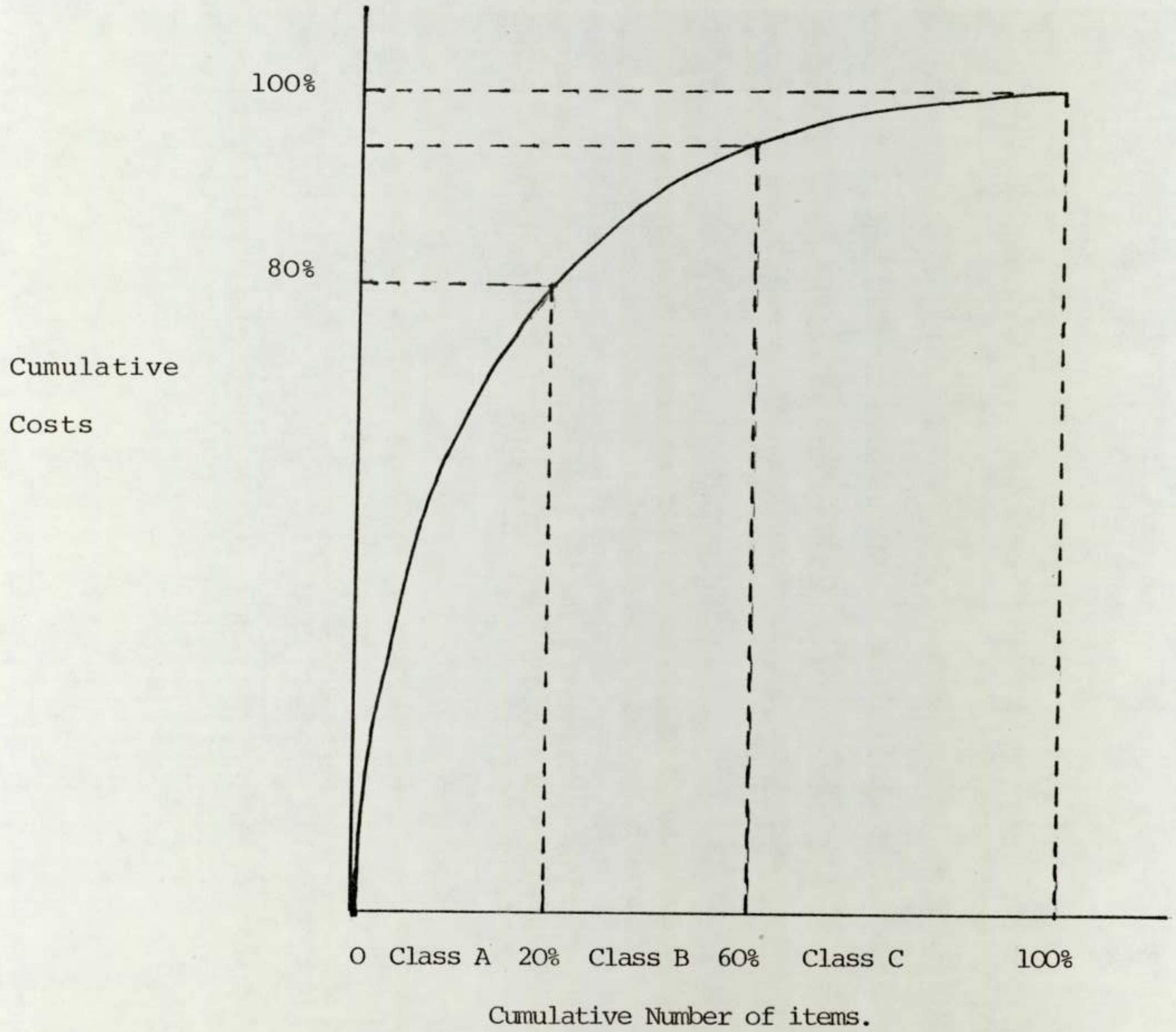


Figure 4-4 Parts Analysis of Manufacture.

Class A: the top 20 per cent of items, which account for the highest values of total inventory costs;

Class B: the middle 20 to 30 per cent of items, which account for a moderate share of the investment;

Class C: the large remaining group of stock-keeping items, which account for a small fraction of total investment.

It is obvious from the above classification that class A items constitute a large proportion of total investment and they need detailed control. As the items are usually special parts and their quantities being small, the control cost could be small. In addition, as they have a high value, the reduction in the stock investment would be greater than the control cost. These items are suitable for period batch control ordering system based on the annual usage. If items are bought parts or materials, the firms can negotiate with suppliers to deliver items in small quantities with call-off notes against long-term supply contract. If items are made parts, scheduling will be made in value order and processing the most expensive parts last but with the top priorities in scheduling. Class B are most of the bought parts and materials. These types of items are generally ordered by period batch control. Class C items are generally materials and low value common parts, such as steel plate, sheet steel, nuts, bolts, washers etc. These items have low value and excess stocks make little impact in total inventory. In addition since most of these items are used for more than one product, there is little risk of material obsolescence. Hence, stock control systems are acceptable for class C items.

Burbidge (1) states that the key features of GT are group layout, short cycle flow control and a planned sequence of loading; no one of these features will give major savings on its own. The change of plant layout in GT will arrange machines to form groups. This will simplify the loading problems. From the loading point of view each group is treated as one 'synthetic machine' with control concentrated on the key machine (see figure 3-1)(32). The supporting or secondary machines will be under-utilised and the flexibility of operator will be used to overcome bottlenecks and to achieve maximum labour utilisation.

CHAPTER FIVE

SCHEDULING

5.1 Introduction

An important aspect of industrial control is the dependence on the precise use of given manufacturing facilities at each instant of time. Several factors have to be considered in making these decisions such as, the availability of resources, cost of implementing the decisions, time factor involved in production and so forth. This kind of decision making is known as 'Scheduling' (45) or 'Sequencing', however, there are basic differences between the two operations. In the case of sequencing it is concerned with the ordering of operations on a single machine; whereas scheduling is a simultaneous and synchronised sequence of several machines (46).

In practice, the problems of scheduling do not arise until some fundamental planning problems are resolved. Thus, it must be recognised that scheduling decisions are of secondary importance to a broader set of managerial decisions. Market research and economic analysis are used to determine the market demand before technological planning is used to focus on the question of how the products or components should be manufactured. At the same time, the availability of resources is a crucial one and the facilities concerned with machine loading should be considered before making scheduling decisions. The loading function is to determine the total hours of demand relating to the capacity for a given time period in a job shop or a group. The scheduling decision is the detailed assignment of jobs within the production cycle.

There has been an increased amount of interest over the recent years in the field of scheduling research. This research can be classified mainly into two categories (47):

i) theoretical research dealing with optimising procedures limited to the static problems;
ii) experimental research dealing with scheduling rules in both static and dynamic cases.

In a real-world situation, the problem of scheduling which is dynamic in nature may be considered as a static case owing to the modern advance information systems (48). Thus, a successful scheduling for the static problem has promising prospects for practical use.

In the theoretical research on scheduling, an electronic computer is usually required in searching for an optimal solution and therefore computational costs will be high. Sisson (52) has pointed out that the researchers must not only be concerned with obtaining an optimal solution but also with the practical and economic application of the solution technique. It is the second aspect of the problem which has led to the second category of research; ie. the experimental research. A number of scheduling rules and techniques have been developed by these experimental researchers. These rules do not guarantee obtaining the optimal solution. However, near optimal solutions can be obtained with limited computational effort and their computational requirements are predictable for problems of a given size. Moreover, the procedural steps can be kept simple so that the problem solver does not lose sight of the overall view of the problem, thus enabling him to make the best use of his intuition and judgement.

The selection of an appropriate rule or technique depends on the complexity of the problem and the choice of criteria. A difference in criterion will often lead to differences in methods of solution. There are a number of criteria such as, throughput time, mean throughput time, work-in-progress, machine and labour utilisation, job lateness, idle time, etc. Different scheduling rules may produce different performances for each of these criteria but it is impossible to use a simple rule to maximise all of these criteria, since many of them are mutually contradictory. It follows that certain criteria must be selected for preferential maximisation, on the condition that others should be kept within certain limits.

5.2 Scheduling Rules and their Classifications

As the problems of scheduling become increasingly involved so rules and procedures are designed for making scheduling decisions. These are analogous to those rules devised for playing chess where the number of possible moves are usually large. However, these rules do not guarantee the best solution even if the 'best' is known. But it is found that a set of rules when applied consistently, would give better results than a series of inspired guesses. Hence, a scheduling rule is just a means to dictate which job among those waiting for service is to be scheduled in preference to the others. In the past, terms such as scheduling rule, dispatching rule, priority rule or heuristic rule are often used synonymously.

Gere (49) considers priority rules as simply a technique by which a number or value is assigned to each waiting job according to some methods. The job with minimum 'value' would be selected. He defines a heuristic rule to be simply some 'rule of thumb', whereas a scheduling rule can consist of a combination of one or more priority rules and/or one or more heuristic rules. Conway and Maxwell (50) consider 'local' dispatching rules as those requiring information only about those jobs that are waiting at a machine, while 'global' rules require additional information about jobs or machine states at other machines or waiting lines.

Panwalker and Iskander (47) classify the scheduling rules according to the following categories;

I(a) Simple Priority Rules

These are usually based on information related to a specific job such as its due date, processing time, remaining number of operations, etc.

Some of the examples are listed as follows:

a) SPT - it is a selection of job with the shorter processing time;

b) DD - it is a selection of job with the earliest due date;

c) FIFO - it is a selection of job with the first in, first out order.

I(b) Combination of Simple Priority Rules

Generally, a queue is divided into two or more priority groups. Different rules are applied to different groups for assigning jobs. Some of the examples are given as follows:

a) FIFO/SPT - from jobs waiting for more than a specific time, select according to FIFO; if all waiting jobs are in the queue for a smaller duration, select according to SPT;

b) DDSU - select the jobs with the earliest due dates; in the case of a tie, select the job that required no set up time.

I(c) Weighted Priority Indices

These rules are the result of combining a set of simple priority rules based on I(a) or I(b) with different weightings assigned to them. Generally, priority is given for the job having the smallest index value. Some of the examples are listed as follows:

a) P + WKR - select the job with smallest weighted sum of the next processing time and work remaining;

b) P/WKR - select the job with the smallest weighted ratio of the next processing time to work remaining.

II Heuristic Scheduling Rules

These rules are usually used in conjunction with the rules in Category I. However, a much more involved consideration such as anticipated machine loading, the effect of alternate routing, scheduling alternate operation, etc. is required to make the rules effective. In some cases non-mathematical aspects of human intelligence may be involved such as inserting a job in an idle time slot by visual inspection of a schedule. Some of the examples are given as follows:

a) Subset - determine critical jobs, schedule these first, and then schedule other jobs around the critical jobs;
b) Manipulation - try to improve the schedule by manipulating different operations while the Gantt chart is being laid out;
c) Look Ahead - study the effect of scheduling a job (determined by a simple rule) on another job that may arrive in the queue before the schedule job is completed.

III Other Rules

These rules are usually designed for a specific shop using combination of priority indices based on mathematical functions of job parameters. Some of the examples are as follows:

a) PTF (Processing Time Factor) - an index based on the weighted product of the processing time of i-th job and the sum of processing times of jobs at certain machine groups;
b) OSF (Operation Slack Factor) - an index based on operation due dates, processing time of operation, and arrival time of the job.

With the above classification of scheduling rules, it is difficult to say which rule is the best. Each of them has its own merits. Gere (49) states that:

> "We should think of more matters than straightforward priority rules for scheduling; for those interested only in operation as well as those performing research the way is clear for a number of investigations of the use of heuristic scheduling rules, which show great promise".

Most of the researchers (47) appear to agree that a combination of simple priority rules, or a combination of heuristic rules with a simple priority rule works better than an individual priority rule.

5.3 Scheduling in Group Technology Systems

'Group Scheduling' (GS) is the term normally used to refer scheduling associated with group technology application (5). Group scheduling is one of the main factors relating to the efficiency of a group technology application which can lead to economies in production.

If the families of components and groups of machines have been formed correctly, group scheduling is greatly simplified. This is because the scope of the problems is reduced from the general consideration of the entire shop to that of a small group of machines. Unlike the functional job shop scheduling in which the sequence of every operation of the component has to be assigned by production control department; in group scheduling more often a family (or families) of components is assigned by the production control department to a group and the sequence of components is left entirely up to the foreman of the group. At this stage, the duty of the foreman is to issue components in the correct sequence to minimise the cost of production.

The sequencing problem can be solved manually or with the aid of computer.

The most common criterion for scheduling problems is to minimise the throughput time of components. This objective will be associated with the following benefits:-

i) minimise idle time on the machines.
ii) maximise operator utilisation
iii) minimise lateness of components in relation to their due dates.
iv) minimise work-in-progress and inventory.
v) quick reaction to the changing circumstances.

Of course, there are many other criteria other than the throughput time. But, as can be seen from the above, throughput time plays a vital role in the scheduling criteria.

The basic problem of group scheduling is to search for both the optimal family sequence and the job sequence in each group. This two-phase scheduling technique reduces the computational effort if some effective scheduling rules are to be used. However, very few works have so far been published, both in United Kingdom and in other countries, specifically dealing with group scheduling. The two most recently published papers by Hitorni and Ham (5, 6) provide the optimal solution for family sequence and job sequence in each group for a single machine and the multi-stage manufacturing system. Optimal scheduling algorithms were developed using both the theorem derived and the branch-and-bound method. The criteria of scheduling are: the total flow time (total throughput time), the mean flow time and the total tardiness (sum of job lateness).

PERA (5) dealt with loading and scheduling of work in a GT cell by considering batch overlapping and machine breakdown delay using several rules such as SPT rule and COVERT rule (scheduling according to the high value of the ratio of delay cost over processing time).

The most comprehensive book covering group scheduling is written by Petrov (3). His book is based on the results of introducing group technology into eighty one companies in Russia. A systematic approach has been used to study the group technology organisation and planning, and to obtain a 'good' schedule through several heuristic rules. Using such rules, Petrov showed that stable and near optimal results were obtained. His approach is mathematical and tempered with logic to reduce the possible number of alternatives. He also made a comparison of his rules with methods developed by other Soviet scientists and found that his rules are more reliable and general. More details of Petrov's heuristic rules will be discussed in Section 5.3.1.

But none of the above methods has considered the operator scheduling and it is an important factor in group technology application. Thornley (2, 7) states that:-

> "Increase machine utilisation may, or may not, result

> depending upon the circumstances. In general, key machines will be better utilised but less important machines may be under-utilised. It is, therefore, important that certain members of the workforce should be conversant with the operation of more than one type of machine."

This leads to the concept on flexibility of operator. The operator is no longer to be an integral part of the machine as with conventional types of schedule, but can be moved from machine to machine within a group or between groups. The mobility of operator is determined by the work load of the groups, scheduling rules applied, and the nature of the work. But normally the operators who operate the bottleneck or key machines are seldom moved because the work load on these machines are usually sufficient to justify permanent operators. The operators on the supporting or less utilised machines are more liable to move as their operations are secondary and their work load will vary. The main functions of the secondary machined are to support and to ensure continuous flow at the bottleneck machines. Hence for efficient group scheduling, it requires a formal method for drawing up a plan not only for the job but also for the even movement of the operators. Gantt chart methods have been suggested by Connolly et al (7) to schedule both job and operator although no detailed procedures were given. A technique of using Gantt chart methods has been proposed by English (8) for job and operator scheduling in group flow line manufacturing systems. He assumes that all operators have equal ability, that is, they are capable of operating all types of machine in the flow-line. But in practice, this will not always be realised, as the skills of operatorswill impose constraints on their movement. Therefore, the level of skill required will depend upon the type of work being carried out, and the type of machines in use in the group. These factors must be taken into account for the capacity planning at the outset of machine group formation.

5.3.1 The Technique of Petrov's Heuristic Rules (3)

Since the 1950's the Soviet scientists and researchers have been developing a number of methods to solve the group scheduling problems. Their main criteria are to minimise the idle time on machine tools and work-in-progress in the group. With the exception of Petrov's method, these methods have dealt with group flow-line systems only. Petrov developed a set of heuristic rules for scheduling which covers both group flow-line and group layout systems. According to Petrov there are four basic possibilities for scheduling in group technology systems (see Figure 5-1) and these are:-

a) The component flow is unidirectional but not necessarily the identical route and one or more operations may be missed out. An operation will only be started after the batch quantity has been completed by the preceeding operation.

b) The component flow is identical or unidirectional. Operation can be overlapped, ie. the succeeding operation can be started before the batch quantiy has been completed by the preceeding operation.

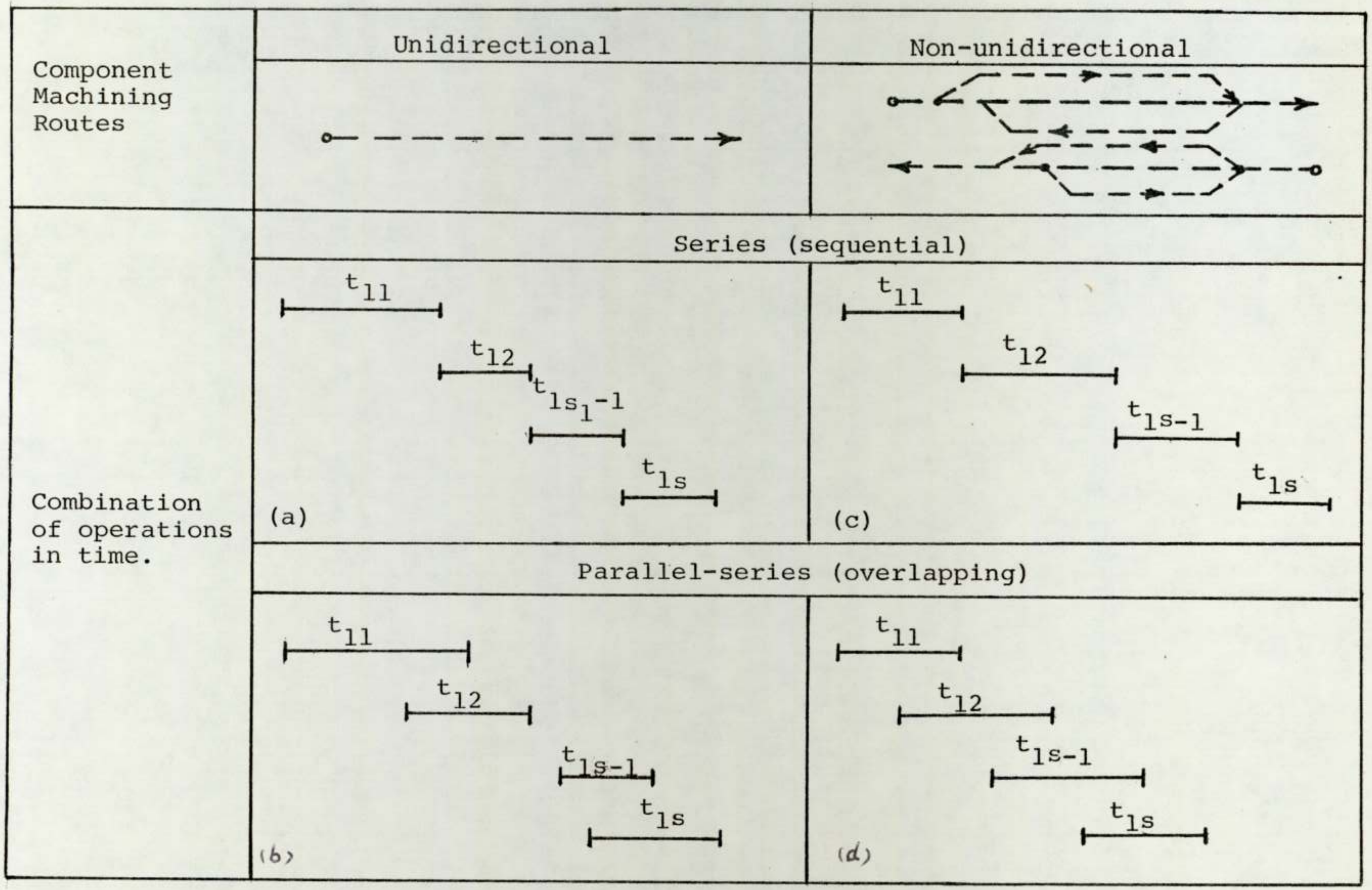


FIG 5-1 The Four Basic Possibilities for Schedule Construction (After Petrov)

c) The component flow is dissimilar or non-unidirectional. Missing out or back-tracking operations are allowed. An operation will only be started after the batch quantity has been completed by the preceeding operation.

d) The component flow is similar to type (c) but overlapping operations are allowed, ie. the succeeding operation can be started before the batch quantity has been completed by the preceeding operation.

Types (a) and (b) belong to group flow-line system and types (c) and (d) are included in the group layout system. The use of batch overlapping as in types (b) and (d) are only suitable for large batch production. Types (a) and (c) are more common and typical cases in small and medium batch productions.

The main aim of the Petrov's rules is to minimise the interruptions in machine tool operation. The basic idea of his rules was developed from the group flow-line system.

Let t_{ij} be the processing time for a batch of the i-th component ($i = 1, 2 \ldots\ldots k$) in the j-th operation ($j = 1, 2 \ldots\ldots s$)

This processing time per batch is determined from the simple relationship:-

processing time per batch = operation time per batch + set up time per batch.

$$\text{ie. } t_{ij} = Q_i t_{pij} + T_{uij} \qquad \ldots \qquad \ldots \qquad \ldots \qquad (1)$$

where Q_i is the batch size for the i-th component

t_{pij} is the piece time for the j-th operation on the i-th component in time unit.

T_{uij} is the set-up time for the j-th operation on the i-th component in time unit.

Then the processing time of a production system consisting of s machines engaged on the machining of k components can be written in the following matrix form:

$$\begin{vmatrix} t_{11} & t_{12} & \cdots & t_{1s} \\ t_{21} & t_{22} & \cdots & t_{2s} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ t_{k1} & t_{k2} & \cdots & t_{ks} \end{vmatrix} \qquad t_{ij} > 0$$

The processing chart of the production system is illustrated in Figure 5-2.

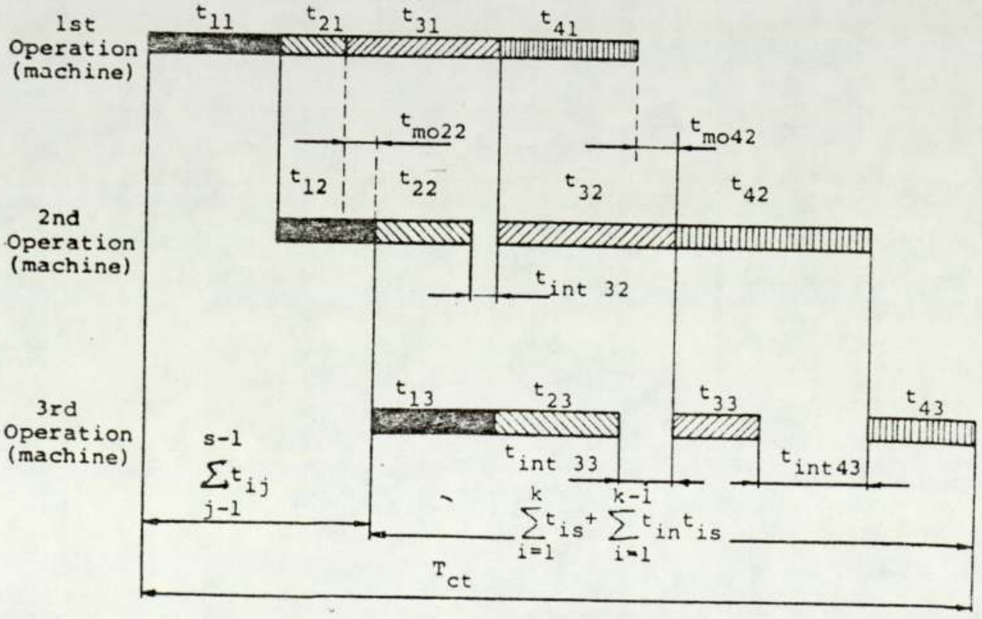


FIG 5-2 Processing Chart of a Production System (After Petrov)

Due to the fact that the piece times vary from operation to operation and the batch sizes of individual runs also vary it is not possible to synchronise the processes and every machine may experience periods (Fig 5-2) during which it is either still occupied on the previous batch when the next batch arrives ($t_{mo_{i,\ j+1}}$) or standing idle waiting for the arrival of the next batch from the preceeding operation ($t_{int_{i,\ j+1}}$).

The throughput time (production cycle) for an entire set of components can be expressed as follows:

$$T_{ct} = \sum_{j=1}^{s-1} t_{ij} + \sum_{i=1}^{k} t_{is} + \sum_{i=1}^{k-1} t_{int_{is}} \qquad .. \qquad (2)$$

where $t_{int_{is}}$ is the idle time on the machine completing the last (s-th) operation, between finishing work on the i-th batch and starting work on the (i + 1)-th batch.

Since in equation (2), the second term ($\sum_{i=1}^{k} t_{is}$) is constant, therefore, the throughput time is a function of the first and third terms which are affected by the order in which the batches of components are issued to the machines. Hence, in order to achieve a minimum throughput time, it has to issue components in a correct sequence which will ensure minimum idle time over the various machines.

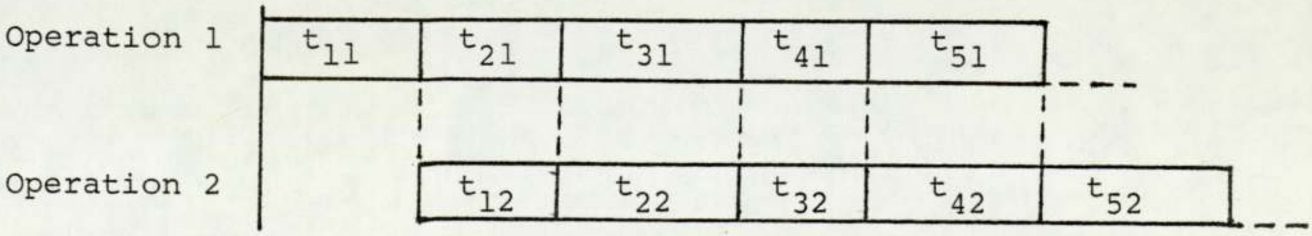


Fig 5-3 A 2-operation process, with no idle time

Referring to Fig 5-3 for a 2-operation process, the condition to avoid idle time between successive batches of components arriving at the second machine can be expressed by the following system of inequalities:-

Between components 1 and 2,

$$(t_{12} - t_{21}) \geqslant 0$$

Between components 2 and 3,

$$(t_{12} - t_{21}) + (t_{22} - t_{31}) \geqslant 0$$

Between components 3 and 4,

$$(t_{12} - t_{21}) + (t_{22} - t_{31}) + (t_{32} - t_{41}) \geqslant 0$$

Between component (k-1) and k,

$$(t_{12} - t_{21}) + (t_{22} - t_{31}) + \ldots\ldots + (t_{k-1,2} - t_{k1}) \geqslant 0$$

The sum of these inequalities for the entire set of components in a 2-operation process will be:

$$(k-1)(t_{12} - t_{21}) + (k-2)(t_{22} - t_{31}) + \ldots\ldots + (t_{k-1,2} - t_{k1}) \geqslant 0 \quad \ldots \quad \ldots \quad (3)$$

OR $$(k-1)t_{12} + (k-2)t_{22} + (k-3)t_{32} + \ldots\ldots + t_{k-1,2} - (k-1)t_{21} - (k-2)t_{31} - \ldots\ldots - t_{k1} \geqslant 0 \quad \ldots \quad (4)$$

OR $$(k-1)t_{12} + \sum_{i=2}^{k}(k-i)(t_{i2} - t_{i1}) - \sum_{i=2}^{k} t_{i1} \geqslant 0 \quad (5)$$

It is obvious that if there exists a greater value on the left-hand side of the inequality (3), there will be less possibility in general terms of idle time being incurred on the second machine as the successive batches of components from the first (i=1) to the last (i=k) are machined. The inequality (3) also reflects that the throughput time is dependent on the order in which components are issued for machining. Since inequality (3) shows that the coefficients are in decreasing magnitude, therefore, in order to have greater value on the left-hand side of the inequality, t_{i2} must be arranged in decreasing order and t_{i1} must be arranged in increasing order. But from the inequality (5), it shows that the decisions have to be made in the following procedures:-

i) If $(t_{i2} - t_{i1}) \geq 0$, sequence components in increasing order of t_{i1}, and

ii) If $(t_{i2} - t_{i1}) < 0$, sequence components in decreasing order of t_{i2}.

It can also be seen that the left-hand side of the inequality (5) will be made greater by arranging $(t_{i2} - t_{i1})$ in the decreasing order, since their coefficients are also in decreasing order. Therefore, to ensure minimum idle time on the second machine, the components have to be sequenced in the order of decreasing order of $(t_{i2} - t_{i1})$.

Petrov shows that the number of components and machines involved in the process will not affect the above conditions for avoiding idle time. Hence the operational matrix of a system can always be divided into two parts with equal number of operations.

For an even number of operations, the total machining labour content for a batch of components in the first half of the matrix will be:

$$T_{i1} = t_{i1} + t_{i2} + \ldots\ldots + t_{i,e-1} + t_{ie} = \sum_{i=1}^{e} t_{ij},$$

similarly for the second half of the matrix,

$$T_{i2} = t_{i,e+1} + t_{i,e+2} + \ldots\ldots + t_{i,s-1} + t_{is} = \sum_{j=e+1}^{s} t_{ij}$$

where $e = \frac{s}{2}$

For an odd number of operations:

$$T_{i1} = t_{i1} + t_{i2} + \ldots\ldots + t_{i,e-1} + t_{ie} = \sum_{i=1}^{e} t_{ij}$$

$$T_{i2} = t_{ie} + t_{i,e+1} + \ldots\ldots + t_{i,s-1} + t_{is} = \sum_{i=e}^{s} t_{ij}$$

where $e = \frac{s+1}{2}$

As in the 2-operation process, the optimum sequence of operations must be found by arranging T_{i1} in the increasing order and T_{i2} in the decreasing order. To find the correct sequence of components with minimum throughput time, Petrov proposed four heuristic rules for scheduling as follows:

Rule I: i) If $T_{i2} - T_{i1} \geq 0$, sequence components in increasing order of T_{i1}, and
ii) If $T_{i2} - T_{i1} < 0$ sequence components in decreasing order of T_{i2}.

Rule II: Sequence components in decreasing order of $(T_{i2} - T_{i1})$.

If Rule I has an indeterminate solution, ie. there are several batches of componetns with identical values of T_{i1} or T_{i2}, the deciding criterion is according to Rule II. If the application of Rule II produces an indeterminate situation, ie. if several batches of componetns have identical values for the differences $(T_{i2} - T_{i1})$, the deciding criterion is according to Rule I.

To reduce the error of Rule I and II, two supplementary rules were proposed by taking the average processing time for machining batches of components in each half of the matrix ($\bar{T}_{i1}$ or $\bar{T}_{i2}$),

$$\text{ie.} \quad \bar{T}_{i1} = \frac{T_{i1}}{S_{i1}}, \text{ and } \bar{T}_{i1} = \frac{T_{i2}}{S_{i2}}$$

where S_{i1} and S_{i2} are the number of operations in the first and second halves respectively of the machining process on the components concerned. Hence, Rule III and IV are as follows:-

Rule III:
i) If $\bar{T}_{i2} - \bar{T}_{i1} \geq 0$, sequence components in increasing order of $\bar{T}_{i1}$, and
ii) If $\bar{T}_{i2} - \bar{T}_{i1} < 0$, sequence components in decreasing order of $\bar{T}_{i2}$.

Rule IV: Sequence components in decreasing order of $(\bar{T}_{i2} - \bar{T}_{i1})$

The indeterminate solutions of Rule III and IV are solved in the similar procedures as Rule I and II. These four heuristic rules are applicable to any four of the basic possible scheduling problems in group technology systems. Petrov claims that these rules are capable of producing throughput time within 10% of the optimal solution. In addition, Rule III and IV will produce more accurate answers which involve the smallest error.

An example used by Petrov is used here to illustrate the procedures of applying the rules. Table 5-1 shows the machining time matrix of components. The calculated values are determined as follows:

For component 1:

$T_{11} = 9 + 6 = 15$ $\qquad$ $\bar{T}_{11} = \frac{15}{2} = 7.5$

$T_{12} = 8 + 3 = 11$ $\qquad$ $\bar{T}_{12} = \frac{11}{2} = 5.5$

$(T_{12} - T_{11}) = 11 - 15 = -4$ $\qquad$ $(\bar{T}_{12} - \bar{T}_{11}) = 5.5 - 7.5 = -2.0$

For component 2:

$T_{21} = 2 + 6 = 8$ $\qquad$ $\bar{T}_{21} = \frac{8}{2} = 4.0$

$T_{22} = 8 + 5 = 13$ $\qquad$ $\bar{T}_{22} = \frac{13}{2} = 6.5$

$(T_{22} - T_{21}) = 13 - 8 = +5$ $\qquad$ $(\bar{T}_{22} - \bar{T}_{21}) = 6.5 - 4.0 = +2.5$

and so on. Then, the sequence of the components can be determined by applying the heuristic rules. The throughput time of the components can be determined by the Petrov's algorithm or by Gantt chart methods.

COMPONENTS	MACHINES					CALCULATED VALUES						SEQUENCES			
												PETROV's RULES			
	T	C	M	G	D	T_{i1}	T_{i2}	$(T_{i2}-T_{i1})$	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2}-\bar{T}_{i1}$	I	II	III	IV
1	9_1	6_2		8_3	3_4	15	11	-4	7.5	5.5	-2.0	2	2	2	2
2	5_4		8_3	6_2	2_1	8	13	+5	4.0	6.5	+2.5	6	6	6	6
3	7_1	8_2		5_3	4_4	15	9	-6	7.5	4.5	-3.0	4	5	1	5
4	6_3	10_2	5_1	4_5	3_4	21	13	-8	7.0	4.3	-2.7	1	1	5	1
5	4_3		6_3	3_2	10_1	13	10	-3	6.5	5.0	-1.5	5	3	3	4
6	7_3	8_2	4_1	10_5	5_4	19	22	+3	6.8	7.3	+0.5	3	4	4	3

TABLE 5-1 MACHINING TIME MATRIX AND SEQUENCES OF COMPONENTS UNDER DIFFERENT RULES (AFTER PETROV)

CHAPTER SIX

OBJECTIVES AND METHODOLOGY OF THE SCHEDULING PROJECT

6.1 Objectives of the Scheduling Project

From the literature survey, it was found that little work has been done on group scheduling. Most of the works were concerned with group scheduling in line layout, and the operator was seldom taken into consideration. The basic aim of this scheduling project is to develop a heuristic method for machine shop loading, machine and operator scheduling of group layout in GT systems. Manual simulation of Gantt charts is used in the project to help the scheduling of machines and operators.

Group scheduling can be split into two stages, viz:

i) general factory loading covering the loading of the individual groups of the GT systems; and
ii) machine shop loading covering the detailed loading of each group.

Development of the current project is to be based on the concept of stage two. It is assumed that a family of components or jobs has been identified for common manufacturing facilities to be used. The list of components are arranged in the order of increasing due dates, beginning with the component having the earliest due date. It is proposed to use this family of components to set up a model in order to illustrate the proposed method of group scheduling.

The objectives of this scheduling project are:-

a) to minimise the throughput time;
b) to maintain maximum labour utilisation
c) to maintain minimum work-in-progress.

The minimisation of the throughput time is the main objective of the project. As with a fixed labour force, the minimisation of throughput time will indirectly maximise the labour utilisation and will also reduce the work-in-progress. Moreover, Dutkosky and Ham (52) state that the minimisation of throughput time will indirectly have the following results:

1) A lower amount of work-in-progress;
2) A shorter average customer delay time;
3) A lower amount of all currently booked jobs, thus the greater the capacity to take on additional work as new orders materialise.

So, the results of the proposed method based on objectives (a) the minimisation of throughput time and (b) the maximisation of labour utilisation are used to compare with Petrov's heuristic rules III and IV (3).

6.2 Proposed Method of Scheduling in GT Systems

The proposed method of scheduling is based on two principles:-

1) to issue a job to the bottleneck machines as early as possible; and
2) to minimise the idle time.

The basic idea of the proposed method is developed from the Petrov's heuristic rules. In group technology system, the operations required and the sequence of operations on components in the same family will be quite similar, though not necessarily identical. Therefore, the processing time (t_{ij}) of a production period can always be written in the matrix form as in Fig 6-1:

$$
\begin{array}{lccccc}
 & t_{12} & t_{11} & t_{13} & \ldots\ldots & t_{1s} \\
 & t_{21} & t_{22} & t_{23} & \ldots\ldots & t_{2s} \\
 & t_{32} & t_{31} & t_{33} & \ldots\ldots & t_{3s} \\
 & \cdot & \cdot & \cdot & \cdot\;\cdot\;\cdot\;\cdot\;\cdot & \cdot \\
 & \cdot & \cdot & \cdot & \cdot\;\cdot\;\cdot\;\cdot\;\cdot & \cdot \\
 & \cdot & \cdot & \cdot & \cdot\;\cdot\;\cdot\;\cdot\;\cdot & \cdot \\
 & t_{k1} & t_{k2} & t_{k3} & \ldots\ldots & t_{ks} \\
\cline{2-6}
\text{Capacity Required} & T_a & T_b & T_c & \ldots\ldots & T_j \\
\cline{2-6}
\text{M/c loaded order} & K_3 & K_2 & K_1 & \ldots\ldots & K_s
\end{array}
\qquad t_{ij} \geq 0
$$

Fig 6-1 Processing Time Matrix in a production period.

Instead of dividing the processing time of the components into two equal parts, the proposed method divides them into two parts with different numbers of operations which depend on the bottleneck machines. Since the bottleneck machines are used as dividers, the first step to be done is to determine the bottleneck machines by adding up the total processing times of each machine in the production period. In Figure 6-1, T_a, T_b ..... T_j indicate the capacity required or total load of each machine and K_1, K_2 ..... K_s indicates the machine loaded order with K_1 as the highest loaded, K_2 as the next highest and so on; ie. $K_1 > K_2 > K_3 > \ldots\ldots > K_s$ in terms of work load. For each components, the highest loaded machine in the system utilised by the component is used to divide the operations into two parts. The first part, M_{i1}, is the total processing times of the i-th component from the first operation to the operation of the bottleneck machine inclusively. The second part, M_{i2}, is the total processing times from the operation on the bottleneck machine to the last operation of the i-th component. M_{i1} and M_{i2} can be expressed as follows:-

$$M_{i1} = t_{i1} + t_{i2} + \ldots\ldots + t_{in} = \sum_{i=1}^{n} t_{ij}$$

$$M_{i2} = t_{in} + t_{i,n+1} + \ldots\ldots\ t_{is} = \sum_{i=n}^{s} t_{ij}$$

where n is the highest loaded machine in the system utilised by i-th component.

Apply the principle of Petrov's rule II to M_{i1} and M_{i2} by sequencing components in the decreasing order of $(M_{i2} - M_{i1})$ This type of arrangement will reduce idle time which is supported by the rough argument presented in Figure 6-2. Blocks 1, 2, 3 represent components with decreasing order of $(M_{i2} - M_{i1})$ They fit together most economically in the order of 1, 2, 3 and most wastefully with idle times in the reverse order.

The arrangement of the decreasing order of $(M_{i2} - M_{i1})$ also implies that components with small value of M_{i1} and large values of M_{i2} will be sequenced in the first priority. Since M_{i1} is defined as the total processing time in operations preceding the bottleneck machine, therefore, components will be assigned to the bottleneck machine as early as possible with less possibility of idle time. In addition, the early assignment of components with large values of M_{i2} will also reduce the idle time on the second part of the machines. This is one of the principles of the optimal scheduling of the flow shop systems (54).

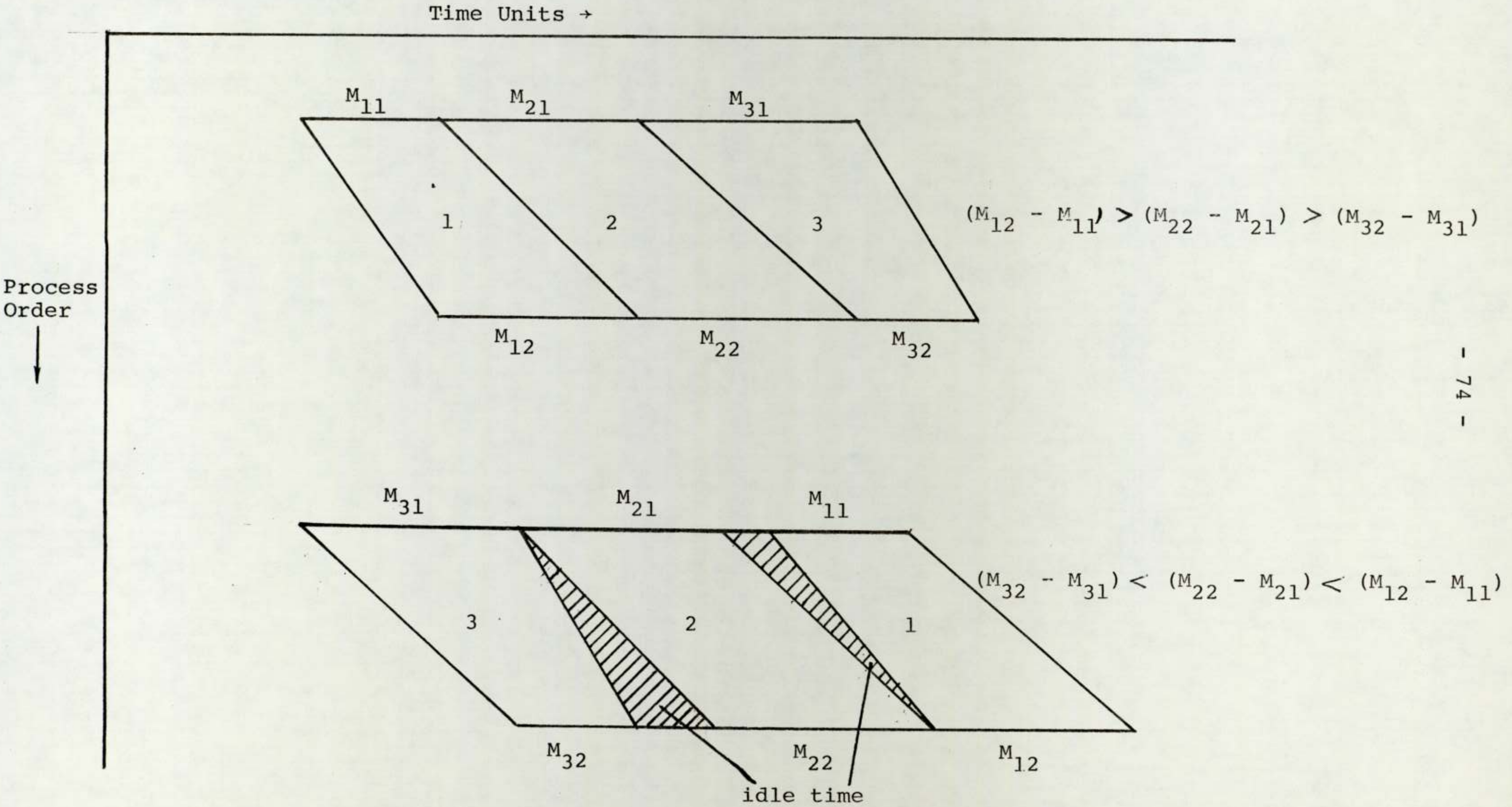


Fig 6-2 Fit of Simple Schedule in Decreasing and Increasing Order of $(M_{i2} - M_{i1})$

Therefore, in order to find the correct sequence of components with minimum idle time, the proposed rule (Rule Y) is to sequence components in the decreasing order of the differences $(M_{i2} - M_{i1})$. This can be expressed symbolically as:

$$(M_{i2} - M_{i1})\downarrow$$

If ties occurs, ie. several components have identical values of the differences $(M_{i2} - M_{i1})$, the following methods are recommended:

a) If $(M_{i2} - M_{i1}) \geqslant 0$, sequence components in the increasing order of M_{i1}; and
b) If $(M_{i2} - M_{i1}) < 0$, sequence components in the decreasing order of M_{i2}.

The procedure for the application of the proposed rule can be illustrated by the example shown in Figure 6-3.

Component 1: $M_{11} = 3 + 4 = 7$
$M_{12} = 4 + 2 + 3 = 9$
$M_{12} - M_{11} = 9 - 7 = +2$

Component 2: $M_{21} = 6$
$M_{22} = 6 + 4 + 1 + 2 = 13$
$M_{22} - M_{21} = 13 - 6 = +7$

and so on.

	Component No.	Time Required per Batch in Time Units						Total Processing Times	Calculating Parameter			SEQUENCES		
												Proposed Rule	Petrov's Rule	
		A	B	C	D	E	F		M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y	III	IV
PERIOD N	1	3_1	4_2		2_3		3_4	12	7	9	+2	7	7	7
	2	4_2	6_1	1_3		2_4		13	6	13	+7	5	5	1
	3		7_1	2_3	2_2	1_4		12	7	12	+5	6	6	4
	4	7_1			1_4	2_2	4_3	14	7	14	+7	4	1	5
	5	8_2	9_1		3_3			20	9	20	+11	2	4	3
	6		10_1	4_3		4_2	2_4	20	10	20	+10	3	3	2
	7	2_1		3_2	4_4	5_3		14	2	14	+12	1	2	6
Capacity Required		24	36	10	12	14	9	105						
M/c loaded value Order		K_2	K_1	K_5	K_4	K_3	K_6							

Fig 6-3 Matrix of the Time Required and Determination of Order-of-Priority

The final sequence of the components by the proposed method is 7-5-6-4-2-3-1. Without considering the labour capacity, the throughput time of the proposed method is 41 time units as shown in Figure 6-4a.

The sequence of the components determined by Petrov's heuristic rules III and IV are also shown in Figure 6-3 and their throughput times are 41 and 43 time units respectively as shown in Figure 6-4b and Figure 6-4c.

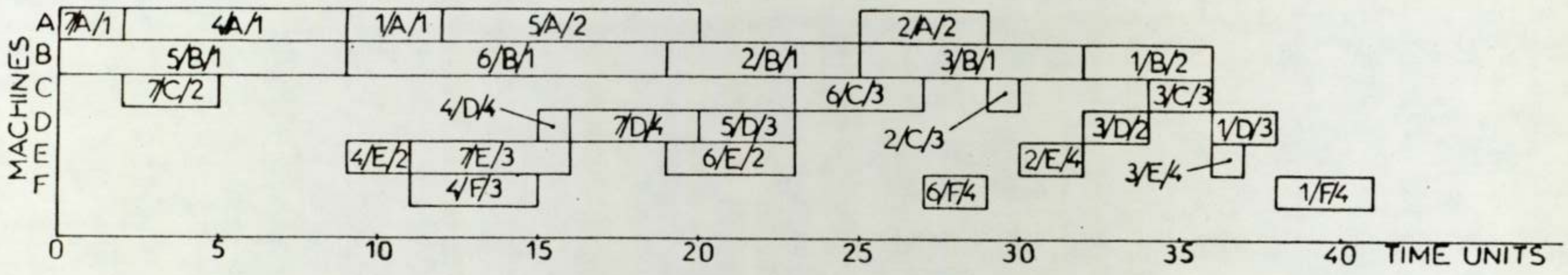
6.3 The Formation of Short-term Production Programmes from A Long-term Production Programme

In Section 6-2 the procedures of the proposed method for a short-term scheduling is discussed. And in this section it shows how the short-term production programmes are formed from a long-term production programme. It is assumed that a family of components has to be identified for each group together with the given capacity of machines and labour. Then short-term production programmes can be formed. The formation of short-term production programmes and the sequence of components are outlined in the following steps:

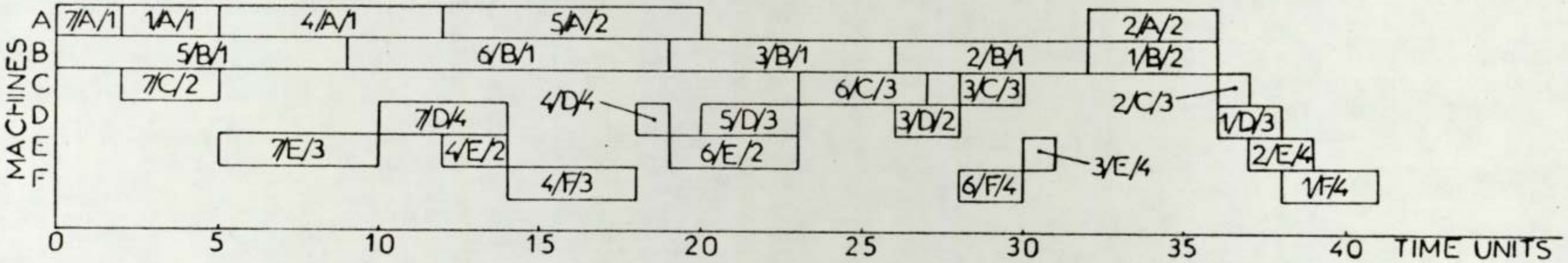
Step 1: List components or jobs in the order of increasing due dates, beginning with the job having earliest due date.

Step 2: Break down the booking list into production periods, eg. one week per production period. The conditions to be satisfied are:

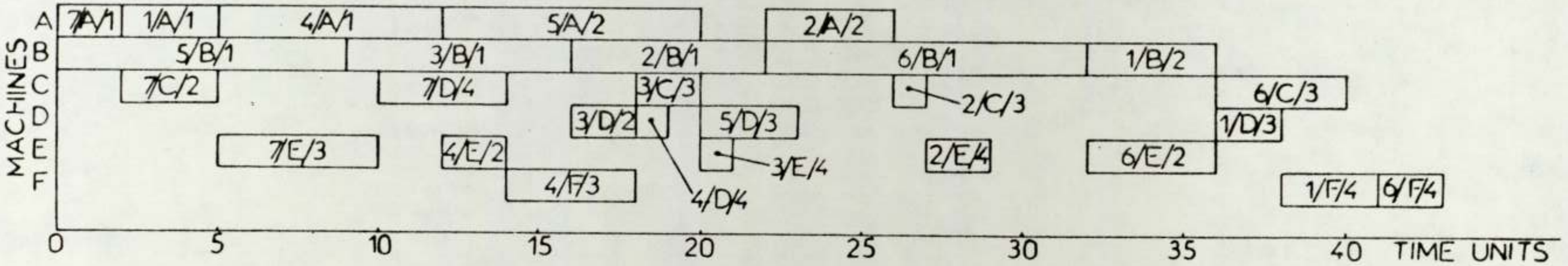
- i) the work load and labour capacity must not differ by more than 10%



(a) Proposed Rule Y



(b) Petrov's Rule III



(c) Petrov's Rule IV

C/M/O C = Component Number M = Machine Code O = Operation Number

Fig 6-4 Gantt Chart for Group Schedule

ii) Also the work load of each type of machine and its capacity must not exceed by more than the above percentage.

Step 3: If conditions (i) and (ii) are not satisfied, then adjustment or rearrangement has to be done on the list of components especially at the bottom end of the current period in order to obtain reasonable usage of capacity.

Step 4: In a production period, specify the machines according to work load with K_1, K_2, K_3 ..... K_s for all machines in the decreasing order of loads;
ie. K_1 has the highest loaded value and K_2 has the next highest and so on.

Step 5: For every component, the highest loaded machine (bottleneck machine) in the system utilised by the component is used to divide the operations of the component into two parts, and with the exception of those components being manipulated from the previous period due to the conditions (i) and (ii) in Steps 2 and 3.

Step 6: Calculate the parameter M_{i1} and M_{i2} for all the components.

Step 7: Compute the value of $(M_{i2} - M_{i1})$. This value is referred as priority index.

Step 8: Set up orders in which components are machined in sequence of decreasing differences of M_{i2} and M_{i1}, ie. $(M_{i2} - M_{i1})\downarrow$.
However, those components which have been manipulated from the previous period to the current period, then, they should be placed at the top priority according

to their order of increasing due dates. If ties occur, the following method is recommended;

a) If $(M_{i2} - M_{i1}) \geqslant 0$, then arrange components in the increasing order of M_{i1}.

b) If $(M_{i2} - M_{i1}) < 0$, then arrange components in the decreasing order of M_{i2}.

Step 9: Return to Step 2 for the rest of the long-term programmes.

6.4 Manual Scheduling Technique of Machines and Operators by Using Gantt Chart

There are quite a number of graphical forms of manual scheduling, such as network analysis, Gantt charts, matrices etc. One of the most widely known and effective means for manual scheduling is by means of Gantt charts (53). As this project is concerned with manual scheduling the Gantt chart technique is used to represent the schedule for both machines and operators. The machines and operators are listed in the left-hand vertical axis and time scale is listed on the horizontal axis, as shown in Figure 6-5.

In group scheduling, an operator is no longer assumed to be an integral part of a machine. He is allowed to move from machine to machine depending on the work load and nature of works. As such, there are in effect three variables to be considered, component operations, machines and operators. In the GT philosophy, the number of machines are normally greater than the number of operators in a group, consequently, some flexibility of operators will be required to operate different machines. In an ideal situation, the operators are completely flexible,

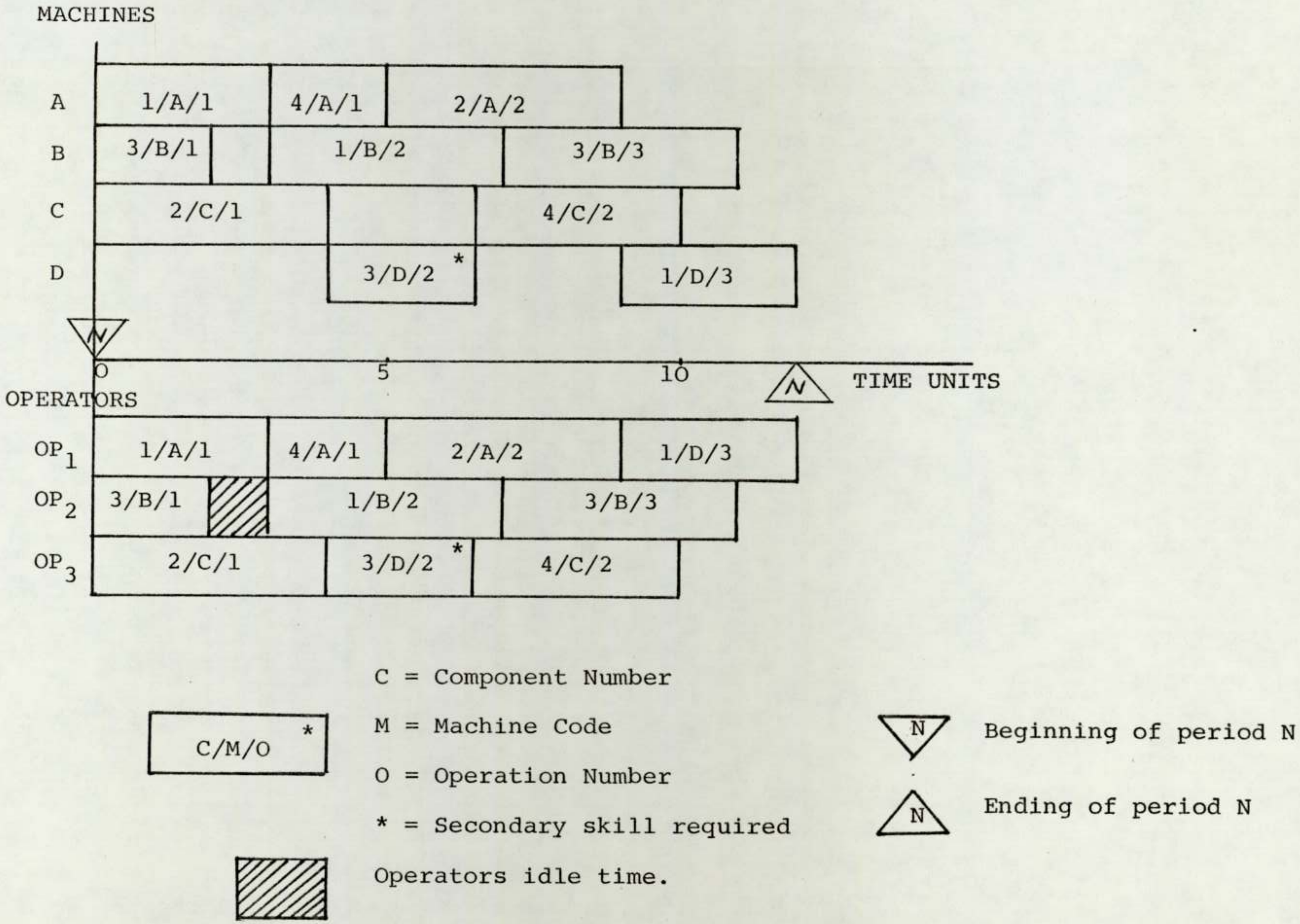


Fig 6-5 Schedule and Load Operators

ie. operators can operate all types of machines in the group. But, in the real-world it is not so. Certain constraints are imposed on the movement of operators such as skills of operators and union policies. Therefore, it is advisable to devise a technique for operator loading before scheduling is being carried out.

An operator in a group may have a variety of skills and different performances on each skill. For instance, the main skill of a turning operator is the turning operation but he may possess some secondary skills such as drilling and milling operations. But the performance of the secondary skill will not be as good as the main skill. So, when loading, the operators having the main skill must be assigned first before considering those having secondary skill. If all the operators having the main skill have been allocated and the machine is free for the available jobs, then operators having secondary skill will be taken into consideration.

In any case there are three basic situations to assign operators (8):

Case 1: $\text{OPCT} = \text{PST}$

Case 2: $\text{OPCT} < \text{PST}$

Case 3: $\text{OPCT} > \text{PST}$

where $\text{OPCT} \equiv$ Operator Completion Time

$\text{PST} \equiv$ Possible Start Time of Operator

The operator completion time is the completion time for the previous operation to be allocated to an operator. The possible start time is the time governed by the logical constraint of the operation and the availability of machine and some examples shown in Figure 6-5 are as follows;-

Possible start time of operation 1/A/1 = 0 time units
Possible start time of operation 3/B/1 = 0 time units
Possible start time of operation 4/C/2 = 5 time units.

Case 1, 2 and 3 represent the order of priority for which operations are considered for allocation to operators.
Case 1 is in first priority. If this situation is not possible Case 2 is considered, and if case 2 is not possible than the final case (case 3) is considered. The three different cases are illustrated by the following examples:-

Case 1. Operator Completion Time is EQUAL to Possible Start Time of Operator (OPCT = PST).

1a) If only one situation in which the operator completion time is equal to the possible start time exists (OPCT = PST) as shown in Figure 6-6, I and II, then the operation can be allocated to the operator.

1b) If more than one situation in which the operator completion time is equal to the possible start time exist (OPCT = PST) as shown in Figure 6-6, III then the operation is allocated in the following order of priority:-

   i) allocate operation to the operator who operates the preceding operation on the same component as shown in Figure 6-6 IIa.

   ii) allocate operation to the operator who operates the same machine as shown in Figure 6-6 IIIb.

iii) if none of the above situations occurs, then operation is to be allocated to any one of these operators.

Case 2. Operator Completion Time is LESS than Possible Start Time of Operator (OPCT $<$ PST).

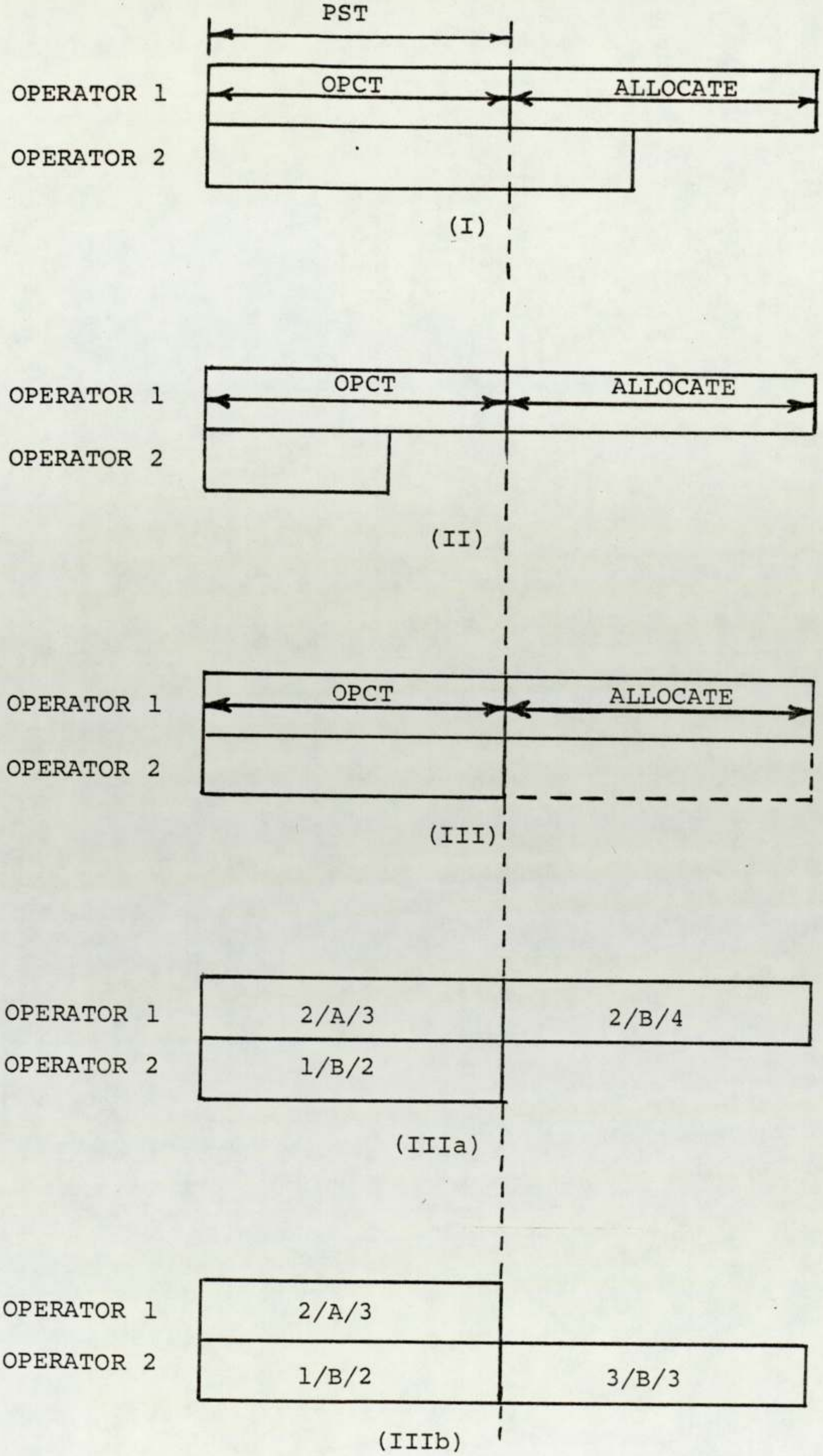
2a) If only one situation in which the operator completion time is less than the possible start time exists (OPCT $<$ PST) as shown in Figure 6-7 I, then operation can be allocated to the operator.

2b) If more than one situation in which the operator completion time is less than the possible start time exist (OPCT $<$ PST where OPCT's are not equal as shown in Figure 6-7 II), then allocate the operation to the operator with the maximum value of OPCT.

2c) If more than one situation where values of the operator completion time (OPCT) are equal and less than the possible start time (PST) exist (See Figure 6-7 III), then the operation is allocated with the order of priority as in Case 1(b).

Case 3. Operator Completion Time is GREATER than Possible Start Time of Operator (OPCT $>$ PST).

3a) If more than one situation in which the operator completion time is greater than the possible start time of operator exist (OPCT $>$ PST where OPCT's are not equal as shown in Figure 6-8 I), then allocate the operation to the operator with the minimum value of OPCT.



<u>Fig 6-6 OPCT = PST</u>

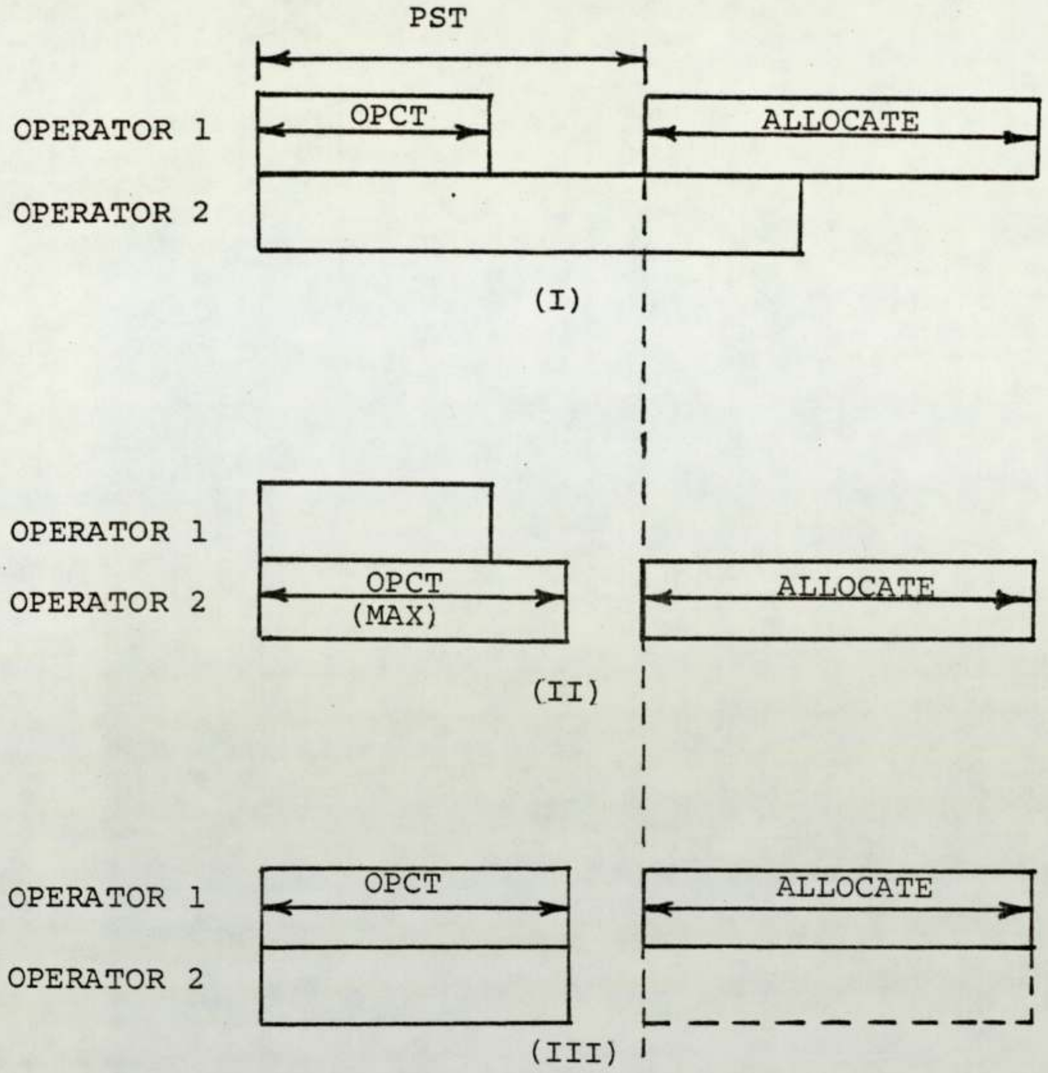


Fig 6-7 OPCT < PST

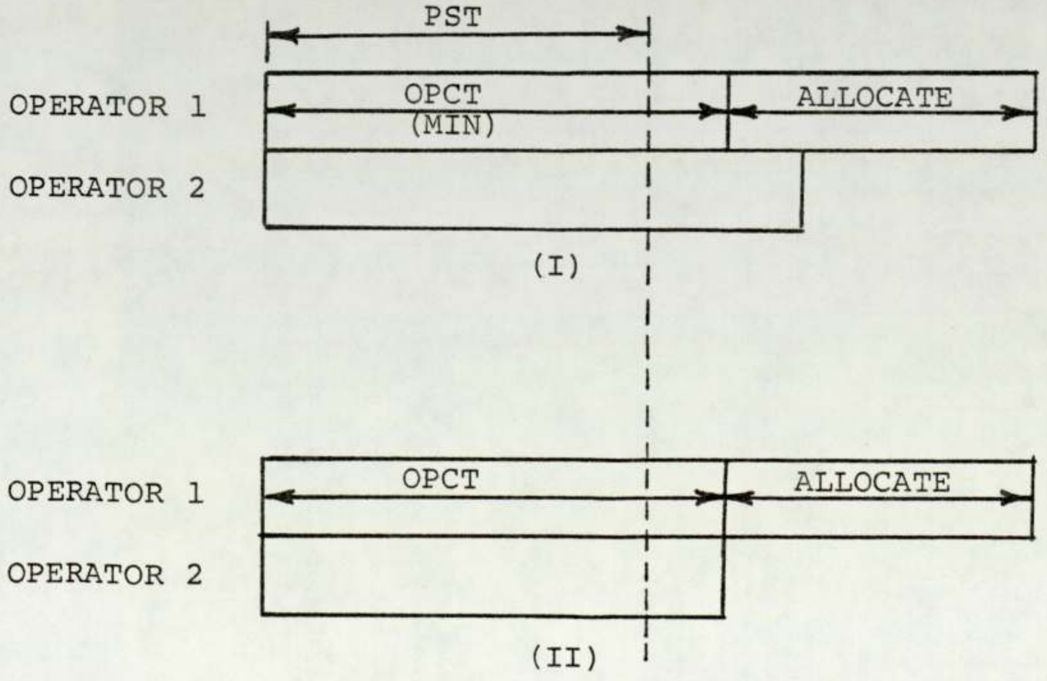


Fig 6-8 OPCT > PST

3b) If more than one situation where values of the operator completion time (OPCT) are equal and greater than possible start time of operator (PST) exist (see Figure 6-8 II), then the operation is allocated with the order of priority as in Case 1(b).

Having devised the technique of operator loading, the scheduling of machines and operators can be done as follows:-

1. Select the first operation of the component which is the first priority in accordance with the loading sequence determined by the rule used and assign to:-
   i) the respective machine;
   ii) tentatively allocate the respective machine taking account of precedence - to determine the possible start time (PST).
      a) Examine Case 1: If operation can be allocated, make firm tentative assignment (ii). If operation cannot be allocated go to (b).
      b) Examine Case 2: If operation can be allocated, make firm tentative assignment (ii). If operation cannot be allocated go to (c).
      c) Examine Case 3: Allocate operator and adjust tentative assignment (ii) accordingly.

2. If the operation has been allocated to any one of the three cases, then return to step 1 and repeat the precedures for

the first operations of the remaining components.

3. If all the first operations have been allocated, then repeat the procedures of steps 1 and 2 for the second and remaining operations of all the components.

The above procedures are illustrated by a case study in the following chapter.

CHAPTER SEVEN

CASE STUDY TO ILLUSTRATE THE PROCEDURES OF THE PROPOSED METHOD OF SCHEDULING AND LOADING

7.1 Company Background

The company under study manufactures machine tools and is totally committed to the group technology systems. There are 26 cells designed by the employee's engineers. Subsequent to a series of discussions, it was agreed that the existing layout was suitable for the proposed procedure. The cell for rotational components were suggested because of their larger size. Moreover, it was found that the rotational components exhibit a certain feature of high annual usage and low machining content.

The range of the rotational components was divided into three groups viz; Cell A, Cell B and Cell C. Cell A consisted of all components with diameter ranging from 2 inches to 4 inches which require the common machining processes such as turning, milling, grinding and drilling.

Cell B consisted of all components with diameter from 2 inches to 6 inches. The operations of Cell B include the basic machining process identical to Cell A plus additional processes such as Thread Milling, Cridan Automill, Hurth etc.

Cell C consisted of all components with diameter above 6 inches and require operations identical to Cell A.

In studying the performance of Cell A, a sample of 150 components was taken such that a six month production programme involving a total quantity of 19,210 units could be studied under observation.

7.2 Data Collection

The information provided by the company was as follows:

a) the component/machine matrix in the computer printout;
b) the component coding and classification number;
c) the machining unit time and set up time of each component;
d) the quantity of each component;
e) the number of machines required.

As the project was concerned with scheduling, the sequence of operation and due dates of the components are the essential information. However, this information could not be directly obtained. Hence, assumption and modification have had to be made in order to set up the final production programme.

Certain components from the given component/machine matrix have been deliberately omitted because they required only one or two operations. The quantity of components was found to be within the range of 14 to 787. The number of operations ranged from 3 to 9 and the average number of operations is five. There were eleven machines in the cell concerned. Out of which, five were turning machines, two drilling machines, two grinding machines, one milling machine and a keyseating machine. In order to have a homogeneous mix for the components, a random sampling technique was used such that the components were drawn randomly from a bag containing cards with numbers from 1 to 150. The sequence of the number being drawn represented the order of components in due dates. After this sampling process, the corresponding components were then renumbered from one to 150 accordingly.

The machines required to manufacture the components were given in the component/machine matrix, without including the sequence of operations. Therefore, the sequence of operations of each component has to be assumed. As the cell is the rotational one, most of the components would go through the turning machines before other machines. Hence, it is assumed that operations of each component would consist of a) turning operations and b) non-turning operations. Every operation required for each component was separately recorded on a card and subsequently divided into two groups a) and b) as above. The sequence of operations for each component was then determined by the sampling method. In this case, the sampling method was carried out by drawing the cards randomly first in group a), and later in group b). The final six months production programme with the sequence of operations for 150 components is shown in Appendix I.

7.3 Workload and Operator Required

The summary of the workload of each machine is given in Appendix II. It is assumed that there are 24 working weeks in the six month period. There are five working days in a week with 8 hours per shift. The cell is running at one shift per day. Therefore the standard capacity of a machine with an effective performance of 75% a week is determined as follows:

The effective machining capacity of a machine in a week
= 5 x 8 x 75% hours
= 30 hours
= 1800 minutes
= 18 time units*

* NOTE: In the remaining sections, 1 time unit = 100 minutes, unless otherwise stated.

Hence, the effective machining capacity of a machine for six months is 432 time units (24 x 18 time units). The theoretical machine utilisation of a machine can be calculated from the following equation:-

$$\text{Machine Utilisation} = \frac{\text{Total Workload}}{\text{Effective Machining Capacity}} \times 100\%$$

For instance, by using the above equation, the theoretical machine utilisation of machine A as shown in Appendix II can be determined as follows:

Theoretical machine utilisation of machine A

$$= \frac{35950 \text{ min}}{43200 \text{ min}} \times 100\%$$

$$= 83.2\%$$

The number of operators required is determined by the total workload of the long-term programmes. It is assumed that each operator works 8 hours a day in 5 working days per week. The effective performance of an operator in a week is determined as follows:-

The effective capacity of an operator in a week

= 5 x 8 x 75% hours

= 30 hours

= 1800 minutes

= 18 time units.

Hence, the effective capacity of an operator for six months with 24 working weeks is 43200 min. The number of operators, N, for a cell is determined by the long-term workloads and the effective capacity of the operator. Their relationships are shown by the following equation:-

$$\text{Number of Operator, } N = \frac{\text{Total Workload}}{\text{Effective Capacity of an Operator}}$$

Therefore, the number of operators required by the simulation project can be determined by using the above equation;

$$\begin{aligned} N &= \frac{303100 \text{ min}}{43200 \text{ min}} \\ &= 7.01 \\ &= 7 \text{ operators.} \end{aligned}$$

In this case, seven operators are required by the cell. The standard labour capacity of the cell in a week is 126 time units (7 x 18 time units) which is one of the constraints for short-term periodic production programmes. The numbers of each type of operator required are determined by the total utilisation of each machine type. For instance, the half annual usage of turning machines is 413.4% (Appendix II) and therefore, four turners are required. The number of type of machines and operators required, the effective capacity and utilisation of machines are given in Appendix II.

Having determined the labour capacity, the long-term production programme (Table 7-1) can be broken down into short-term periodic production programmes by using the precedures detailed in the previous chapter. Appendix III shows that there are 25 periods of short-term periodic production programmes together with the sequence of components determined by different rules. Each production period is equivalent to one week.

7.4 Experimental Conditions and Assumptions

Unless otherwise stated, the simulations are based on the following conditions and assumptions:-

1. The cell consists of eleven machines with two identical machines (C_1 and C_2) and the cell is able to handle all the incoming orders.
2. No machine has the similar machining function, except the duplicated turning machines C_1 and C_2.
3. Each component may go through different number of operations which vary from three to nine stages.
4. The machines required for each component have been predetermined.
5. The operation sequence for each component will be predetermined and fixed.
6. Two consecutive operations on the same machine were not permitted.
7. The processing is assumed to include operation time and set up time.
8. Each operation, once started, must be performed to completion; ie. no pre-emption was allowed.
9. An operation will only be started after the batch quantity has been completed by the preceding machine.
10. All components are available simultaneously in each period.
11. Machines do not breakdown
12. Material required has been pre-planned and there was no

shortage of material.

13. The labour force in the cell has been pre-planned and fixed (seven operators).
14. Operators are capable of setting up machines which they operate.
15. Operators can operate more than one machine; but certain constraints are specified in Table 7-1.

In order to compare the three heuristic rules (the proposed heuristic rule Y and Petrov's heuristic rules III and IV) with identical conditions, each rule would include the same set of components in such a way that the batches of components arrived at the same time in the same period. The method of operator loading was applied in the similar way to the three heuristic rules. The only thing that changed in each period was the order in which the components were processed on the various machines as determined by the heuristic rule employed.

7.5 Analysis and Discussion of the Simulation Run

7.5.1 The Steady State and Transient Periods

The mathematical model as outlined earlier was constructed in Gantt charts (Appendices IV, V, VI) with the use of Petrov's heuristic rules III and IV and the proposed heuristic rule Y. For the puspose of illustration, Appendix VI with 3 periods (periods 8, 9 and 10) was enlarged as shown in Appendix VII to show the procedures of loading and order of manufacture for each machine together with the operator.

Type of Operator	Main Skill	Secondary Skill
Turner (TO)	Turning Operation	Drilling Operation Milling Operation
Driller (DO)	Drilling Operation	
Miller (MO)	Milling Operation Keyseating Operation	Drilling Operation
Grinder (GO)	Grinding Operation	Drilling Operation Milling Operation

Table 7-1 Operator Constraints

From Appendices IV, V and VI, it can be seen that in each Gantt chart there are two transient periods; ie.

i) the initial run-in-period at the beginning of the schedule until a steady state of loading of operator is achieved,

ii) the run-out-period of the schedule from a steady state to the end of activity.

These two transient periods are the unstable states. But, for a fair measurement of performance and comparison, they should be excluded. Therefore, only the period of steady state between these two transient periods were taken for the measurement of performance and comparison. The periods of steady state and the two transient periods of each Gantt chart are given in Appendix VIII.

7.5.2 Operator Utilisation

A summary of operators' idle times, utilisation percentage and the secondary skills required is given in Appendix IX. It can be seen from the table that the operators' idle times scheduled by Rule Y is slightly less than that of the Petrov's Rules III and IV. Consequently, the overall percentage of utilisation of operator scheduled by Rule Y (81.88%) is higher than that of Petrov's Rules III (80.42%) and IV (80.96%). These different rules exhibit a fairly high percentage of utilisation of operator and this is one of the desirable aims of group technology systems. From Appendix II and Appendix V, it can be seen that the machine types with high percentage of utilisation are associated with the corresponding high percentage of utilisation of operator. So, it is important that a detailed loading analysis has to be done before forming families of components to feed the machines in the cell.

Appendix IX also shows the secondary skill required by operators. They are almost identical. The total time required to operate secondary skill operations in Rule Y is 200.0 time units and in Petrov's Rules III and IV are 221.0 and 221.6 time units respectively. These figures account for about 6% of the total operators' utilisation times. This shows that the approach of the method to determine the number of types of operator required is quite satisfactory.

7.5.3 The Throughput Time and Work-in-progress

The throughput time of each rule is shown in Appendix X. The mean (average) throughput time of Rule Y is 47.86 time units and the mean throughput times of Petrov's Rules III and IV are 48.12 and 48.00 time units respectively. This situation is shown in graphical display in Appendix XI.

It can be seen from the Appendix XI that there are few surges in the graph for all three different rules employed. The surge in Period 14 is due to the machine F which had been overloaded beyond the condition (ii) as stated in the previous chapter for short-term periodic production programmes. The workload of maching F is 21.1 time units which is 17.2% greater than the standard capacity (18.0 time units) where the allowable variation is 10%.

The surge on Periods 16 and 21 are due to the overloading of the grinding machines H and I. The total load of H and I were found to exceed the labour capacity by 35% in Period 16 and by 11.7% in Period 21. These two percentages are above the allowable limit (10%).

The surge on Period 18 is due to a higher than the normal number of operations required for component 110. It consists of nine stages of operation which are very much higher than the average number of stages, usually five, required for the components.

The above analysis shows that the throughput time of each period will be affected by the machine and labour capacities and the number of operations on the components. The machine and labour capacities are considered as controllable factors. The surges on the Periods 14, 16 and 21 are deliberately done to show that work load must be matched with machine and labour capacities when forming short-term production programmes. The number of operations on components depends on the nature of the component which normally cannot be controlled by scheduling techniques. However, this factor can be adjusted in the design department for a number of possible combinations in order to reduce the number of operations for the component.

Appendices XII and XIII show the cumulative (total) throughput time of the simulation run. The total throughput time of 25 periods is 549.4 time units by Rule Y, 563.5 and 552.9 time units by Petrov's Rules III and IV respectively. The 'humps' in the curves (Appendix XIII) are caused by the same reasons on the mean throughput time as described in the previous paragraphs.

From the 25 periods schedule, the results show that the total and mean throughput time of Rule Y are slightly less than Petrov's Rules III and IV. Since Petrov proves that his rules will give consistent solution within 10% of the theoretical optimal solution in terms of throughput time, therefore, it can also be said that Rule Y will produce solution within the same limit of 10%. Moreover, Rule Y is also a manual scheduling method which requires little computational effort. It can be carried out in a cell by foreman or group leader with a desk calculator. With the help of visual loading board, the Gantt chart can be easily laid out for constant checking of loading situation.

The shorter throughput time produced by Rule Y will allow a much simpler system to be used and thus enable a reliable delivery date to be achieved. Consequently, the work-in-progress would be reduced owing to the shorter throughput time. Moreover, it can be seen in any of the Gantt charts (Appendices IV, V and VI) that further reduction of work-in-progress can sometimes be achieved by using free float of operator and machine. This can be achieved by delaying the starting time of the operation by a certain number of time units equal to free float duration without affecting the finishing time of the overall operations. For instance, the job 59/B/1 (see appendix VII) starts at 190.6 time units and could have been delayed to start at 193.2 time units without affecting the later operations. Such advantage can be easily obtained, especially for short-term scheduling, by using some visual loading board.

Further improvement of throughput time and work-in-progress can sometimes be obtained by rearranging the few jobs at the end of the operation period. For instance, if the sequence of job 90/F/5 (See Figure 7-1c) was interchanged with job 92/F/5, the throughput time of the Period 15 will be 335.9 time units instead of 337.1 time units. Normally, this type of manipulation can be done after the Gantt chart has been laid out using the rule employed.

The above model is based on the assumption that all operators are capable of setting up machines which they operate. If this assumption is not valid, ie. operators cannot set up the machines, then special setters will be required in the cell. In this case, the extension of the Gantt charts to include setters might be possible in order to make sure of the availability of setters to get the machines ready set before the operators can carry out the operations.

7.6 The Possibility of Applying Rule Y to Group Flow-Line System

An optimal algorithm for solving group flow-line scheduling problems has been recently published by Hitomi and Ham (5). They used the branch and bound method to obtain the optimal family sequence and job (component) sequence (See Table 7-3a) of an example. The basic data of the example is given in Table 7-2. The optimal throughput time of this problem is 1031 time units (See Figure 7-1a). They also used Petrov's heuristic rule to schedule the same problem. The family sequence and job sequence for the near-optimal solution by Petrov's rule is given in Table 7-3b. Figure 7-1b shows that the throughput time of the Petrov's solution is 1091 time units.

For further illustration, Rule Y has been applied using the same data as the above example to test if it is applicable in group flow-line system. With a slight modification, Rule Y can also be used to obtain a 'good' family sequence. The procedure is as follows: first determine the highest loaded machine by adding up the total processing time of each machine for all families. In this case, machine 4 or stage 4 is the highest loaded machine. By using stage 4 as a common stage divide the processing time of each family into two parts; ie. (i) stage 1 to stage 4 and (ii) stage 4 to stage 5. Then Rule Y is applied to determine the family sequence. The calculation of family sequence is shown in Table 7-4 and the calculation of job sequence is given in Table 7-5. A summary of family sequence and job sequence determined by Rule Y is given in Table 7-6. The solution is found to be 1075 time units from Gantt Chart (Fig 7-1c). By comparing the results obtained using Petrov's Rule and Rule Y with the optimal solution, the corresponding percentage error can be determined and is shown in Table 7-7.

It can be seen from the Table 7-7 that both Petrov's Rule and Rule Y could produce reasonably good solutions with percentage error of 5.82% and 4.27% respectively. Both of these rules require little computational effort. Perhaps, this is one of the many reasons why heuristic and priority rules are used in industry to obtain near-optimal solution rather than using exact algorithms with a large amount of computational cost and time to obtain optimal solutions.

At this stage, it is difficult to confirm that Rule Y is better than Petrov's rules based on one simulation result. It is suggested that further research work is carried out to obtain more information regarding the relative merits of Rule Y in group flow-line system.

Family No.	Job No.	Set-Up and Process Time	STAGE NO.				
			1	2	3	4	5
G_1		S_{1K}	30	15	25	30	10
	J_{11}	P_{11K}	41	65	39	79	52
	J_{12}	P_{12K}	75	75	68	71	61
	J_{13}	P_{13K}	32	25	62	73	54
CAPACITY REQUIRED			178	180	194	253	177
G_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
CAPACITY REQUIRED			208	143	182	202	258
G_3		S_{3K}	15	25	30	20	10
	J_{31}	P_{31K}	29	55	46	37	31
	J_{32}	P_{32K}	26	20	37	51	28
	J_{33}	P_{33K}	72	66	40	47	62
CAPACITY REQUIRED			142	166	153	155	131
G_4		S_{4K}	25	30	10	25	35
	J_{41}	P_{41K}	47	71	29	38	24
	J_{42}	P_{42K}	27	69	42	75	57
	J_{43}	P_{43K}	78	45	73	74	29
	J_{44}	P_{44K}	22	42	35	68	17
CAPACITY REQUIRED			199	257	189	280	162
TOTAL CAPACITY REQUIRED			727	746	718	890	728
MACHINE LOADED VALUE ORDER			K_4	K_2	K_5	K_1	K_3

Table 7-2 Set-up and Process Time of the Example

FAMILY SEQUENCE	JOB SEQUENCE
G_4	J_{44} J_{42} J_{43} J_{41}
G_2	J_{21} J_{22} J_{23} J_{24}
G_1	J_{13} J_{12} J_{11}
G_3	J_{33} J_{31} J_{32}

Table 7-3a The Optimal Family and Job Sequence

FAMILY SEQUENCE	JOB SEQUENCE
G_2	J_{22} J_{21} J_{23} J_{24}
G_1	J_{13} J_{11} J_{12}
G_4	J_{44} J_{42} J_{43} J_{41}
G_3	J_{32} J_{33} J_{32}

Table 7-3b The Family and Job Sequence by Petrov's Rule

MOST HIGHEST LOADED M/C:STAGE 4				
FAMILY No.	M_{i1}	M_{i2}	$M_{i1}-M_{i2}$	GROUP SEQUENCE
G_1	805	430	-375	G_2
G_2	735	460	-275	G_3
G_3	616	286	-330	G_1
G_4	925	442	-483	G_4

Table 7-4 Family Sequence by Rule Y

FAMILY No.	M_{i1}	M_{i2}	$M_{i1}-M_{i2}$	JOB SEQUENCE
G_1	223	131	-92	2
	289	132	-157	3
	192	127	-65	1
G_2	209	55	-154	2
	211	64	-147	1
	262	62	-200	4
	211	52	-159	3
G_3	84	169	+85	2
	46	136	+90	1
	138	215	+77	3
G_4	185	62	-123	3
	213	132	-81	1
	270	103	-167	4
	167	85	-82	2

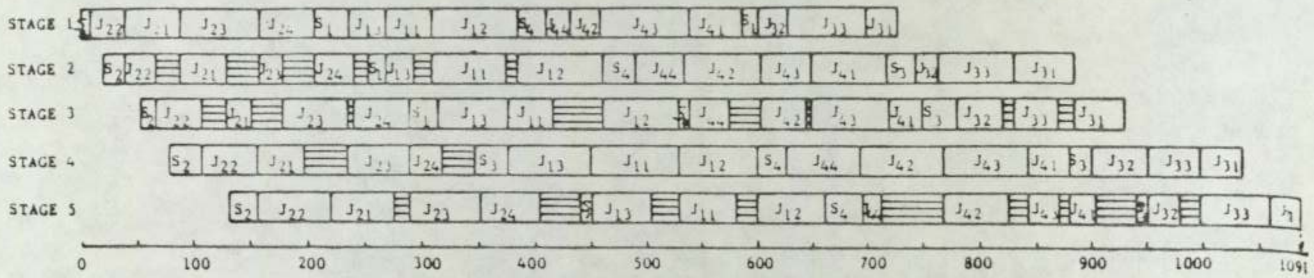
Table 7-5 Job Sequence by Rule Y

FAMILY SEQUENCE	JOB SEQUENCE
G_2	J_{22} J_{21} J_{24} J_{23}
G_3	J_{32} J_{31} J_{33}
G_1	J_{13} J_{11} J_{12}
G_4	J_{42} J_{44} J_{41} J_{43}

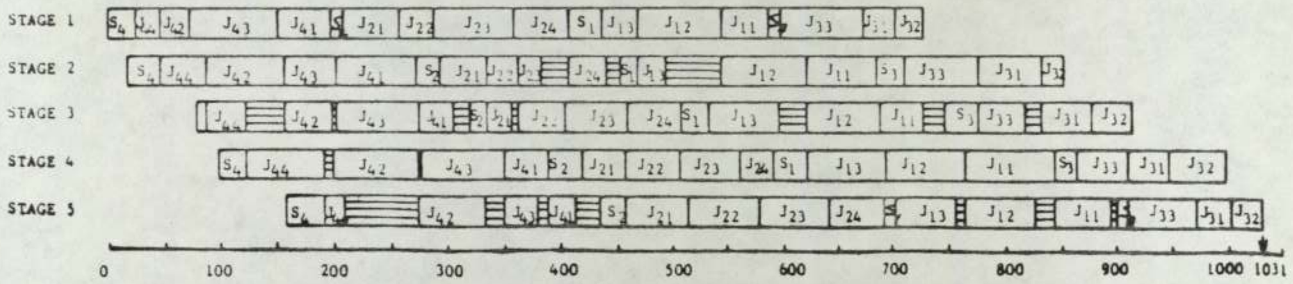
Table 7-6 Family and Job Sequence by Rule Y

	Throughput Time	Error (%)
Optimal	1031	0.00
Petrov	1091	5.82
Rule Y	1075	4.27

Table 7-7 Percentage Error with known Optimal Solution



(a) Petrov's method for near-optimal group schedule



(b) Branch and bound method for optimal group schedule

Fig 7-1 Gantt Charts for Optimal Schedule

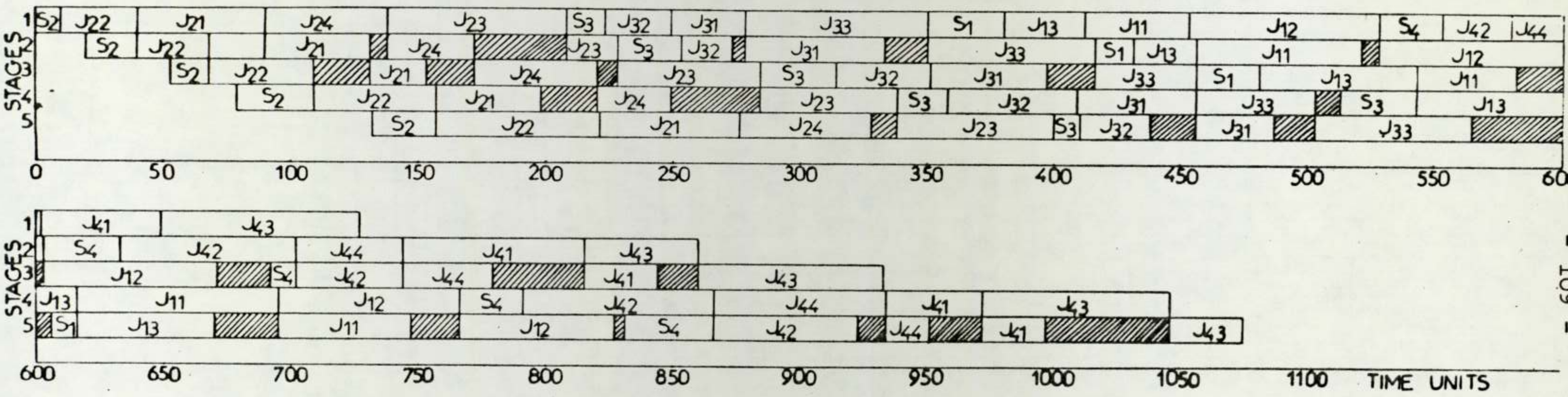


Fig 7-1c Gantt Charts for Group Schedule by Rule Y

CHAPTER EIGHT

CONCLUSION

1. As the proposed scheduling method is a heuristic method, it would not guarantee an optimal answer, but it will produce a 'good' one. This was supported by the comparison between the proposed method and Petrov's method which claimed to be within 10% of the theoretical optimum in terms of throughput time.

2. The proposed method required little computation effort. The scheduling method can be carried out in each cell by the forman or group leader with a simple desk calculator.

3. As the operation sequences are varied for each component, in order to reduce set up time, it is essential to design group tooling which could accept a number of components such as composite component principles.

4. In order to maximize operator utilisation, the sequencing of batches for manufacture is essential.

5. To cater for the manual scheduling problem of flexibility of operator, a formal method for operator loading is required. The Gantt chart is found to be a suitable tool for this purpose which is simple to operate as shown in the project.

6. The method for operator loading is found to be suitable for manual scheduling in both proposed rule Y and Petrov's rules.

7. The Gantt chart technique is also a useful tool for obtaining information regarding degree of flexibility of operator which can be used as information for plant layout purposes.

8. The flexibility of operator must require the cooperation of the trade unions and the skill requirements of the various jobs must not be excessive.

9. The movement and the duration of movement of the operator depends on the arrival job and its operation requirements; eg. when it is physically impossible to work at a machine, the operator moves to a machine where work is possible. But normally operators with a high level of skill and experience are not subject to flexible manning arrangements.

10. As each cell can be considered as a synthetic machine, the work content of a cell is determined by the key machines and the labour force of the cell. This greatly simplifies the scheduling and loading process. The production controller's job is to issue work and material at the right time and monitor the output of each cell to record completion. This will increase the delegation of decision making to the shop floor, such as material flow decision, decisions involved due to additional functions, and administrative decisions.

11. The results of mean throughput time, total throughput time and utilisation of operator by the proposed Rule Y

are found to be as good as or better than the established Petrov's rules.

12. The shorter and stable throughput time will undoubtedly allow a much simpler and effective production control system to be used and thus enable a reliable delivery date to be achieved.

13. In a given workload with a fixed labour force, the minimisation of throughput time will indirectly maximise the labour utilisation and will also reduce work-in-progress.

14. Further improvement of throughput time and work-in-progress can sometimes be obtained by rearranging the few jobs at the end of the operation period.

15. The reduction of work-in-progress can sometimes also be achieved by using free float of operator and machine. This can be easily obtained, expecially for short-term scheduling, by using some visual loading board.

16. The throughput time of each production period is affected by the machine and labour capacities. Therefore, in each period, the workload must be matched with the machine and labour capacities, otherwise, unnecessary long throughput time will occur.

17. The number of operations on a component is also one of the functions of throughput time. Rationalisation of

the design will help reduce throughput time.

18. Machine types with a high percentage of utilisation are normally associated with the corresponding high percentage of utilisation of operator. Therefore, it is essential to analyse the workload before determining the type and number of operators required.

19. The proposed scheduling rule seems to be applicable in group flow-line systems, but it needs further research to obtain more information regarding the relative merits of it.

CHAPTER NINE

RECOMMENDATIONS FOR FUTURE WORK

The main objectives of the present work are to develop a heuristic rule to schedule workload and assign operators in a GT cell. Some group technology systems have been developed to the more advanced stage, ie. the group flow-line system, and it is an interesting area in which to investigate some scheduling rules. The model example that has been dealt with in this work can be used as a starting point. The proposed rule was tested in an example by Hitomi and Ham (5). The result turned out to be quite promising with only 4.27% of percentage error which is slightly better than the established Petrov's rule (5.82% of percentage error). But it is difficult to confirm that the proposed rule is better than the Petrov's rule based on one simulation result. Further research work should be carried out to obtain more information regarding the relative merits of the proposed rule in group flow-line system.

The present work is concerned with the flexibility of operator within a cellular group, but owing to the union policies and operators' skill, the mobility of operator may sometimes be limited and thus reduce the advantage of the utilisation of operator. Therefore, flexibility of operator between cellular group is an area which deserves future investigation in either GT cell or group flow-line system. In addition, if setters are required for setting up machines, a different setter scheduling chart might be required to match with the scheduling chart of operators. This is one of the interesting areas for future study.

A further point for future investigation would be studying the problem of the under-utilisation of secondary or supporting machines. Sharing secondary machines between cells to raise machine utilisation may require further analysis.

APPENDICES

APPENDIX I

Table showing Long-term (Six-month) Production Programme.

(All Figures are in Time Units)

KEY

P_n: where P = Processing Time

n = Operation Sequence Number

APPENDIX I

machines / components	A	B	C	D	E	F	G	H	I	J		Batch sizes	Total Processing Times
1	2.3_3		2.7_2	2.9_1		4.5_5		2.5_4	0.7_6			36	15.7
2	2.3_1		5.2_2				5.3_4	3.7_3				46	16.5
3	2.6_2	2.5_1		7.3_3	2.3_5		2.0_6			1.0_4		100	17.2
4	2.2_2	2.2_1		3.1_3			1.5_6	1.7_4	1.4_5			46	12.1
5			9.2_1		3.7_5		1.8_2		1.2_3	3.6_4		102	19.5
6	3.8_2		12.9_1		4.1_3				2.3_4			196	23.1
7	2.7_2			5.5_1		3.1_4	4.5_3			1.8_5		123	17.6
8	2.3_1	2.1_3	4.0_2		1.9_6		2.2_4	2.7_5				128	15.2
9	2.5_2		6.1_1			5.9_3		2.5_4	1.0_5	0.3_6		72	18.3
10			14.1_1		4.5_3				2.2_2			196	20.8
11	2.7_2		5.4_1		2.2_3		6.9_4			2.1_5		96	19.3
12	2.9_2		6.5_1			5.8_3	2.4_4			1.4_5		118	19.0
13	3.3_3	2.6_1	5.1_2			3.3_5		7.1_6		0.4_4		14	21.8
14	2.4_2		6.3_1				2.8_3	4.3_5	1.5_4			72	17.3
15	2.4_1		8.7_2				4.9_3	2.3_4		2.0_5		59	20.3

machines / components	A	B	C	D	E	F	G	H	I	J		Batch sizes	Total Processing Times
16		2.4_1		6.9_2	1.6_5		9.2_3		1.3_4			72	21.4
17	2.5_1	2.3_2	8.0_3			2.8_5			1.7_4			154	17.3
18		5.8_2		10.8_1					1.7_3			170	18.3
19	2.4_2	2.7_1	8.3_3		2.1_5		2.0_6		2.6_4			72	20.1
20	3.9_2	3.8_3	3.9_1		1.7_5		1.1_6	1.3_4	0.6_7	0.7_8		36	17.0
21		4.1_1	3.8_2	2.0_3	2.8_4		1.9_6		0.8_5			42	15.4
22		4.0_1			8.4_3		5.5_4		4.4_2			409	22.3
23	2.3_2		6.0_1			2.6_3		1.5_5	1.4_4			72	13.8
24	2.3_2		5.0_1			2.8_3	6.9_4	3.7_5	0.8_6			155	21.5
25		6.3_2	6.2_1			3.2_5	5.4_3	1.4_4	2.2_6			115	24.7
26		4.1_1	10.3_2		8.7_3	6.2_4				1.8_5		424	31.1
27	5.3_2	5.2_1		5.4_3		3.2_5				1.7_4		115	20.8
28			10.5_1			2.3_3	3.4_4		1.6_2			59	17.8
29	2.4_2	2.8_3	11.6_1		4.2_4				4.3_5			110	25.3
30	2.3_2		3.8_1			2.9_4	7.3_5	2.3_3				36	18.6

APPENDIX I (contd)

machines / components	A	B	C	D	E	F	G	H	I	J		Batch sizes	Total Processing Times
31	2.4_3	2.4_1	8.7_2			1.6_4	1.6_5					72	16.7
32	2.3_1			3.7_2	2.0_3		2.9_5	1.8_4		0.9_6		59	13.6
33	2.8_1		8.4_2		5.0_3			2.9_4				112	19.1
34	2.3_1	2.4_3	8.0_2		3.5_4			2.6_5				72	18.8
35	3.8_1			6.2_2		10.8_4		2.9_3				196	23.7
36	2.5_2	2.7_1	6.0_3				1.9_5	6.3_4				108	19.4
37	3.8_1		8.6_3	8.6_2		3.2_5				1.3_4		198	25.5
38	2.4_1		6.1_2			5.2_3		2.6_5	1.7_4			59	18.0
39	3.6_2			7.3_1		5.4_5	1.9_3			1.2_4		156	19.4
40			10.6_1		1.7_3	3.1_2	1.6_5		1.9_4			148	18.9
41	2.4_1		4.0_2		3.1_3	5.2_4		1.3_5	1.3_6			110	17.3
42	3.1_3	3.1_2		10.0_1				4.6_4		1.6_5		111	22.4
43	2.9_2	3.0_1	6.8_3					3.2_4	3.9_5			102	19.8
44		3.1_1		8.6_3		5.5_2						202	17.2
45	2.6_1	2.6_3		5.2_2	1.7_5		2.4_4	0.6_7	2.0_6			59	17.1

APPENDIX I (contd)

machines / components	A	B	C	D	E	F	G	H	I	J		Batch sizes	Total Processing Times
46	2.9_1		8.0_2		3.3_5		1.9_3			1.6_4		108	17.7
47	4.0_1		8.4_3	7.9_2					2.7_4			131	23.0
48		9.0_1		4.3_2		2.1_3	1.3_4	1.9_5				130	18.6
49	2.8_1		14.8_2		2.4_4				2.9_3			110	22.9
50	2.5_2			4.6_1		10.3_4		1.5_3	1.0_5			72	19.9
51	2.4_3	2.3_2		1.4_1		2.8_7	6.4_6	1.0_8	0.8_5	0.4_4		54	17.5
52	3.6_1		5.9_2				3.9_4		2.9_3	3.0_5		222	19.3
53	2.2_1		10.6_2			2.0_5		2.0_3	0.7_4			54	17.5
54	2.8_1	2.7_2		11.5_3			2.2_4		1.5_5			133	20.7
55	2.8_2	5.2_1	5.8_3			2.8_5	3.2_6			1.0_4		132	20.8
56	2.3_3	2.3_2	5.8_1		2.7_4			1.7_5	4.5_6			59	19.3
57	2.2_1		8.0_2					1.9_4	1.1_3			32	13.2
58	2.6_1		8.8_2		2.1_5	3.5_4		2.3_3				72	19.3
59	5.9_2	3.2_1		10.6_3	1.4_5				1.3_4			110	22.4
60	2.4_1			3.7_4	3.8_5		2.4_3	1.6_6		1.2_2		59	15.1

APPENDIX I (contd)

machines / components	A	B	C	D	E	F	G	H	I	J		Batch sizes	Total Processing Times
61				5.0_1		4.7_5	2.8_4	3.0_3	2.9_2			59	18.4
62	4.7_2			8.0_1	6.3_4				2.1_3			196	21.1
63	4.3_3	3.8_1		12.2_2					1.7_5	2.6_4		96	24.6
64	2.6_2	2.7_1	3.8_3		4.2_4	5.2_5			1.3_6			111	19.8
65		2.8_1		11.9_2		5.7_4			1.7_3			156	22.1
66	2.3_1	2.3_3	7.3_2		2.0_5				4.5_4			59	18.4
67	2.4_3	2.2_2		4.3_1	2.3_7		1.9_5	1.7_4	2.1_6			46	16.9
68	2.6_1		6.8_2		3.2_5		2.0_3	1.2_4				115	15.8
69	2.5_2	2.4_3	6.9_1			4.1_5		1.9_4		0.7_6		72	18.5
70		11.5_1			6.9_3		4.6_2					334	23.0
71		7.7_2	5.5_1		3.5_5	1.4_4			1.3_3			72	19.4
72	5.4_1	4.7_3		3.6_2		2.3_4	2.0_5					72	18.0
73	2.3_1		7.9_2			1.4_3	2.7_5	1.0_4		2.7_6		54	18.0
74	2.3_1		5.7_2			3.2_5		3.7_4	0.5_3			36	15.4
75	6.5_2			5.1_1		5.7_3	6.6_4					497	23.9

machines / components	A	B	C	D	E	F	G	H	I	J		Batch sizes	Total Processing Times
76	3.5_3	6.2_1	7.5_2		6.2_5				3.2_4	0.4_6		28	27.0
77	2.9_2	3.2_3	8.1_1			1.9_5		$13._4$				116	17.4
78	2.6_2	2.9_1		14.3_3			2.1_5		1.4_4			223	23.3
79	2.7_2	2.6_3	7.7_1		4.5_4	3.2_5						102	20.7
80	6.0_2		10.1_1		3.2_4				1.5_3			108	20.8
81	2.8_2			4.7_1	3.9_4		4.9_3			2.0_5		102	18.3
82	2.4_1		9.7_2		3.8_4			1.3_5	0.8_3			59	18.0
83	5.5_3	5.7_1		3.6_2		4.1_4	1.5_6		0.9_5			72	21.3
84	2.3_2		5.0_1				3.0_5		3.0_4	0.9_3		100	14.2
85	7.5_2		7.8_1			3.6_5	4.9_6		1.3_3	0.6_4		72	25.7
86	2.9_2	5.0_3		3.6_1		6.9_5		2.3_4	1.7_6			172	22.4
87			7.6_1				10.0_3		8.0_2	2.5_4		178	28.1
88		2.6_2		6.6_1		6.5_4			2.7_3			110	18.4
89		3.0_1	12.4_2		4.2_3				2.3_4			198	21.9
90	7.9_3	3.8_2		5.5_1		4.4_5			1.7_4			133	23.3

APPENDIX I (contd)

machines / components	A	B	C	D	E	F	G	H	I	J		Batch sizes	Total Processing Times
91		13.4_1			2.2_3	3.2_4		6.0_2				100	24.8
92	2.4_2	2.5_3	9.2_4	4.9_1		2.4_5			1.2_6			108	22.6
93	4.1_1			12.1_2			5.7_4		3.2_3			424	25.1
94	2.5_2	4.6_1	10.4_3		2.9_4			2.4_5				133	22.8
95	2.2_1		3.3_2				12.3_3	0.8_4	0.5_5			128	19.1
96	3.5_3	2.4_1		3.1_2		1.6_7	7.0_6	2.4_5	1.1_4			108	21.1
97	2.6_1		10.5_2		2.6_3					1.7_4		115	17.4
98	2.4_2		7.8_3	6.1_1		4.8_4			1.8_5			100	22.9
99	3.8_1				7.4_2			9.6_3				359	20.8
100			10.3_1		5.8_3	4.4_2			1.4_4			133	21.9
101		7.5_1	8.6_2				3.0_4		3.8_3			198	22.9
102		11.7_1			2.1_3		1.8_5		4.1_4	1.4_2		96	21.1
103	2.7_1	2.8_3	6.0_2			2.0_5			1.8_4			108	15.3
104	4.0_1	4.0_2			8.4_4		7.1_3		4.7_5			409	28.2
105	2.9_1		7.4_2		3.1_4	2.4_3	6.4_5					206	22.2

machines / components	A	B	C	D	E	F	G	H	I	J		Batch sizes	Total Processing Times
106	3.2_3	3.4_1	8.9_2		2.7_4				1.7_5			123	19.9
107	2.8_1		11.1_2		3.8_5	3.5_4				0.4_3		28	21.6
108	2.4_2	2.9_1	2.9_3		4.7_5		1.9_4		2.4_7	1.0_6		108	18.2
109	9.3_2	2.5_3		7.2_1	2.2_4		1.8_5		1.4_6			100	24.4
110	2.6_2	2.3_1	2.8_3	3.3_4		1.4_5	5.6_6	2.2_9	0.7_8	1.3_7		14	22.2
111	3.4_1		13.3_2		6.9_4		5.2_3					202	28.8
112	2.6_2		11.8_1				3.6_4			1.8_3		123	19.8
113	2.3_1		2.9_2		1.9_3		4.5_5	3.6_4		0.4_6		28	15.6
114		3.3_2		9.6_1	7.3_4		3.7_3					256	23.9
115	3.3_2			12.4_1		2.0_3	3.7_4			2.4_5		256	23.8
116	3.2_1	3.4_3	11.9_2		6.9_4				2.2_5			202	27.6
117	7.2_1	5.8_2			3.7_5	6.4_3			2.1_4			136	25.2
118	2.6_2		11.7_1		3.8_3				2.0_4			172	20.1
119		7.1_1		9.8_2	5.3_3	2.8_5			2.0_4			256	27.0
120	3.9_1	6.7_2	8.1_3		2.9_4				2.6_5	0.5_6		36	24.7

APPENDIX I (contd)

machines / components	A	B	C	D	E	F	G	H	I	J		Batch sizes	Total Processing Times
121		9.9_2	2.4_1			4.1_4		6.4_3				256	22.8
122	2.4_3	2.3_2		3.2_1	3.8_6	2.9_7	2.4_5			0.9_4		59	17.9
123	2.3_2	2.4_1	6.6_3			1.4_6		5.6_5	4.3_4			128	22.6
124	2.8_2		4.8_1		3.6_4		4.0_3					108	15.2
125	2.3_1	2.2_3	2.6_2	3.2_4		5.3_7		2.2_6	0.8_5			36	18.6
126		6.5_1			3.3_4		3.1_2			1.6_3		118	14.5
127		2.5_1		10.0_2	1.7_3	1.8_4			1.3_5			72	17.3
128			2.3_1	4.8_2		3.1_3			3.3_5	1.0_4		72	14.5
129	3.4_1		16.6_2		4.2_3	1.6_4		2.0_5				198	27.8
130	3.1_2			7.7_1		6.5_3			2.0_5	1.4_4		108	20.7
131	3.2_1		8.7_2				1.8_4		4.1_3			72	17.8
132	2.5_2	2.4_1	7.0_3			2.7_5			2.1_4	0.3_6		75	17.0
133	4.1_2	2.6_1		7.1_3		3.4_4						115	17.2
134		13.7_1	8.6_2		2.6_3		3.2_5	1.2_4				112	29.3
135	2.3_2		7.8_1			5.6_3			3.6_4			100	19.3

machines / components	A	B	C	D	E	F	G	H	I	J		Batch sizes	Total Processing Times
136	2.2_1			4.5_2		2.0_4	5.4_3	1.5_6	1.1_5			128	16.7
137		6.7_1		14.4_2	5.4_3				4.3_4			429	30.8
138		4.0_2	9.6_1			3.2_3	1.3_4					72	18.1
139	2.8_2		7.2_1		4.8_4	3.2_3				0.9_5		54	18.9
140		13.9_1			8.7_2		5.7_3		2.3_4			787	30.6
141	2.8_2	3.0_3		3.3_1		2.8_5			0.4_4	2.9_6		196	15.2
142			8.4_1	8.0_2		5.4_4			2.1_3			156	23.9
143	2.7_1	2.4_3	6.9_2				1.7_4		3.4_5			72	17.1
144	2.8_1		5.8_2			3.5_5	2.7_3	2.8_4				110	17.6
145	3.1_2		6.2_1			3.6_3	1.8_4		1.4_5			123	16.1
146	2.9_1	2.9_3	8.6_2			3.6_4	4.3_5					172	22.3
147	2.2_2	2.3_1	5.6_3			3.8_5	6.1_7		0.7_4	0.7_6		59	21.4
148	2.4_3	2.3_2	4.8_1		3.8_5					0.5_4		59	14.8
149	2.3_2		2.9_1				9.9_5	1.1_6	0.5_3	1.1_4		28	17.8
150		6.4_1				2.3_2	6.4_3			3.0_4		208	18.1

APPENDIX II

The effective machine capacity for 6 months = 24 x 40 x 75% = 720 hours
= 43200 minutes
= 432 time units

Type of Machine		Workloads (Time Units)	Machine Utilisation (%)	Number of Machines	Total Utilisation of each machine type (%)	Number of Operators
Turning Machines	A	359.5	83.2	1	413.4	4 (Turner)
	B	346.7	80.3	1		
	C_1 & C_2	719.0	166.4	2		
	D	360.6	83.5	1		
Drilling Machines	E	263.6	61.0	1	127.1	1 (Driller)
	F	285.6	66.1	1		
Milling Machines	G	292.7	67.8	1	67.8	1 (Miller)
Grinding Machines	H	146.9	34.0	1	77.7	1 (Grinder)
	I	188.9	43.7	1		
Keyseating Machines	J	66.6	15.4	1	15.4	(Manned by Miller)
TOTAL WORKLOADS		3030.1				

Labour and Machine Requirements

APPENDIX III

Table Showing Short-term (One-week) Production Programme.

(All Figures are in Time Units).

KEY

P_n: where P = Processing Time

n = Operation Sequence Number

$\bar{T}_{i1}$ and $\bar{T}_{i2}$ are Calculating Parameters of Petrov's Rules III and IV

M_{i1} and M_{i2} are Calculating Parameters of Proposed Rule Y.

APPENDIX III

													SEQUENCE								
													PETROV'S RULES					PROPOSED RULE			
COMPONENTS \ MACHINES		A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 1	1	2.4_3		2.7_2	2.9_1		4.5_5		2.5_4	0.7_6		15.7	2.7	2.6	-0.1	2	2	5.6	12.8	+7.2	5
	2	2.3_1		5.2_2				5.3_4	3.7_3			16.5	3.8	4.5	+0.7	6	1	7.5	14.2	+6.7	6
	3	2.6_2	2.5_1		7.3_3	2.3_5		2.0_6			1.1_4	17.7	4.1	1.8	-2.3	5	8	5.1	15.2	+10.2	3
	4	2.2_2	2.2_1		3.1_3			1.5_6	1.7_4	1.4_5		12.1	2.5	1.5	-1.0	1	4	4.4	9.9	+5.5	1
	5			9.2_1		3.7_5		1.8_2		1.2_3	3.6_4	19.5	4.1	2.8	-1.3	8	5	9.2	19.5	+10.3	2
	6	3.8_2		12.9_1		4.1_3				2.3_4		23.1	8.4	3.2	-5.2	3	3	12.9	23.1	+10.2	8
	8	2.3_1	2.1_3	4.0_2		1.9_6		2.2_4	2.7_5			15.2	2.8	2.3	-0.5	4	6	6.3	12.9	+6.6	4
CAPACITY REQUIRED		15.6	6.8	34.0	13.3	12.0	4.5	12.8	10.6	5.6	4.7	119.8									
M/C LOADED VALUE ORDER		K_2	K_7	K_1	K_3	K_5		K_4	K_6	K_8	K_9										

APPENDIX III (contd)

													SEQUENCE									
													PETROV'S RULES					PROPOSED RULE				
MACHINES / COMPONENTS		A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 2	7	2.7_2			5.5_1		3.1_4	4.5_3			1.8_5	17.6				7	7				7
	9	2.5_2		6.1_1			5.9_3		2.5_4	1.0_5	0.3_6	18.3	4.8	1.3	-3.5	11	11	6.1	18.3	+12.2	11
	10			14.1_1		4.5_3				2.2_2		20.8	8.2	3.4	-4.8	13	13	14.1	20.8	+6.7	9
	11	2.7_2		5.4_1		2.2_3		6.9_4			2.1_5	19.3	3.4	3.7	+0.3	10	14	5.4	19.3	+13.9	13
	13	3.3_3	2.6_1	5.1_2			3.3_5		7.1_6		0.4_4	21.8	3.7	3.6	-0.1	14	9	7.7	19.2	+11.5	14
	14	2.4_2		6.3_1				2.8_3	4.3_5	1.5_4		17.3	3.8	2.9	-0.9	9	10	6.3	17.3	+11.0	10
CAPACITY REQUIRED		13.9	2.6	37.0	5.5	6.7	12.3	14.2	13.9	4.7	3.9	115.1									
M/C LOADED VALUE ORDER		K_3	K_9	K_1	K_6	K_5	K_4	K_2	K_3	K_7	K_8										

APPENDIX II (contd)

	MACHINES / COMPONENTS	A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	SEQUENCE								
													PETROV'S RULES					PROPOSED RULE			
													$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 3	12	2.9_2		6.5_1			5.8_3	2.4_4			1.4_5	19.0				12	12				12
	15	2.4_1		8.7_2				4.9_3	2.3_4		2.0_5	20.3	5.3	3.1	-2.2	17	17	16.0	9.2	-6.8	16
	16		2.4_1		6.9_2	1.6_5		9.2_3		1.3_4		21.4	6.2	4.0	-2.2	16	23	9.3	19.0	+9.7	23
	17	2.5_1	2.3_2	8.0_3			2.8_5			1.7_4		17.3	4.3	4.2	-0.1	18	16	12.8	12.5	-0.3	18
	18		5.8_2		10.8_1					1.7_3		18.3	8.3	3.8	-4.5	15	15	10.8	18.3	+7.5	17
	20	3.9_2	3.8_3	3.9_1		1.7_5		1.1_6	1.3_4	0.6_7	0.7_8	17.0	3.2	1.0	-2.2	23	20	15.7	2.4	-13.3	15
	23	2.3_2		6.0_1			2.6_3		1.5_5	1.4_4		13.8	3.6	1.8	-1.8	20	18	6.0	13.8	+7.8	20
CAPACITY REQUIRED		14.0	14.3	33.1	17.7	3.3	11.2	17.6	5.1	6.7	4.1	127.1									
M/C LOADED VALUE ORDER		K_5	K_4	K_3	K_1	K_{10}	K_6	K_2	K_8	K_7	K_9										

APPENDIX II (contd)

													SEQUENCE								
													PETROV'S RULES					PROPOSED RULE			
	MACHINES / COMPONENTS	A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 4	19	2.4_2	2.7_1	8.3_3		2.1_5		2.0_6		2.6_4		20.1				19	19				19
	21		4.1_1	3.8_2	2.0_3	2.8_4		1.9_6		0.8_5		15.4	3.3	1.8	-1.5	24	24	7.9	11.3	+3.4	24
	22		4.0_1			8.4_3		5.5_4		4.4_2		22.3	4.2	7.0	+2.8	22	22	22.3	5.5	-16.8	29
	24	2.3_2		5.0_1			2.8_3	6.9_4	3.7_5	0.8_6		21.5	3.4	3.8	+0.4	29	21	5.0	21.5	+16.5	21
	29	2.4_2	2.8_3	11.6_1		4.2_4				4.3_5		25.3	5.6	3.8	-1.8	31	29	11.6	25.3	+13.7	31
	31	2.4_3	2.4_1	8.7_2			1.6_4	1.6_5				16.7	4.5	1.9	-2.6	21	31	11.1	14.3	+3.2	22
CAPACITY REQUIRED		9.5	16.0	37.4	2.0	17.5	4.4	17.9	3.7	12.9		121.3									
M/C LOADED VALUE ORDER		K_6	K_4	K_1	K_9	K_3	K_7	K_2	K_8	K_5											

												SEQUENCE								
												PETROV'S RULES					PROPOSED RULE			
MACHINES / COMPONENTS		A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 5	25		6.3_2	6.2_1			3.2_5	5.4_3	1.4_4	2.2_6		24.7				25	25				25
	26		4.1_1	10.3_2		8.7_3	6.2_4				1.8_5	31.1				26	26				26
	27	5.3_2	5.2_1		5.4_3		3.2_5				1.7_4	20.8	5.3	3.4	-1.9	33	32	5.2	20.8	+15.6	27
	28			10.5_1			2.3_3	3.4_4		1.6_2		17.8	6.1	2.9	-3.2	27	33	10.5	17.8	+7.3	28
	32	2.3_1			3.7_2	2.0_3		2.9_5	1.8_4		0.9_6	13.6	2.7	1.9	-0.8	28	27	8.0	7.6	-0.4	33
	33	2.8_1		8.4_2		5.0_3			2.9_4			19.1	5.6	4.0	-1.6	32	28	11.2	16.3	+5.1	32
CAPACITY REQUIRED		10.4	15.6	35.4	9.1	15.7	14.9	11.7	6.1	3.8	4.4										
M/C LOADED VALUE ORDER		K_6	K_3	K_1	K_7	K_2	K_4	K_5	K_8	K_{10}	K_9										

APPENDIX II (contd)

MACHINES / COMPONENTS		A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	SEQUENCE								
													PETROV'S RULES					PROPOSED RULE			
													$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 6	30	2.3_2		3.8_1			2.9_4	7.3_5	2.3_3			18.6				30	30				30
	34	2.3_1	2.4_3	8.0_2		3.5_4			2.6_5			18.8	4.2	2.8	-1.4	36	35	2.3	18.8	+16.5	37
	35	3.8_1			6.2_2		10.8_4		2.9_3			23.7	5.0	6.9	+1.9	43	36	3.8	23.7	+19.9	35
	36	2.5_2	2.7_1	6.0_3				1.9_5	6.3_4			19.4	3.7	4.7	+1.0	35	43	5.2	16.7	+11.5	34
	37	3.8_1		8.6_3	8.6_2		3.2_5				1.3_4	25.5	7.0	4.4	-2.6	37	34	3.8	25.5	+21.7	36
	43	2.9_2	3.0_1	6.8_3					3.2_4	3.9_5		19.8	4.2	4.6	+0.4	34	37	5.9	16.8	+10.9	34
CAPACITY REQUIRED		17.6	8.1	33.2	14.8	3.5	16.9	9.2	17.3	3.9	1.3	125.8									
M/C LOADED VALUE ORDER		K_1	K_7	K_4	K_5	K_8	K_3	K_6	K_2	K_9	K_{10}										

APPENDIX II (contd)

													SEQUENCE									
													PETROV'S RULES					PROPOSED RULE				
MACHINES / COMPONENTS		A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 7	38	2.4_1		6.1_2			5.2_3		2.6_5	1.7_4		18.0				38	38				38
	39	3.6_2			7.3_1		5.4_5	1.9_3			1.2_4	19.4	4.3	2.8	-1.5	47	47	7.3	19.4	+12.1	39
	40			10.6_1		1.7_3	3.1_2	1.6_5		1.9_4		18.9	5.1	1.7	-3.4	39	41	13.7	8.3	-5.4	47
	41	2.4_1		4.0_2		3.1_3	5.2_4		1.3_5	1.3_6		17.3	3.2	2.6	-0.6	41	39	14.7	7.8	-6.9	45
	45	2.6_1	2.6_3		5.2_2	1.7_5		2.4_4	0.6_7	2.0_6		17.1	3.2	1.7	-1.5	46	45	7.8	14.5	+6.7	46
	46	2.9_1		8.0_2		3.3_5		1.9_3			1.6_4	17.7	4.3	2.3	-2.0	45	46	10.9	14.8	+3.9	40
	47	4.0_1		8.4_3	7.9_2					2.7_4		23.0	6.0	5.6	-0.4	40	40	11.9	19.0	+7.1	41
CAPACITY REQUIRED		17.9	2.6	37.1	20.4	9.8	18.9	7.8	4.5	9.6	2.8	131.4									
M/C LOADED VALUE ORDER		K_4	K_{10}	K_3	K_1	K_5	K_2	K_8	K_7	K_6	K_9										

APPENDIX II (contd)

												SEQUENCE									
												PETROV'S RULES					PROPOSED RULE				
COMPONENTS \ MACHINES		A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 8	42	3.1_3	3.1_2		10.0_1				4.6_4		1.6_5	22.4				42	42				42
	44		3.1_1		8.6_3		5.5_2					17.2				44	44				44
	48		9.0_1		4.3_2		2.1_3	1.3_4	1.9_5			18.6	5.1	1.8	-3.3	52	52	13.3	9.6	-3.7	52
	49	2.8_1		14.8_2		2.4_4				2.9_3		22.9	8.8	2.7	-6.1	49	48	17.6	20.1	+2.5	53
	52	3.6_1		5.9_2				3.9_4		2.9_3	3.0_5	19.3	4.1	3.3	-0.8	48	53	9.5	15.7	+6.2	49
	53	2.2_1		10.6_2			2.0_5		2.0_3	0.7_4		17.5	4.9	1.6	-3.3	53	57	12.8	15.3	+2.5	57
	57	2.2_1		8.0_2					1.9_4	1.1_3		13.2	5.1	1.5	-3:6	57	49	10.2	11.0	+0.8	48
CAPACITY REQUIRED		13.9	15.2	39.3	22.9	2.4	9.6	5.2	10.4	7.6	4.6	131.1									
M/C LOADED VALUE ORDER		K_4	K_3	K_2	K_1	K_{10}	K_6	K_8	K_5	K_7	K_9										

APPENDIX II (contd)

													SEQUENCE									
													PETROV'S RULES					PROPOSED RULE			
COMPONENTS \ MACHINES		A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 9	50	2.5_2			4.6_1		10.3_4		1.5_3	1.0_5		19.9				50	50				50
	51	2.4_3	2.3_2		1.4_1		2.8_7	6.4_6	1.0_8	0.8_5	0.4_4	17.5				51	51				51
	54	2.8_1	2.7_2		11.5_3			2.2_4		1.5_5		20.7	5.7	5.1	-0.6	54	56	17.0	15.2	-1.8	56
	55	2.8_2	5.2_1	5.8_3			2.8_5	3.2_6			1.0_4	20.8	4.6	2.3	-2.3	56	54	17.6	6.0	-11.6	54
	56	2.3_3	2.3_2	5.8_1		2.7_4			1.7_5	4.5_6		19.3	3.5	3.0	-0.5	58	58	10.4	11.2	+0.8	55
	58	2.6_1		8.8_2		2.1_5	3.5_4		2.3_3			19.3	4.6	2.6	-2.0	55	55	17.2	5.6	-11.6	58
CAPACITY REQUIRED		15.4	12.5	20.4	17.5	4.8	19.4	11.8	6.5	7.8	1.4	117.5									
M/C LOADED VALUE ORDER		K_3	K_4	K_6	K_2	K_9	K_1	K_5	K_8	K_7	K_{10}										

APPENDIX II (contd)

													SEQUENCE									
													PETROV'S RULES					PROPOSED RULE				
COMPONENTS \ MACHINES		A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 10	59	5.9_2	3.2_1		10.6_3	1.4_5				1.3_4		22.4	6.6	4.4	-2.2	60	60	19.7	13.3	-6.4	66
	60	2.4_1			3.7_4	3.8_5		2.4_3	1.6_6		1.2_2	15.1	2.0	3.0	+1.0	64	64	9.7	9.1	-0.6	61
	61				5.0_1		4.7_5	2.8_4	3.0_3	2.9_2		18.4	3.6	3.5	-0.1	59	61	5.0	18.4	+13.4	68
	64	2.6_2	2.7_1	3.8_3		4.2_4	5.2_5			1.3_6		19.8	3.0	3.6	+0.6	61	66	5.3	17.1	+11.8	64
	66	2.3_1	2.3_3	7.3_2		2.0_5				4.5_4		18.4	4.0	2.9	-1.1	66	69	2.3	18.4	+16.1	69
	68	2.6_1		6.8_2		3.2_5		2.0_3	1.2_4			15.8	3.8	2.1	-1.7	69	68	2.6	15.8	+13.2	60
	69	2.5_2	2.4_3	6.9_1			4.1_5		1.9_4		0.7_6	18.5	3.9	2.2	-1.7	68	59	9.4	11.6	+2.2	59
CAPACITY REQUIRED		18.3	10.6	24.8	19.3	14.6	14.0	7.2	7.7	10.0	1.9	128.4									
M/C LOADED VALUE ORDER		K_2	K_6	K_5	K_1	K_3	K_4	K_9	K_8	K_7	K_{10}										

APPENDIX II (contd)

	MACHINES / COMPONENTS	A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	SEQUENCE								
													PETROV'S RULES					PROPOSED RULE			
													$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 11	62	4.7_2			8.0_1	6.3_4				2.1_3		21.1				62	62				62
	63	4.3_3	3.8_1		12.2_2					1.7_5	2.6_4	24.6				63	63				63
	71		7.7_2	5.5_1		3.5_5	14.4_4			1.3_3		19.4	4.8	2.1	-2.7	76	74	13.2	13.9	+0.7	76
	73	2.3_1		7.9_2			1.4_3	2.7_5	1.0_4		2.7_6	18.0	3.9	2.1	-1.8	74	73	2.3	18.0	+15.7	73
	74	2.3_1		5.7_2			3.2_5		3.7_4	0.5_3		15.4	2.8	2.5	-0.3	73	76	2.3	15.4	+13.1	74
	76	3.5_3	6.2_1	7.5_2		6.2_5				3.2_4	0.4_6	27.0	5.7	3.3	-2.4	71	71	6.2	27.0	+20.8	71
CAPACITY REQUIRED		17.1	17.7	26.6	20.2	16.0	6.0	2.7	4.7	8.8	5.7	125.5									
M/C LOADED VALUE ORDER		K_3	K_2	K_5	K_1	K_4	K_7	K_{10}	K_9	K_6	K_8										

												SEQUENCE									
												PETROV'S RULES					PROPOSED RULE				
	MACHINES / COMPONENTS	A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 12	65		2.8_1		11.9_2		5.7_4			1.7_3		22.1				65	65				65
	67	2.4_3	2.2_2		4.3_1	2.3_7		1.9_5	1.7_4	2.1_6		16.9				67	67				67
	70		11.5_1			6.9_3		4.6_2				23.0				70	70				70
	75	6.5_2			5.1_1		5.7_3	6.6_4				23.9	5.8	6.2	+0.4	75	75	5.1	23.9	+18.8	75
	77	2.9_2	3.2_3	8.1_1			1.9_5		1.3_4			17.4	4.7	2.1	-2.6	80	77	14.2	6.4	-7.8	80
	80	6.0_2		10.1_1		3.2_4				1.5_3		20.8	8.1	2.4	-5.7	77	80	16.1	10.7	-5.4	77
CAPACITY REQUIRED		17.8	19.7	18.2	21.3	12.4	13.3	13.1	3.0	5.3		124.1									
M/C LOADED VALUE ORDER		K_3	K_2	K_7	K_1	K_6	K_4	K_5	K_9	K_8											

APPENDIX II (contd)

														SEQUENCE								
														PETROV'S RULES					PROPOSED RULE			
	COMPONENTS \ MACHINES	A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 13	72	5.4_1	4.7_3		3.6_2		2.3_4	2.0_5				18.0				72	72				72
	78	2.6_2	2.9_1		14.3_3			2.1_5		1.4_4		23.3	6.6	5.9	-0.7	87	87	19.8	17.8	-2.0	82
	79	2.7_2	2.6_3	7.7_1		4.5_4	3.2_5					20.7	4.3	3.4	-0.9	78	84	10.4	13.0	+2.6	79
	82	2.4_1		9.7_2		3.8_4			1.3_5	0.8_3		18.0	4.3	2.0	-2.3	79	78	2.4	18.0	+15.6	78
	84	2.3_2		5.0_1				3.0_5		3.0_4	0.9_3	14.2	2.7	2.3	-0.4	84	79	14.2	3.0	-11.2	84
	87			7.6_1				10.0_3		8.0_2	2.5_4	28.1	7.8	9.0	+1.2	82	82	25.6	12.5	-13.1	87
CAPACITY REQUIRED		15.4	10.2	30.0	17.9	8.3	5.5	17.1	1.3	13.2	3.4	122.3									
M/C LOADED VALUE ORDER		K_3	K_6	K_4	K_1	K_7	K_8	K_2	K_{10}	K_5	K_9										

													SEQUENCE								
													PETROV'S RULES					PROPOSED RULE			
	COMPONENTS \ MACHINES	A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 14	81	2.8_2			4.7_1	3.9_4		4.9_3			2.0_5	18.3				81	81				81
	83	5.5_3	5.7_1		3.6_2		4.1_4	1.5_6		0.9_5		21.3				83	83				83
	85	7.5_2		7.8_1			3.6_5	4.9_6		1.3_3	0.6_4	25.7	5.3	3.0	-2.3	88	88	20.8	8.5	-12.3	89
	86	2.9_2	5.0_3		3.6_1		6.9_5		2.3_4	1.7_6		22.4	3.8	3.6	-0.2	86	86	20.7	8.6	-12.1	88
	88		2.6_2		6.6_1		6.5_4			2.7_3		18.4	4.6	4.6	0.0	89	85	18.4	6.5	-11.9	86
	89		3.0_1	12.4_2		4.2_3				2.3_4		21.9	7.7	3.3	-4.4	85	89	3.0	21.9	+18.9	85
CAPACITY REQUIRED		18.7	16.3	20.2	18.5	8.1	21.1	11.3	2.3	8.9	2.6	128.0									
M/C LOADED VALUE ORDER		K_2	K_4	K_6	K_3	K_8	K_1	K_5	K_{10}	K_7	K_9										

APPENDIX II (contd)

MACHINES / COMPONENTS		A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	SEQUENCE								
													PETROV'S RULES					PROPOSED RULE			
													$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 15	90	7.9_3	3.8_2		5.5_1		4.4_5			1.7_4		23.3	5.7	4.7	-1.0	92	92	9.3	17.8	+8.5	100
	91		13.4_1			2.2_3	3.2_4		6.0_2			24.8	9.7	2.7	-7.0	90	90	13.4	24.8	+11.4	95
	92	2.4_2	2.5_3	9.2_4	4.9_1		2.4_5			1.2_6		22.6	2.6	4.3	+1.7	95	95	9.8	15.3	+5.5	91
	95	2.2_1		3.3_2				12.3_3	0.8_4	0.5_5		19.1	5.9	4.5	-1.4	100	100	5.5	16.9	+11.4	90
	97	2.6_1		10.5_2		2.6_3					1.7_4	17.4	6.6	2.2	-4.4	91	97	13.1	14.8	+1.7	92
	100			10.3_1		5.8_3	4.4_2			1.4_4		21.9	7.4	3.6	-3.8	97	91	10.3	21.9	+11.6	97
CAPACITY REQUIRED		15.1	19.7	33.3	10.4	10.6	14.4	12.3	6.8	4.8	1.7	129.1									
M/C LOADED VALUE ORDER		K_3	K_1	K_2	K_6	K_5	K_4	K_7	K_8	K_9	K_{10}										

APPENDIX II (contd)

	MACHINES / COMPONENTS	A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	SEQUENCE								
													PETROV'S RULES					PROPOSED RULE			
													$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 16	93	4.1_1			12.1_2			5.7_4		3.2_3		25.1				93	93				93
	94	2.5_2	4.6_1	10.4_3		2.9_4			2.4_5			22.8				94	94				94
	96	3.5_3	2.4_1		3.1_2		1.6_7	7.0_6	2.4_5	1.1_4		21.1	2.5	3.0	+0.5	96	99	2.4	21.1	+18.7	96
	99	3.8_1				7.4_2			9.6_3			20.8	5.6	8.5	+2.9	99	96	3.8	20.8	+17.0	99
	101		7.5_1	8.6_2				3.0_4		3.8_3		22.9	8.1	3.4	-4.7	101	103	7.5	22.9	+15.4	101
	103	2.7_1	2.8_3	6.0_2			2.0_5			1.8_4		15.3	3.8	2.2	-1.6	103	101	11.5	6.6	-4.9	103
CAPACITY REQUIRED		16.6	17.3	25.0	15.2	10.3	3.6	15.7	14.4	9.9		128.0									
M/C LOADED VALUE ORDER		K_2	K_1	K_6	K_4	K_7	K_9	K_3	K_5	K_8											

APPENDIX II (contd)

												SEQUENCE									
												PETROV'S RULES					PROPOSED RULE				
COMPONENTS \ MACHINES		A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 17	98	2.4_2		7.8_3	6.1_1		4.8_4			1.8_5		22.9				98	98				98
	102		11.7_1			2.1_3		1.8_5		4.1_4	1.4_2	21.1	5.1	2.7	-2.4	104	104	15.2	8.0	-7.2	105
	104	4.0_1	4.0_2			8.4_4		7.1_3		4.7_5		28.2	5.0	6.7	+1.7	105	105	23.5	13.1	-10.4	102
	105	2.9_1		7.4_2		3.1_4	2.4_3	6.4_5				22.2	4.2	4.0	-0.2	102	107	15.8	9.5	-6.3	104
	106	3.2_3	3.4_1	8.9_2		2.7_4				1.7_5		19.9	5.2	2.5	-2.7	107	102	18.2	4.4	-13.8	106
	107	2.8_1		11.1_2		3.8_5	3.5_4				0.4_3	21.6	4.8	2.6	-2.2	106	106	21.6	3.8	-17.8	107
CAPACITY REQUIRED		15.3	19.1	35.2	6.1	20.1	10.7	15.3		12.3	1.8	135.9									
M/C LOADED VALUE ORDER		K_4	K_2	K_3	K_7	K_1	K_6	K_4		K_5	K_8										

APPENDIX II (contd)

													SEQUENCE									
													PETROV'S RULES					PROPOSED RULE				
COMPONENTS \ MACHINES		A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 18	108	2.4_2	2.9_1	2.9_3		4.7_5		1.9_4		2.4_7	1.0_6	18.2	2.5	2.5	0.0	108	108	5.3	15.3	+100	111
	109	9.3_2	2.5_3		7.2_1	2.2_4		1.8_5		1.4_6		24.4	6.3	1.8	-4.5	111	110	16.5	17.2	+0.7	110
	110	2.6_2	2.3_1	2.8_3	3.3_4		1.4_5	5.6_6	2.2_9	0.7_8	1.3_7	22.2	2.5	2.2	-0.3	112	111	4.9	19.9	+15.0	108
	111	3.4_1		13.3_2		6.9_4		5.2_3				28.8	8.4	6.1	-2.3	110	112	3.4	28.8	+25.4	109
	112	2.6_2		11.8_1				3.6_4			1.8_3	19.8	7.2	2.7	-4.5	109	109	14.4	8.0	-6.4	112
CAPACITY REQUIRED		20.3	7.7	30.8	10.5	13.8	1.4	18.1	2.2	4.5	4.1	113.4									
M/C LOADED VALUE ORDER		K_1	K_6	K_3	K_5	K_4	K_{10}	K_2	K_9	K_7	K_8										

APPENDIX II (contd)

													SEQUENCE									
													PETROV'S RULES					PROPOSED RULE				
COMPONENTS	MACHINES	A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 19	113	2.3_1		2.9_2		1.9_3		4.5_5	3.6_4		0.4_6	15.6	2.4	2.8	+0.4	113	113	2.3	15.6	+13.3	116
	115	3.3_2			12.4_1		2.0_3	3.7_4			2.4_5	23.8	5.9	2.7	-3.2	116	116	15.7	11.4	-4.3	117
	116	3.2_1	3.4_3	11.9_2		6.9_4				2.2_5		27.6	6.2	4.2	-2.0	117	117	3.2	27.6	+24.4	113
	117	7.2_1	5.8_2			3.7_5	6.4_3			2.1_4		25.2	6.5	4.1	-2.4	118	115	7.2	25.2	+18.0	115
	118	2.6_2		11.7_1		3.8_3				2.0_4		20.1	7.2	2.9	-4.3	115	118	14.3	8.4	-5.9	118
CAPACITY REQUIRED		18.6	9.2	26.5	12.4	16.3	8.4	8.2	3.6	6.3	2.8	112.3									
M/C LOADED VALUE ORDER		K_1	K_5	K_3	K_4	K_2	K_6	K_7	K_9	K_8	K_{10}										

APPENDIX II (contd)

													SEQUENCE								
													PETROV'S RULES					PROPOSED RULE			
	MACHINES / COMPONENTS	A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 20	114		3.3_2		9.6_1	7.3_4		3.7_3				23.9				114	114				114
	119		7.1_1		9.8_2	5.3_3	2.8_5			2.0_4		27.0	7.4	3.4	-4.0	119	131	22.2	10.1	-12.1	131
	120	3.9_1	6.7_2	8.1_3		2.9_4				2.6_5	0.5_6	24.7	6.2	2.0	-4.2	131	119	21.6	6.0	-15.6	119
	129	3.4_1		16.6_2		4.2_3	1.6_4		2.0_5			27.8	8.1	2.6	-5.5	129	120	24.2	7.8	-16.4	120
	131	3.2_1		8.7_2				1.8_4		4.1_3		17.8	6.0	3.0	-3.0	120	129	11.9	14.6	+2.7	129
CAPACITY REQUIRED		10.5	17.1	33.4	19.4	19.7	4.4	5.5	2.0	8.7	0.5	121.2									
M/C LOADED VALUE ORDER		K_5	K_3	K_4	K_2	K_1	K_8	K_7	K_9	K_6	K_{10}										

APPENDIX II (contd)

													SEQUENCE									
													PETROV'S RULES					PROPOSED RULE				
	MACHINES / COMPONENTS	A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 21	121		9.9_2	2.4_1			4.1_4		6.4_3			22.8				121	121				121
	122	2.4_3	2.3_2		3.2_1	3.7_6	2.9_7	2.4_5			0.9_4	17.8				122	122				122
	123	2.2_2	2.4_1	6.6_3			1.3_6		5.6_5	4.3_4		22.4	3.7	3.7	0.0	125	125	2.4	22.6	+20.2	123
	124	2.8_2		4.8_1		3.6_4		4.0_3				15.2	3.8	3.8	0.0	123	123	7.6	10.4	+2.8	127
	125	2.3_1	2.2_3	2.6_2	3.2_4		5.3_7		2.2_6	0.8_5		18.6	2.6	2.9	+0.3	124	124	7.1	13.7	+6.6	125
	127		2.5_1		10.1_2	1.7_3	1.8_4			1.3_5		17.4	4.6	1.6	-3.1	127	127	2.5	17.3	+14.8	124
CAPACITY REQUIRED		9.7	19.3	16.4	16.5	9.0	15.4	6.4	14.2	6.4	0.9	114.2									
M/C LOADED VALUE ORDER		K_5	K_1	K_7	K_2	K_6	K_3	K_8	K_4	K_8	K_9										

APPENDIX II (contd)

													SEQUENCE								
													PETROV'S RULES					PROPOSED RULE			
COMPONENTS	MACHINES	A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 22	126		6.5_1			3.3_4		3.1_2			1.6_3	14.5				126	126				126
	128			2.3_1	4.8_2		3.0_3			3.3_5	1.0_4	14.4	3.4	2.5	-0.9	133	133	7.1	12.2	+5.1	130
	130	3.1_2			7.7_1		6.5_3			2.0_5	1.4_4	20.7	5.8	3.3	-2.5	130	128	7.7	20.7	+13.0	128
	132	2.5_2	2.4_1	7.0_3			2.7_5			2.1_4	0.3_6	17.0	4.0	1.7	-2.3	128	143	16.7	3.0	-13.7	133
	133	4.1_2	2.6_1		7.1_3		3.4_4					17.2	3.4	5.3	+1.9	143	132	13.8	10.5	-3.3	143
	138		4.0_2	9.6_1			3.2_3	1.3_4				18.1	6.8	2.3	-4.5	138	130	16.8	4.5	-12.3	138
	143	2.7_1	2.4_3	6.9_2				1.7_4		3.4_5		17.1	4.0	2.6	-1.4	132	138	12.0	7.5	-4.5	132
CAPACITY REQUIRED		12.4	17.9	25.8	19.6	3.3	18.8	6.1		10.8	4.3	119.0									
M/C LOADED VALUE ORDER		K_5	K_3	K_4	K_1	K_9	K_2	K_7		K_6	K_8										

APPENDIX II (contd)

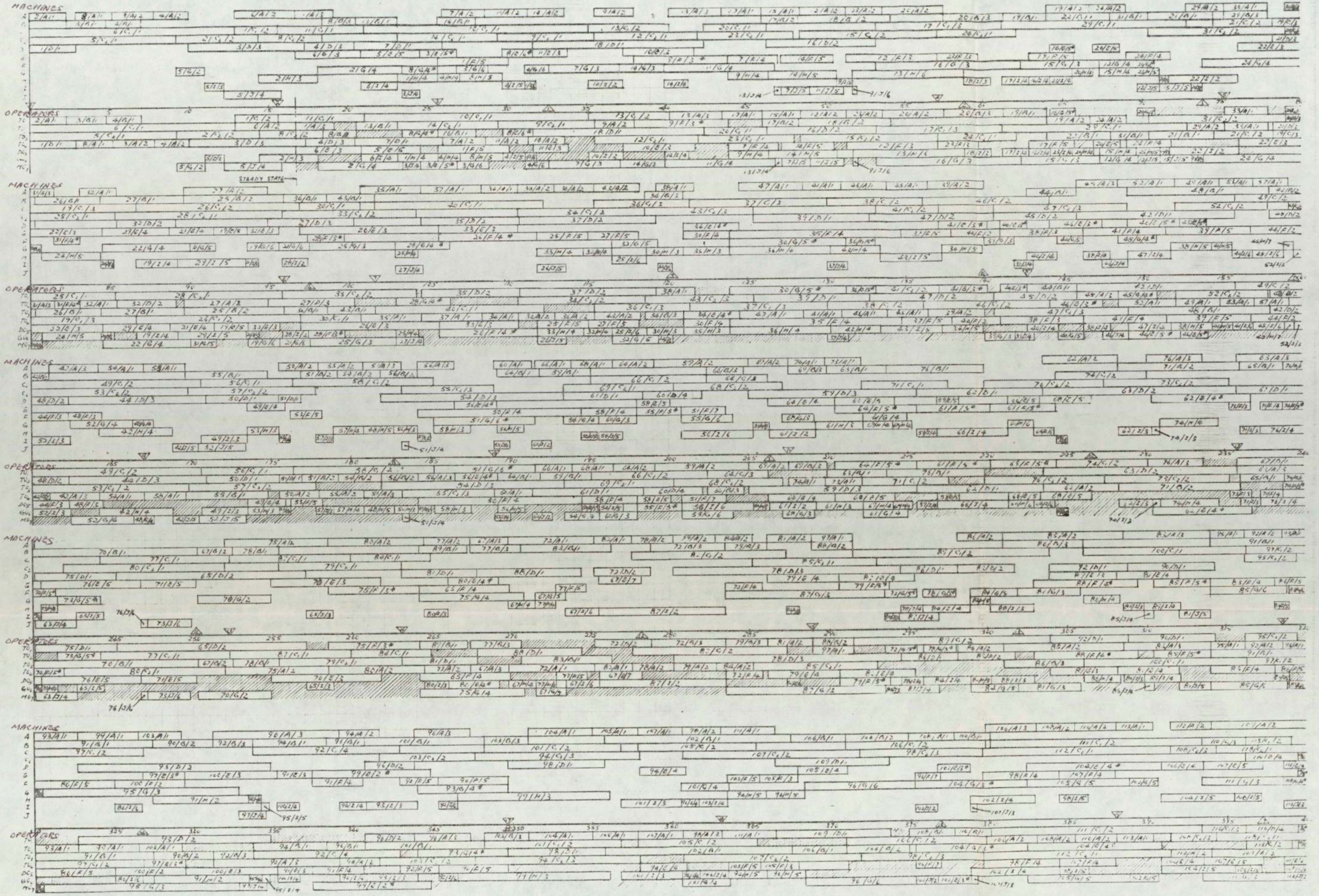
													SEQUENCE									
													PETROV'S RULES					PROPOSED RULE			
COMPONENTS \ MACHINES		A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 23	134		13.7_1	8.6_2		2.6_3		3.2_5	1.2_4			29.3				134	134				134
	135	2.3_2		7.8_1			5.6_3			3.6_4		19.3	5.1	4.6	-0.5	141	141	15.7	9.2	-6.5	139
	136	2.2_1			4.5_2		2.0_4	5.4_3	1.5_6	1.1_5		16.7	4.0	1.5	-2.5	135	135	14.1	4.6	-9.5	135
	139	2.8_2		7.2_1		4.8_4	3.2_3				0.9_5	18.9	4.4	3.0	-1.4	142	139	13.2	8.9	-4.3	141
	141	2.8_2	3.0_3		3.3_1		2.8_5			0.4_4	2.9_6	15.2	3.0	6.1	+3.1	139	136	12.3	5.7	-6.6	136
	142			8.4_1	8.0_2		5.4_4			2.1_3		23.9	8.2	3.8	-4.4	136	142	23.9	5.4	-18.5	142
CAPACITY REQUIRED		10.1	16.7	32.0	15.8	7.4	19.0	8.6	2.7	7.2	3.8	123.3									
M/C LOADED VALUE ORDER		K_5	K_2	K_3	K_4	K_7	K_1	K_6	K_{10}	K_8	K_9										

													SEQUENCE								
													PETROV'S RULES					PROPOSED RULE			
MACHINES / COMPONENTS		A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 24	137		6.7_1		14.4_2	5.4_3				4.3_4		30.8				137	137				137
	140		13.9_1			8.7_2		5.7_3		2.3_4		30.6	11.3	4.0	-7.3	149	149	13.9	30.6	+16.7	140
	144	2.8_1		5.8_2			3.5_5	2.7_3	2.8_4			17.6	3.8	3.0	-0.8	140	144	11.3	9.0	-2.3	144
	145	3.1_2		6.2_1			3.6_3	1.8_4		1.4_5		16.1	4.3	2.3	-2.0	144	145	14.7	3.2	-11.5	149
	149	2.3_2		2.9_1				9.9_5	1.1_6	0.5_3	1.1_4	17.8	1.9	4.0	+2.1	145	140	16.7	11.0	-5.7	145
CAPACITY REQUIRED		8.2	20.6	14.9	14.4	14.1	7.1	20.1	3.9	8.5	1.1	112.9									
M/C LOADED VALUE ORDER		K_8	K_1	K_6	K_3	K_4	K_5	K_2	K_9	K_7	K_{10}										

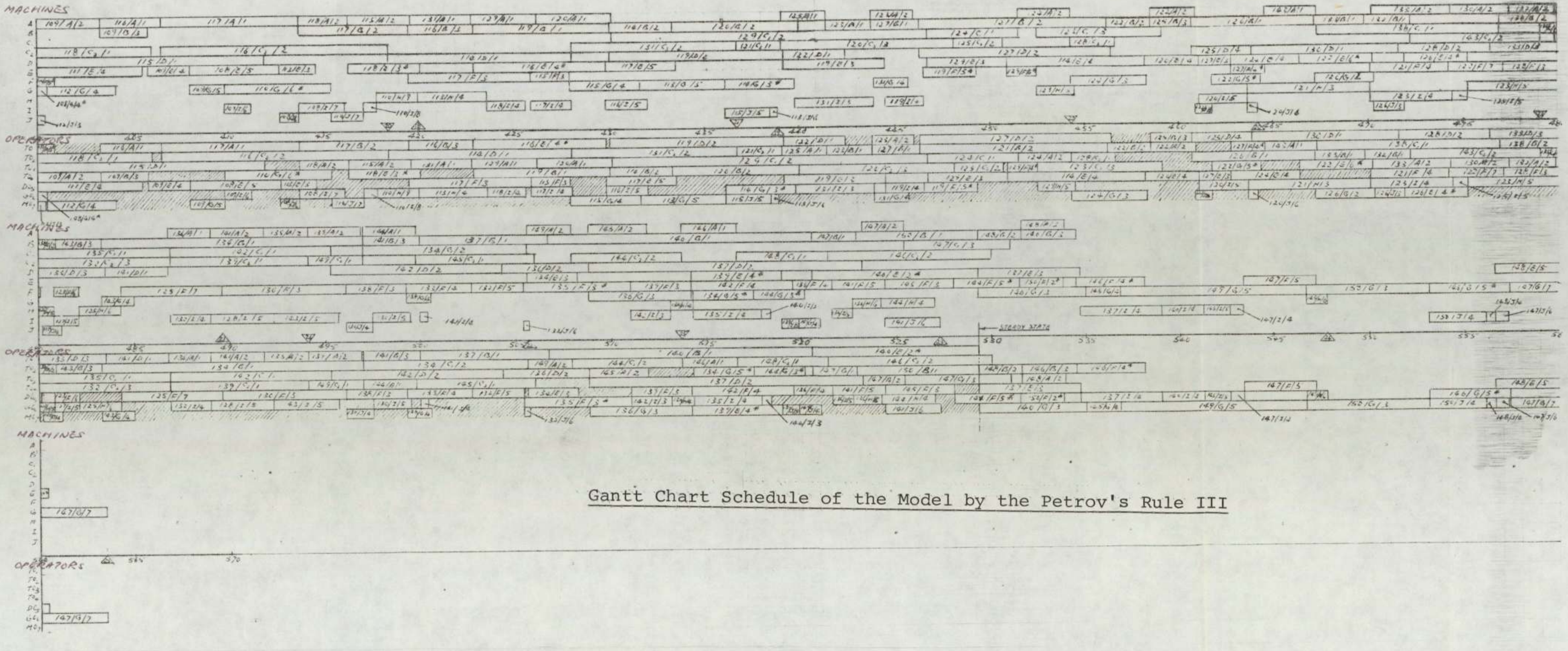
APPENDIX II (contd)

													SEQUENCE									
													PETROV'S RULES					PROPOSED RULE				
MACHINES / COMPONENTS		A	B	C	D	E	F	G	H	I	J	TOTAL PROCESSING TIMES	$\bar{T}_{i1}$	$\bar{T}_{i2}$	$\bar{T}_{i2} - \bar{T}_{i1}$	III	IV	M_{i1}	M_{i2}	$M_{i2} - M_{i1}$	Y
PERIOD 25	146	2.9_1	2.9_3	8.6_2			3.6_4	4.3_5				22.3				146	146				146
	147	2.2_2	2.3_1	5.6_3			3.8_5	6.1_7		0.7_4	0.7_6	21.4	2.7	2.8	+0.1	147	150	21.4	6.1	-15.3	148
	148	2.4_3	2.3_2	4.8_1		3.8_5					0.5_4	14.8	3.2	2.2	-1.0	150	147	7.1	10.0	+2.9	150
	150		6.4_1				2.3_2	6.4_3			3.0_4	18.1	4.4	4.7	+0.3	148	148	15.1	9.4	-5.7	147
CAPACITY REQUIRED		7.5	13.9	19.0		3.8	9.7	16.8		0.7	4.2	75.3									
M/C LOADED VALUE ORDER		K_5	K_2	K_4		K_7	K_3	K_1		K_8	K_6										

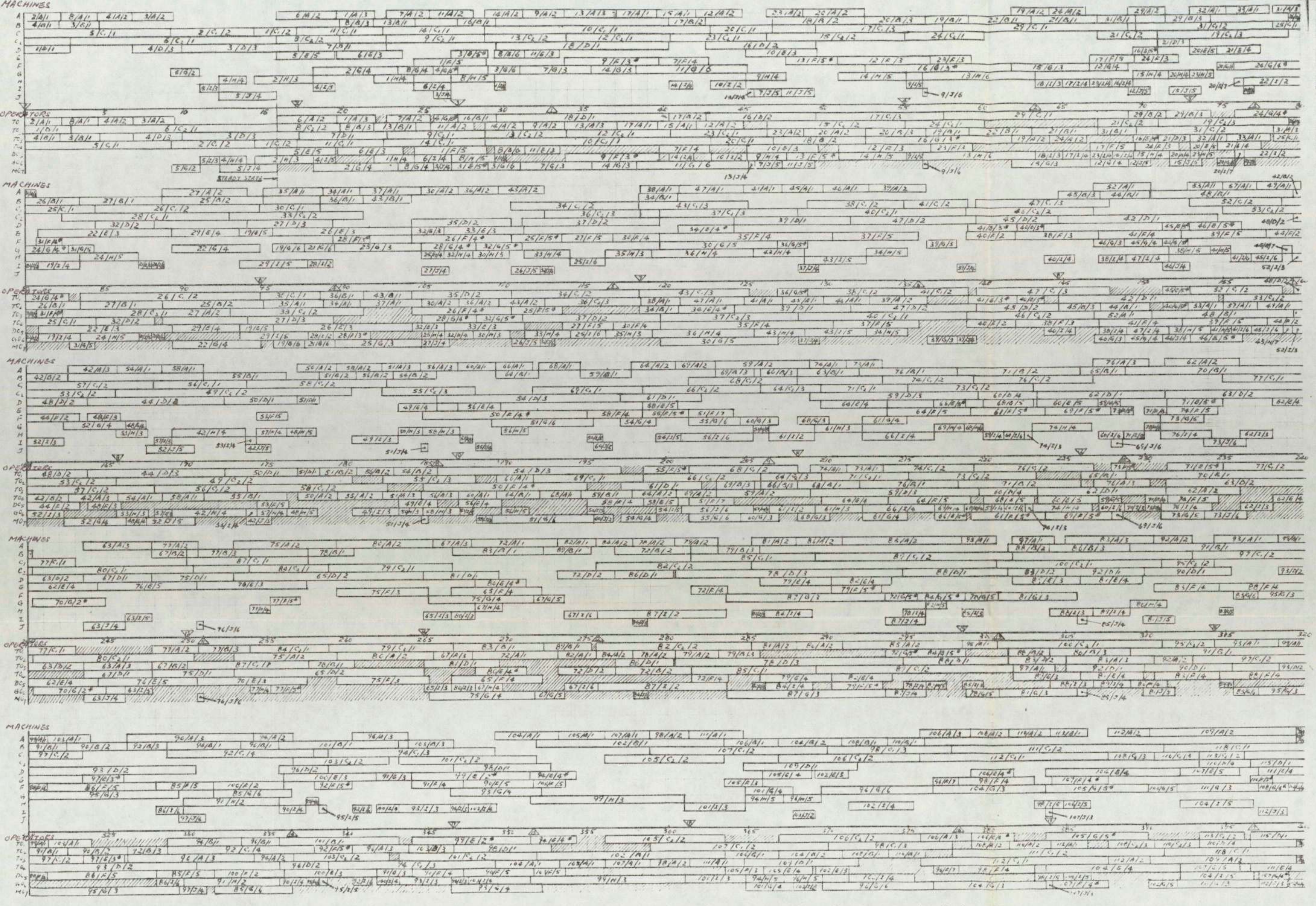
APPENDIX IV



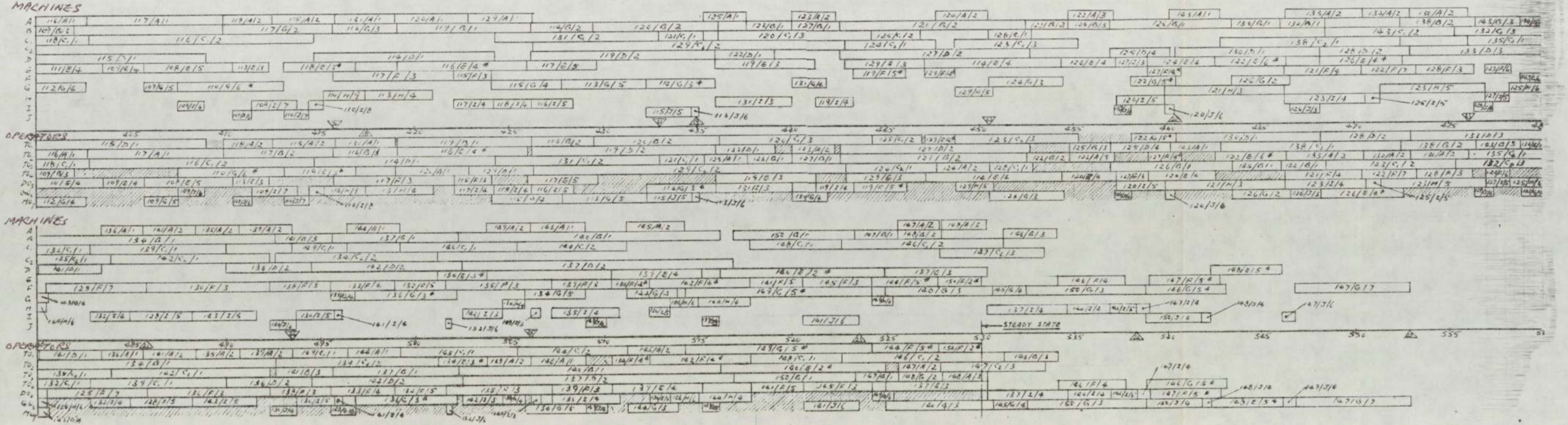
Gantt Chart Schedule of the Model by the Petrov's Rule III



Gantt Chart Schedule of the Model by the Petrov's Rule III

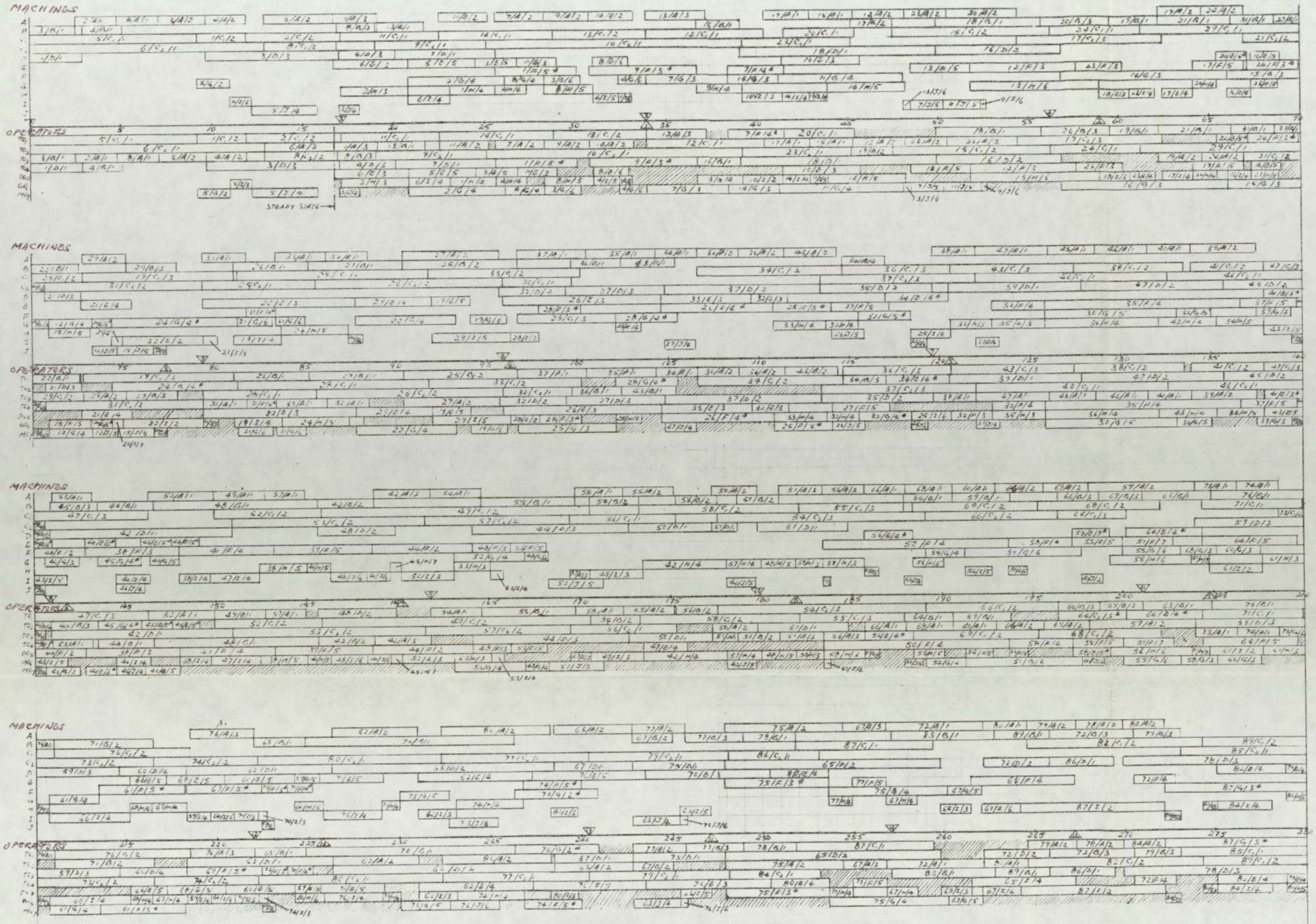


Gantt Chart Schedule of the Model by the Petrov's Rule IV



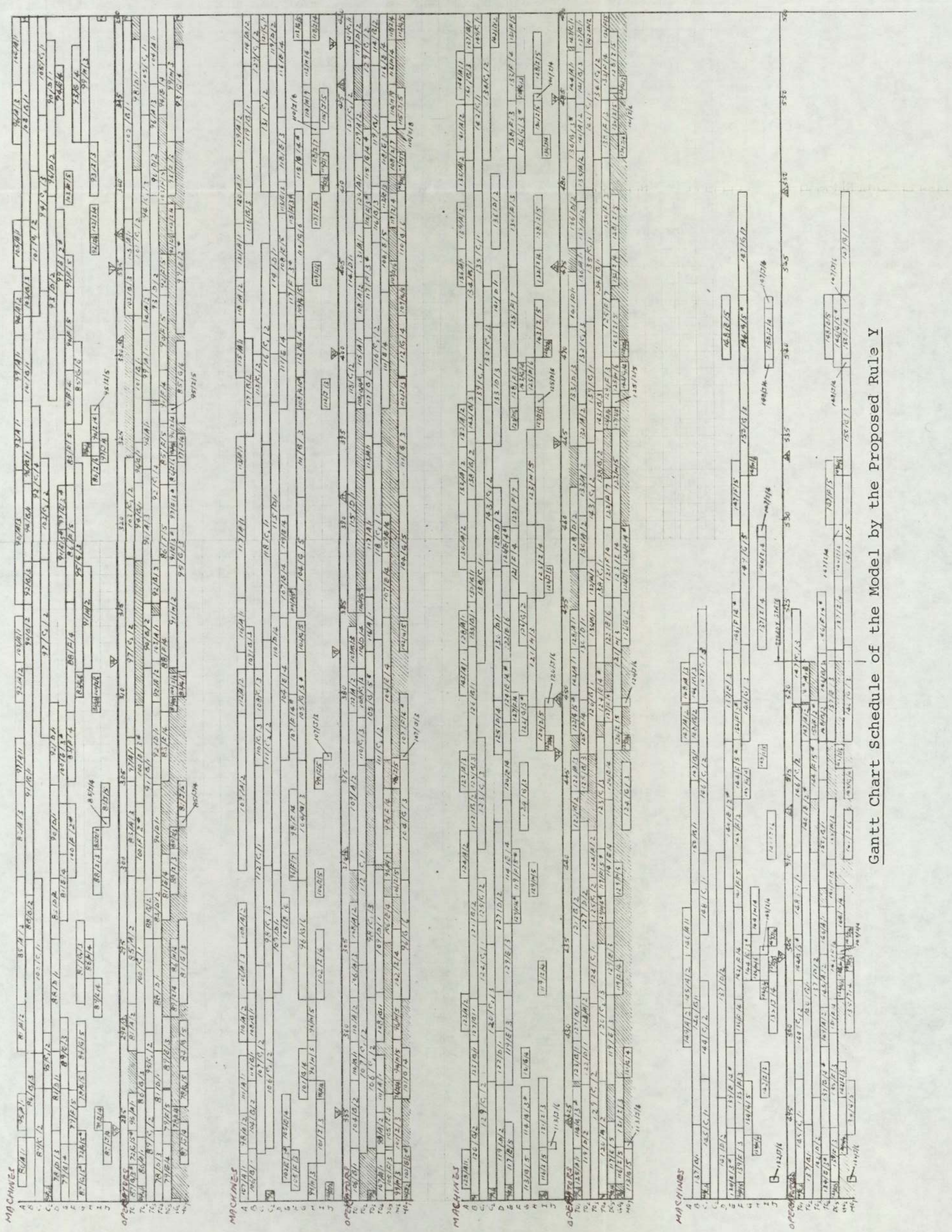
Gantt Chart Schedule of the Model by the Petrov's Rule IV

APPENDIX VI



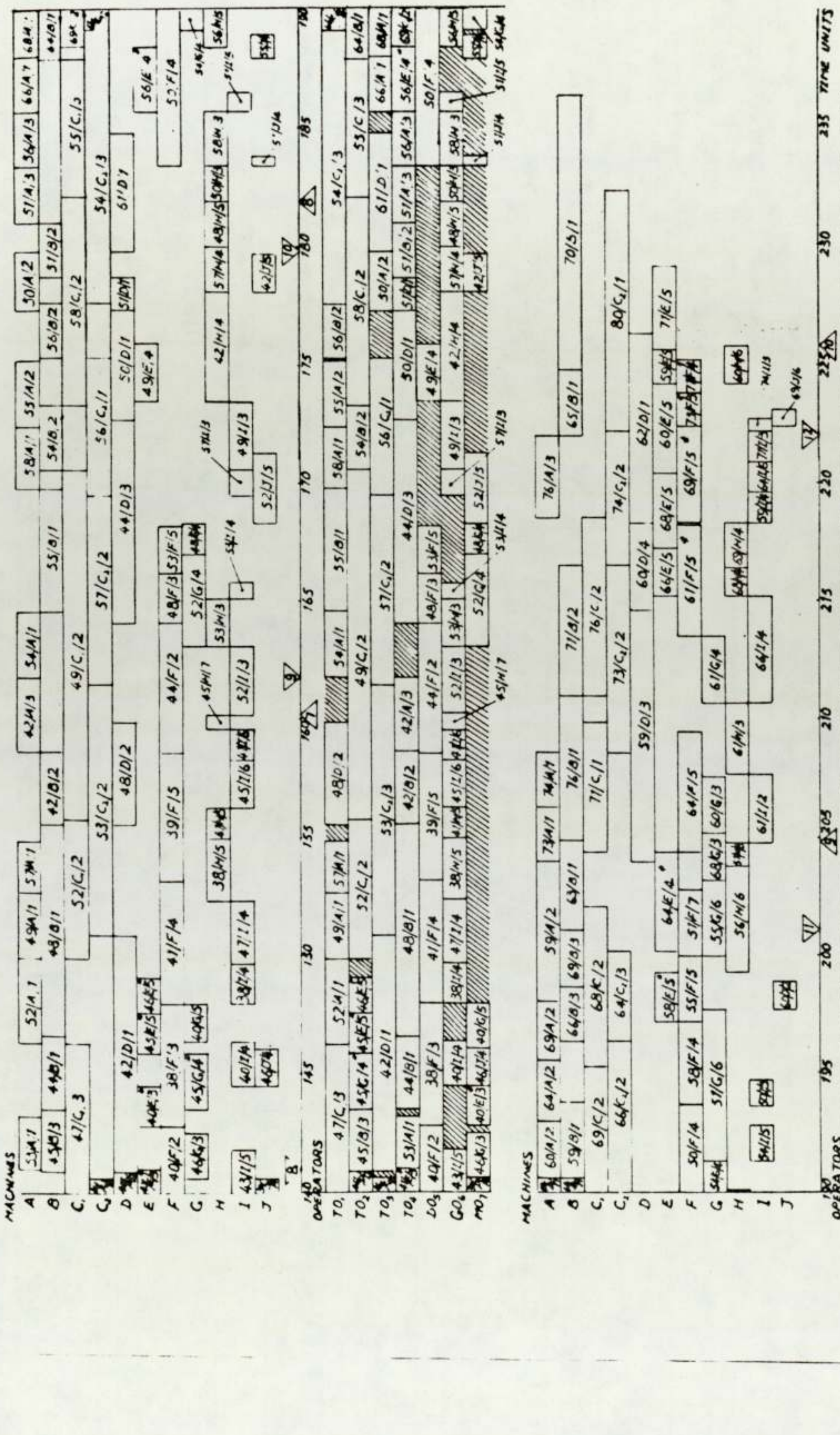
Gantt Chart Schedule of the Model by the Proposed Rule Y

APPENDIX VI (contd)



Gantt Chart Schedule of the Model by the Proposed Rule Y

APPENDIX VII



Gantt Charts Schedule for Periods 8, 9 and 10 by Rule Y (Appendix VI)

APPENDIX VIII

	Appendix IV	Appendix V	Appendix VI
Run-in Transient Period	0.0-16.7	0.0-15.8	0.0-16.7
Run-out Transient Period	529.3-563.5	530.0-552.9	521.7-549.4
Steady state Under consideration	16.7-529.3	15.8-530.0	16.7-521.7
Time Units in Steady Period	512.6	514.2	505.0

(All Figures are in Time Units)

The Steady State and Transient Periods of the Gantt Charts

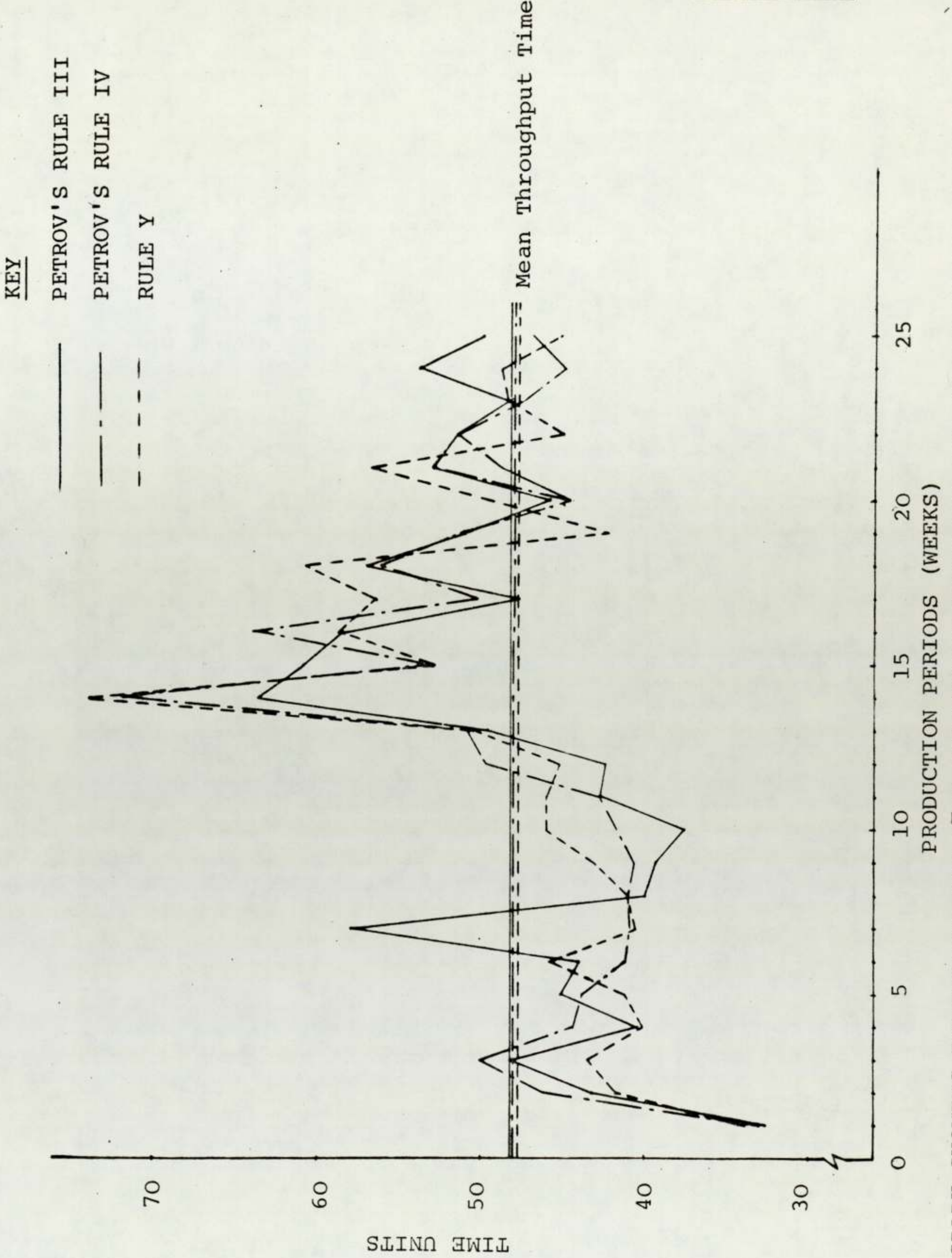
OPERATORS	OPERATORS IDLE TIME (TIME UNITS)			OPERATOR UTILISATION %			SECONDARY SKILL REQUIRED (TIME UNITS)		
	Petrov's Rule		Proposed Rule	Petrov's Rule		Proposed Rule	Petrov's Rule		Proposed Rule
	III	IV	Y	III	IV	Y	III	IV	Y
TO_1	41.4	40.8	43.6	91.92	92.07	91.37	58.9	58.8	31.9
TO_2	57.1	48.2	52.1	88.86	90.63	89.68	24.6	30.5	50.2
TO_3	41.5	34.8	40.1	91.90	93.23	92.06	44.6	43.3	33.8
TO_4	35.0	47.1	24.1	93.17	90.84	95.23	28.7	29.7	32.1
DO_5	137.8	125.7	116.9	73.12	75.55	76.85	-	-	-
GO_6	157.4	156.3	153.5	69.29	69.60	69.60	33.0	35.0	23.9
MO_7	232.4	232.3	210.1	54.66	54.82	58.40	31.2	24.3	28.1
Total	702.6	685.2	640.4	80.42	80.96	81.88	221.0	221.6	200.0
Average									

Summary of Operators' Idle times, Utilisation Percentage and Secondary Skills Required

Rules / Period	Petrov's Rules		Proposed Rule
	III	IV	Y
1	32.6	33.0	33.9
2	43.2	46.2	41.8
3	48.2	50.0	43.5
4	40.4	44.3	40.1
5	45.1	43.8	41.2
6	44.0	41.2	45.9
7	57.9	40.9	40.6
8	40.0	41.0	41.0
9	39.3	40.7	43.0
10	37.6	41.7	46.0
11	42.7	42.8	46.0
12	42.4	49.7	45.2
13	49.6	50.8	50.3
14	63.6	71.7	73.7
15	60.8	53.1	52.9
16	58.3	63.9	58.6
17	47.6	50.2	56.4
18	56.9	56.1	60.7
19	50.9	51.1	42.2
20	45.8	44.6	49.6
21	52.9	52.8	56.7
22	51.4	51.4	45.0
23	48.2	47.4	48.3
24	53.7	44.8	48.7
25	49.8	46.8	45.1
Mean Throughput	48.12	48.00	47.86

Throughput Time (Time Units)

APPENDIX XI



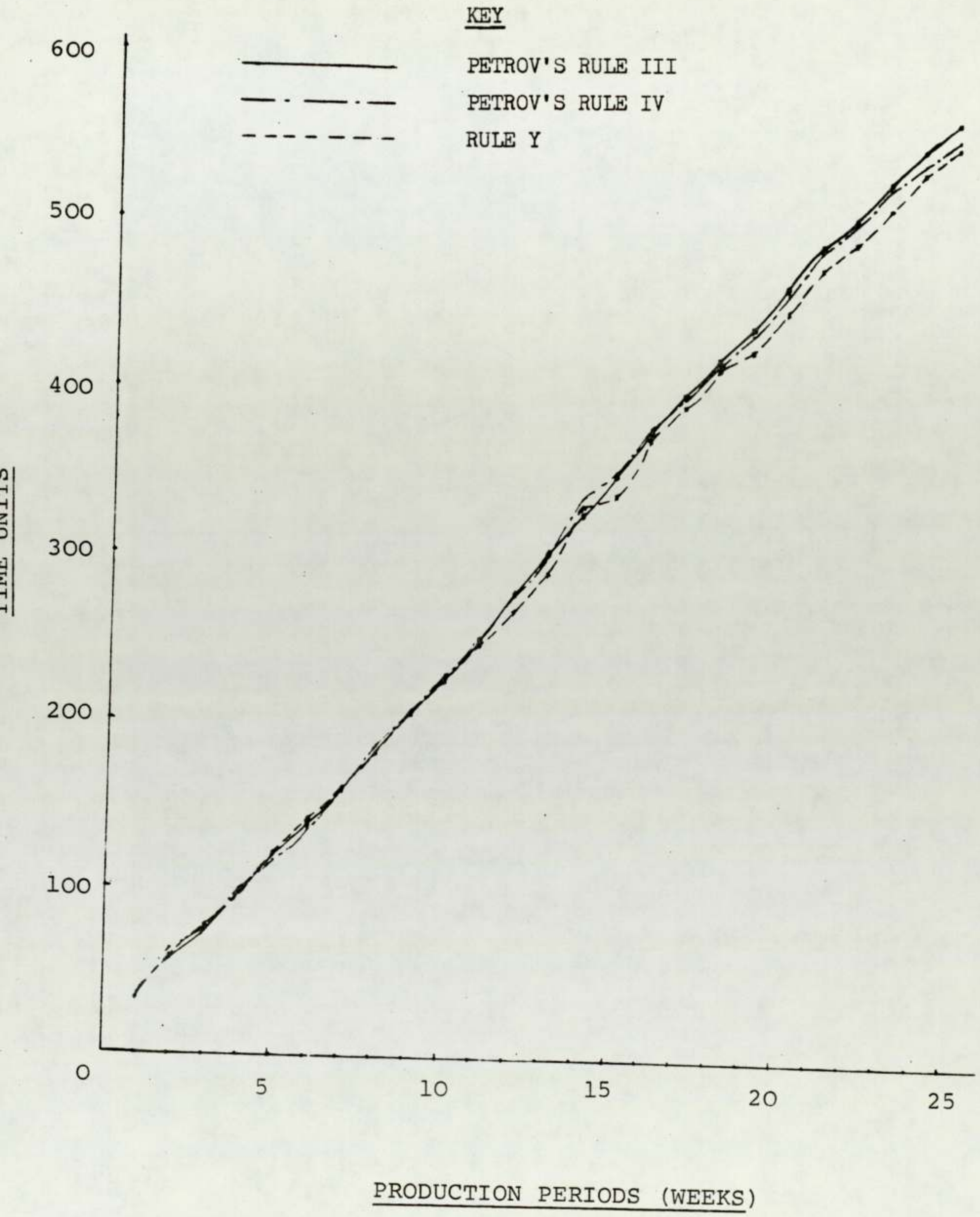
GRAPH SHOWING INDIVIDUAL AND MEAN THROUGHPUT TIMES FOR THE 25 PRODUCTION PERIODS

APPENDIX XII

Rules / Periods	Petrov's Rule		Proposed Rule
	III	IV	Y
1	32.6	33.0	33.9
2	58.8	63.3	58.9
3	73.8	77.1	77.4
4	97.5	99.4	96.3
5	120.3	116.8	120.6
6	139.9	135.9	141.8
7	159.5	159.4	160.2
8	182.7	185.7	181.9
9	206.3	206.4	204.8
10	226.6	228.7	225.8
11	250.2	251.0	247.1
12	278.2	275.7	267.2
13	301.9	300.8	290.7
14	326.7	336.5	330.8
15	349.7	351.6	337.1
16	376.9	378.2	370.5
17	397.3	396.8	391.5
18	420.0	417.4	415.9
19	438.9	435.1	424.6
20	464.2	460.4	449.6
21	489.6	485.8	475.0
22	505.7	501.9	491.3
23	527.3	523.5	512.9
24	547.8	538.3	533.7
25	563.5	552.9	549.4

Cumulative Throughput Time (Time Units)

APPENDIX XIII



GRAPH SHOWING CUMULATIVE THROUGHPUT TIME OVER 25 PRODUCTION PERIODS

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